Compilation of 20 publications from the Vauxhall Irrigated Rotation Study, 2000-11, 2012

Paper	Short title	Full Title
1	Potato agronomy	Conservation management practices and rotations for irrigated processing potato in southern Alberta.
2	Dry bean agronomy	Conservation management practices and rotations for irrigated dry bean production in southern Alberta.
3	Soft wheat agronomy	Soft white spring wheat is largely unresponsive to conservation management in irrigated rotations with dry bean, potato and sugar beet.
4	Sugar beet agronomy	Sugar beet response to rotation and soil management in a 12-year irrigated study in southern Alberta.
5	Dry bean bioassay (2012)	Assessing legacy effects of a 12-yr cropping systems study with a post-hoc bioassay.
6	Surface soil properties at end of study	Surface soil quality attributes following 12 years of conventional and conservation management on irrigated rotations in southern Alberta.
7	Soil property changes during study	Soil changes over 12 yr of conventional vs. conservation management on irrigated rotations in southern Alberta.
8	Soil microbiology 1	Phospholipid fatty acid biomarkers show positive soil microbial community responses to conservation soil management of irrigated crop rotations.
9	Soil microbiology 2	Pyrosequencing reveals profiles of soil bacterial communities after 12 years of conservation management on irrigated crop rotations.
10	Soil microbiology 3	Soil microbial biomass and its relationship with yields of irrigated wheat under long-term conservation management.
11	Soil water	Soil water dynamics over 12 seasons on irrigated dry bean–potato–wheat–sugar beet rotations.
12	Surface residue cover	Soil surface cover on irrigated rotations for potato (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.), and soft white spring wheat (*Triticum aestivum* L.) in southern Alberta.
13	Weed populations	Conservation management and crop rotation effects on weed populations in a 12-year irrigated study.
14	Potato nematodes	Crop rotation effects on *Pratylenchus neglectus* populations in the root zone of irrigated potatoes in southern Alberta.
15	Potato economics	Economic comparison of conventional and conservation management practices for irrigated potato production in southern Alberta.
16	Potato energy use	Energy use efficiency of conventional versus conservation management practices for irrigated potato production in southern Alberta.
17	Dry bean economics	Economics of conventional and conservation practices for irrigated dry bean rotations in southern Alberta.
18	Entomology: Beneficial insects	Carabid assemblages (Coleoptera: Carabidae) in a rotation of three different crops in southern Alberta, Canada: A comparison of sustainable and conventional farming.
19	Potato endophytes 1	Populations, diversity and identities of bacterial endophytes in potato (*Solanum tuberosum* L.) cropping systems.
20	Potato endophytes 2	Plant growth-promoting and phytopathogen-antagonistic properties of bacterial endophytes from potato (*Solanum tuberosum* L.) cropping systems.

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American Journal of Potato Research
The Official Journal of the Potato Association of America

ISSN 1099-209X
Volume 93
Number 1

Am. J. Potato Res. (2016) 93:50-63
DOI 10.1007/s12230-015-9487-z

Springer

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Conservation Management Practices and Rotations for Irrigated Processing Potato in Southern Alberta

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Published online: 17 November 2015

Abstract Irrigated processing potato production is an important part of southern Alberta's agricultural economy. A 12-year (2000–11) study compared conservation (CONS) and conventional (CONV) management for potato in 3- to 6-year rotations which also included dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.), and soft wheat (*Triticum aestivum* L.). Oat (*Avena sativa* L.) and timothy (*Phleum pratense* L.) were added to the longest rotation. Conservation management included reduced tillage, cover crops, feedlot manure compost addition, and solid-seeded dry bean. Averaged over 12 years, a 5-year CONS rotation (potato–wheat–sugar beet–wheat–dry bean) resulted in 18 % higher marketable tuber yield than a 3-year CONV rotation (potato–dry bean–wheat). Reduced incidence of potato early dying was also found with CONS management. Results indicate that integration of CONS management practices led to yield and disease control benefits without negatively impacting tuber quality.

Resumen La producción de papa para proceso con riego es una parte importante de la economía agrícola del sur de Alberta. Un estudio de 12 años (2000–2011) comparó el manejo de la conservación (CONS) y el convencional (CONV) de papa en rotaciones de 3 a 6 años que también incluyó frijol (*Phaseolus vulgaris* L.), remolacha azucarera (*Beta vulgaris* L.) y trigo suave (*Triticum aestivum* L.). La avena (*Avena sativa* L.) y un pasto o hierba triguera (*Phleum pratense* L.) se agregaron a la rotación más larga. El manejo de conservación incluyó labranza reducida, cultivos de cobertura, composta de estiércol de corral de engorda y frijol de grano sólido. Promediando sobre los 12 años, la rotación de cultivos CONS por cinco años (papa, trigo, remolacha, trigo, frijol) dio como resultado un 18 % de más alto rendimiento de tubérculo comercializable que una rotación CONV de tres años (papa, frijol, trigo). También se encontró incidencia reducida de muerte temprana con manejo CONS. Los resultados indican que la integración de las prácticas de manejo CONS conduce a beneficio en rendimiento y control de enfermedades sin impactar negativamente la calidad de tubérculo.

Keywords Rotation · Soil conservation · Compost · Cover crop · Irrigation · Tuber yield · Tuber size · Specific gravity · Potato early dying

Introduction

With the influx of potato processing plants to southern Alberta in the late 1990s, potato production more than tripled from 5182 ha in 1998 to 16,582 ha in 2003 (Statistics Canada 2013). By 2012, Alberta ranked third in Canada for potato area (22,650 ha) behind Prince Edward Island (36,240 ha) and Manitoba (30,770 ha), and ahead of New Brunswick (21,660 ha), a province with a much longer history of production (Statistics Canada 2013). In the 12 years from 2000 to 11, average potato yields in Alberta were 19 % higher than Prince Edward Island and 28 % higher than Manitoba (Statistics Canada 2013) due to irrigation.

Traditionally, conventional potato production has relied on high levels of soil disturbance in fall and spring, e.g., moldboard plowing, chisel-plowing or double-disking (which can render the soil surface prone to wind erosion), and hilling in

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the early growing season for weed control. Tiessen et al. (2007) quantified significant soil displacement associated with potato planting, hilling and harvesting which led to increased soil translocation and erosivity, especially on sloping land. Soil erosion losses of 22 to 34 Mg ha^{-1} were reported with conventional tillage for potato in Prince Edward Island (Carter and Sanderson 2001). Compared to cereals, potato returns low levels of residue to the soil (Carter and Sanderson 2001; Li et al. 2015) which has implications for maintenance of organic matter and soil quality, especially if potato is rotated with other low-residue crops, e.g., dry bean or sugar beet.

The above issues with conventional potato production have led to studies on conservation practices which aim to maintain or enhance tuber yield, while improving soil quality and pest management, and limiting soil degradation. The Maine Potato Ecosystem Project (Gallandt et al. 1998; Mallory and Porter 2007), contrasted amended vs. unamended soil management strategies as they related to pest management and variety choice. Improvements in soil quality were observed within 1–2 years through additions of manure, compost or green manure. Benefits to tuber yield, weed control and crop quality were also realized. However, even after 6 years benefits to disease and insect management were not as clear. Other conservation management studies have examined zone tillage (Pierce and Burpee 1995; Holmstrom et al. 2006), shifting of primary tillage from fall to spring (Carter et al. 1998; Griffin et al. 2009), subsoiling to alleviate soil compaction (Henriksen et al. 2007; Copas et al. 2009); reduced wheel traffic (Dickson and Ritchie 1996); use of organic amendments to improve tuber yield (Ninh et al. 2015), pathogen suppression (Rowe and Powelson 2002), and soil quality (Grandy et al. 2002); more efficient rotations to lower disease pressure (Gallandt et al. 1998; Carter and Sanderson 2001), and improve pest management (Olanya et al. 2006; VanderZaag 2010); and fall cover crops for control of erosion and nitrate leaching (Stark and Porter 2005; Moyer and Blackshaw 2009).

A number of studies have addressed conservation practices for potato production in the potato growing regions of Atlantic Canada e.g., Carter et al. (2009), Ochuodho et al. (2013), and Rees et al. (2014). However, in western Canada, apart from one rotation study in Manitoba (Mohr et al. 2011), there has been a dearth of regional research information on the merits of implementing conservation rotations for potato and their effects on tuber yield and quality or soil properties.

Therefore a rotation study was initiated in 2000 with a focus on conservation (CONS) management and maintenance of soil quality on irrigated land. The study ran for 12 years (2000–11) and compared CONS management with conventional (CONV) management in 3- to 6- year rotations for the following crops: potato, sugar beet, dry bean, and soft white spring wheat. Timothy and oat were included in the 6-year rotation. The CONS rotations were built around four specific management practices: (1) zero or reduced tillage where possible in the rotation; (2) fall-seeded cover crops; (3) composted cattle manure as a substitute for inorganic fertilizer; and (4) solid-seeded narrow-row dry bean. The specific objectives of this paper were to assess potato yield and quality over 12 years in CONV and CONS rotations (3- to 6-years in length).

Materials and Methods

Experimental Design

The study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50° 03′ N, 112° 09′ W, elev. 781 m) on an Aridic Cryoll (Soil Survey Staff 2010). At the 0–15 cm depth, soil texture was sandy loam, soil organic carbon was 12.9 g kg^{-1} and pH was 6.9. The entire plot area was planted to barley (*Hordeum vulgare* L.) in 1999 and 7 rotations established in spring 2000 (Table 1). Potato was grown in six rotations under CONV or CONS management: two 3-year (3-CONV, 3-CONS) and two 4-year (4-CONV, 4-CONS) rotations, one 5-year (5-CONS) and one 6-year (6-CONS) rotation. A seventh continuous wheat (1-CONT) treatment was also included. The 3-CONV and 3-CONS rotations had similar crop sequences (potato–dry bean–wheat) as had the 4-CONV and 4-CONS (potato–wheat– sugar beet–dry bean) (Table 1). The 5-CONS rotation comprised 2 phases of wheat interspersed with the three row crops (potato–wheat–sugar beet–wheat–dry bean), while oat and timothy were added to the 6-CONS rotation (potato–oat–timothy–timothy–sugar beet–dry bean). Each phase of each rotation appeared in each year, resulting in a total of 26 phases (Table 1) in a randomized complete block design with four replicates (104 plots). Individual plots were 10.1×18.3 m (185 m^2), with a 2.1 m inter-plot between plots. The number of rotation cycles at the end of the 2011 growing season (12 years) ranged from 4 (3-year rotations) to 2 (6-year rotation) (Table 1).

Conservation Management Treatments

Details of management treatments on the CONS rotations (Table 1) were provided by Larney et al. (2015). Briefly, four practices were applied as a "package": 1) direct seeding or reduced tillage where possible in the rotation; 2) fall-seeded cover crops after at least one phase; 3) composted cattle manure; and 4) solid-seeded narrow-row dry bean. Conventional management used none of these practices, and hence the CONV rotations had more intensive fall tillage, no cover crops, no organic amendments and dry bean was grown in wide rows. It should be stated that although so-called CONV management has since declined in southern Alberta,

Table 1 Outline of rotation treatments over 12 years (2000–11), Vauxhall, Alberta

Rotation[a]	Crop sequence	No. crop phases	No. rotation cycles[b]
1-CONT	Wheat	1	12
3-CONV	Potato–Dry bean–Wheat	3	4
4-CONV	Potato–Wheat–Sugar beet–Dry bean	4	3
3-CONS	Potato[c]–Dry bean[c]–Wheat[d]	3	4
4-CONS	Potato[c]–Wheat–Sugar beet–Dry bean[d]	4	3
5-CONS	Potato[c]–Wheat–Sugar beet[d]–Wheat–Dry bean[d]	5	2.4
6-CONS	Potato[c]–Oat/(Timothy)[e]–Timothy–Timothy–Sugar Beet–Dry bean[d]	6	2

[a] Integer refers to length of rotation; *CONT*, continuous, *CONV*, conventional management, *CONS*, conservation management

[b] No. rotation cycles=12 (year)/no. crop phases

[c] Fall-seeded cover crop entry point: fall rye [except oat, 2000–02, on 3-CONS (between dry bean and wheat), 4-, 5-, and 6-CONS]

[d] Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-CONS; 5-CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-CONS; 5-CONS after dry bean; 6-CONS) applied after harvest, except 2003 (postponed to spring 2004 due to wet soil conditions)

[e] Oat harvested as silage in July, timothy direct seeded in late August

it was still quite commonplace at the planning stage of this study in the late 1990s.

Fall tillage prior to potato comprised moldboard plowing to 25 cm depth and one pass of a chisel plow on the 3- and 4-CONV rotations. The 3-CONS rotation received one pass of a chisel plow+packers or disc harrow, while one pass of a Dammer Diker® (AG Engineering & Development Co. Inc., Kennewick, WA), a reservoir tillage implement, was used on 4-, 5- and 6-CONS (except 2003, one pass of a disc harrow instead). Reservoir tillage uses paddles on a turning wheel which create depressions (up to 25 cm deep) in the soil surface (Hackwell et al. 1991) to trap water that might otherwise be lost to surface runoff, or snow that may be blown off by wind. In spring, both CONV and CONS potato plots received two passes of a Triple K spring-tine harrow (Kongskilde Industries Inc., Hudson, IL). Details of tillage practices on CONV and CONS rotations for crops other than potato were provided by Li et al. (2015).

Initially two fall-seeded cover crops were used on the CONS rotations: (1) oat to provide fall cover and then winterkill so as to minimize seeding problems in spring, and (2) fall rye (*Secale cereale* L.) which did not winterkill and regrew in spring, thereby providing protection from wind erosion (Moyer and Blackshaw 2009). Cover crops were used at five entry points (Table 1): twice in 3-CONS (between potato and dry bean, and dry bean and wheat); once each in 4- and 5-CONS (between potato and wheat), and once in 6-CONS (between potato and oat). Fall rye was used in 3-CONS (between potato and dry bean) from the outset of the study. The remaining four cover crop entry points used oat from fall 2000–02 (Table 1). However, oat establishment was largely sub-optimal, providing low to non-existent cover, and this cover crop treatment was dropped from the study and fall rye used at all five entry points starting in fall 2003. Cover crops were chemically desiccated in spring and either soil-incorporated or left on the surface. However, since none of the cover crop entry points preceded potato (Table 1), they did not directly impact potato establishment.

Compost, derived from beef feedlot manure, was fall-applied (except 2003 when it was postponed by wet conditions until spring) at five entry points (four of which preceded potato) in the CONS rotations (Table 1). On the shorter 3-CONS rotation compost was applied at 28 Mg ha^{-1} (fresh wt.) between wheat and potato. In the longer 4-, 5- and 6-CONS rotations, a higher rate (42 Mg ha^{-1} fresh wt.) was used between dry bean and potato. The lower rate was also applied at a second entry point (between sugar beet and wheat) in 5-CONS. Compost was sourced from the same feedlot each year and had average concentrations (dry wt., n=11, fall 2000–10) of 182 g kg^{-1} total C, 15.4 g kg^{-1} total N, and 5.4 g kg^{-1} total P.

The fourth CONS practice pertained to dry bean only which was direct drilled in narrow rows (19–23 cm) and direct cut at harvest on CONS rotations (Larney et al. 2015). In contrast, dry bean on CONV rotations was planted with conventional tillage in wide rows (60 cm) with inter-row cultivation and undercutting (soil disturbance) at harvest.

Potato Management

Elite-grade AC LR Russet Burbank (a clonal variant of Russet Burbank resistant to potato leafroll virus developed at Agriculture & Agriculture Canada, Lethbridge Research Centre) seed pieces were planted with a 2-row disc planter (Checchi & Magli Ltd., Budrio, Italy) at 30 cm in-row and 91 cm between-row spacings in 10 rows plot^{-1}. Elite seed tubers were sourced each year from a commercial seed grower, except in 2008 when seed tubers were saved from the 2007 crop. Planting date ranged from 18 April (2005) to 21 May (2010) with a mean of 3 May (n=12). In the first 2 years

(2000–01) potato plots were fertilized in spring. However, in keeping with commercial grower practice, plots were fall-fertilized, starting in fall 2001. Plots on CONV rotations received 134 kg ha^{-1} N, 67 kg ha^{-1} P_2O_5 and 67 kg ha^{-1} K_2O. Since four of the five compost entry points occurred in the fall prior to potato, credit was taken for N and P applied as compost. Fertilizer N was reduced to 62 kg ha^{-1} on plots receiving 28 Mg ha^{-1} of compost (3-CONS) or to 37 kg ha^{-1} on plots receiving 42 Mg ha^{-1} of compost (4-, 5-, 6-CONS). Fertilizer P was not applied to potato plots receiving compost.

At 21 to 35 days after planting (except 2000), plots were visually assessed over several consecutive days to determine when plant emergence exceeded 50 %. Subsequently, plant density was determined on 2 rows plot^{-1}. Hilling was conducted when plants were 20–25 cm tall [29 May (2000) to 30 June (2010); mean (n=12), 11 June]. In 2000 and 2003, a second hilling operation was performed 7–11 days after the first. Hilling was completed, on average, 41 days after planting. At approximate maximum biomass production (late July-early August), plant vigor was visually assessed on a scale of 10 (very feeble plants) to 50 (stood out for fast vigorous growth).

From 2007 to 2011, potato plots were visually assessed for potato early dying (PED) in late August or early September. Incidence was expressed as a percent of the stand exhibiting PED symptoms, e.g., premature and uneven chlorosis of foliage, wilting or death of individual leaflets or vines, or light brown vascular discoloration of basal stem tissues (Rowe and Powelson 2002). Prior to 2007, PED was not noticeable on crops and was therefore not assessed.

Herbicide inputs (at recommended rates) included pre-emergence Gramoxone (paraquat, 2002) or Roundup (glyphosate, 2008, 2009, and 2011) to manage early weed pressures. In-crop weeds were controlled (June-early July) by Eptam (EPTC) in 2000 and Sencor (metribuzin) in subsequent years, except 2001 and 2006 when weed pressures after hilling were minimal. Haulm desiccation with Reglone (diquat) occurred between 26 August (2005) and 9 September (2009) with a mean (n=12) date of 1 September. Insecticides used over the 12 years (at recommended rates) included Admire (imidacloprid), Success (spinosad), Lorsban (chlorpyrifos) or Ambush (permethrin) for Colorado potato beetle (*Leptinotarsa decemlineata*), and Monitor (methamidophos), Cymbush (cypermethrin) or Movento (spirotetramat) for aphids. The fungicides Bravo (chlorothalonil), Curzate (cymoxanil), Manzate (ethylenebisdithiocarbamate), Ridomil (metalaxyl), or Tattoo (propamocarb) were used for late blight [*Phytophthora infestans* (Mont.) de Bary] control. In any given year, the choice of insecticide or fungicide and the number of applications depended on prevailing infestation rates and weather conditions.

All crops were irrigated using a wheel-move system to maintain soil water at ≥50 % field capacity. All plots could be individually irrigated using four quarter circle sprinklers. Annual irrigation amounts for potato ranged from 146 mm (2002) to 826 mm (2007), with a mean of 421 mm (n=12). The initial irrigation occurred as early as 4 May (2001) or as late as 20 July (2010) with a mean of 11 June (n=12). The final irrigation occurred between 18 August (2003) and 8 September (2001, 2011) with a mean of 28 August. During each growing season, precipitation and air temperature were monitored at an automated weather station located ~300 m from the plots.

Potato harvest (2 rows plot^{-1}) took place between 30 August (2005) and 25 September (2002) with a mean date of 14 September (n=12) using a single-row digger (Grimme Group GmbH, Damme, Germany). Rotten tubers were culled and the remainder weighed (total yield) and graded into the following categories: >88 mm (oversize), 48–88 mm, and <48 mm diam. (small). Marketable yield was estimated as all tubers >48 mm diam. The total yield was adjusted to correct for tare soil. Marketable yield was expressed as a percent of total yield and oversize yield as a percent of marketable yield. After grading, tubers with external deformities (growth cracks, knobs, misshapes) were visually separated from the marketable grades and deformities yield was expressed as a percent of marketable yield. Specific gravity (SG) on ~5 kg of 48–88 mm tubers was determined by the weight-in-air/weight-in-water method. Sub-samples of 20 marketable tubers (ten 48–88 mm, ten >88 mm diam.) were halved longitudinally and assessed for internal physiological defects (necrosis, hollow heart) with values expressed as a percent. Non-blanched French fries (10 mm width) from eight marketable tubers were deep-fried at 190 °C for 4 min and scored for colour [7 (light) to 1 (dark)], based on the USDA color chart (USDA 1988), colour uniformity [1 (very variable) to 5 (uniform)], and texture [1 (wet) to 4 (mealy)].

Statistical Analyses

All data were tested for outliers (PROC UNIVARIATE) prior to analysis by year (PROC MIXED) with rotation as a variable (SAS Institute Inc. 2008). Orthogonal contrasts compared management effects: CONV (mean, 3- and 4-CONV) vs. CONS (mean, 3-, 4-, 5- and 6-CONS).

Results

Weather Conditions

The 30-year (1971–2000) normal annual precipitation for Vauxhall, AB is 303 mm of which 240 mm or 79 % is growing season precipitation (GSP, 1 April to 30 September). There was large variation in GSP during the 12-year study from 507 mm (211 % of normal) in 2005 to 118 mm (49 % of normal) in 2001. Other wet growing seasons included 2002 (466 mm, 194 % of normal) and 2010 (376 mm, 157 % or normal), while 2000 (172 mm, 72 % of normal) was the only other relatively dry season. Mean GSP during the study was 290 mm (n=12) or 21 % wetter than the 30-year normal. Adding GSP to irrigation resulted in total water inputs from 570 (2011) to 1066 mm (2007), with a mean of 710 mm (n=12). During the study, 2002 was the coolest growing season (April 1 to September 30) with a mean air temperature of 12.6 °C, and 2006 was warmest (15.2 °C) while the study mean (n=12) was 13.8 °C, which was equivalent to the 30-year (1971–2000) normal.

Heavy rainfall in 2002, 2005 and 2010 led to standing water on low-lying areas of the experimental site. Despite efforts to pump excess water, some plots had to be abandoned due to waterlogging and crop failure. Of the 24 potato plots (6 rotations×4 replicates), two were abandoned in 2002, five in 2005, and nine in 2010. Also June 2011 received 115 mm of precipitation (195 % of normal) which led to the abandonment of three potato plots due to flooding in 2011. No more than two replicates of any rotation were missing in any year. Abandoned plots were treated as missing values in the statistical analyses.

Emergence, Plant Density and Vigor

The number of days from planting to 50 % emergence (across all rotations) ranged from 24 in 2011 to 38 in 2005 and 2008 (data not shown). Only 2 of 11 years showed a significant rotation effect on emergence. In 2004, 3-CONS reached 50 % emergence after 34 days, significantly earlier than 4-CONV (37 days) and 4-CONS (39 days). In 2007, 3-CONV, 3-CONS and 4-CONV showed significantly earlier emergence (29–30 days) than 4-CONS (31 days). Overall, CONV rotations showed significantly earlier emergence than CONS rotations in 3 of 11 years: 2001 (33 vs. 34 days), 2007 (29 vs. 30 days) and 2008 (37 vs. 39 days). Averaged over 12 years, days to 50 % emergence was not significantly affected by rotation or overall management (Table 2).

Across all rotations, plant density ranged from 25,790 plants ha^{-1} in 2010 (a wetter-than-normal year) to 38,650 plants ha^{-1} in 2001, with an average density of 35,490 plants ha^{-1} (data not shown). Rotation had a non-significant effect on plant density in all 12 years, showing that subsequent yield differences were not due to differences in plant populations. However, CONV rotations (34,400 plants ha^{-1}) had significantly higher densities than CONS rotations in 2000 (32,890 plants ha^{-1}) and 2007 (36,420 vs. 35,350 plants ha^{-1}). Averaged over 12 years, plant density (Table 2) was not significantly affected by rotation or management (CONV vs. CONS).

Across rotations, plant vigor (scale of 10 to 50) ranged from 16 in 2008 to 41 in 2003 with an average value of 30 (data not shown). The only year with a significant rotation effect on plant vigor was 2008 when 5- and 6-CONS showed higher vigor scores (18–20) than 3-CONV (9) and 4-CONV (14). Averaged over 12 years, plant vigor was not significantly affected by rotation or management (Table 2).

Potato Early Dying

Potato early dying was observed in 2007 (first year of assessment), 2009 and 2010 but was essentially absent in 2008 and 2011. In 2007, PED incidence (Fig. 1) was significantly higher on 3-CONV (56 %) than 3-CONS (33 %). By 2009 and 2010, there was no significant difference in PED levels between 3-CONV and 3-CONS showing that with increased duration of the study, the high frequency of potato (every third year) likely overruled the mitigating effect of CONS management which was apparent in 2007. However, in 2009, 4-CONS showed significantly lower PED incidence (15 %) than 4-CONV (28 %) indicating the mitigating effect of CONS management practices for a lower frequency of potato (every fourth year). Under CONV management, reducing potato frequency from every third year (3-CONV) to every fourth year (4-CONV) significantly reduced PED from 56 to 23 % in 2007, 45 to 28 % in 2009, and from 38 to 16 % in 2010. In the 3 years that PED was observed, severity was significantly lower on the longer 4-, 5- and 6-CONS rotations (10–23 %) than the 3-CONV and 3-CONS rotations (>33 %), likely due to lower frequency of potato combined with CONS management practices.

Tuber Yield

Marketable tuber (>48 mm) yields ranged from an average (across all rotations) of 24.2 Mg ha^{-1} in 2010 to 51.7 Mg ha^{-1} in 2003 (Table 3). The study average (12 years, all rotations) was 40.8 Mg ha^{-1}. Significant rotation effects were found in 4 of 12 years (2005, 2008, 2009 and 2011). In 2005, the 3-CONV rotation yielded significantly lower (28.6 Mg ha^{-1}) than all other rotations (36.9–45.5 Mg ha^{-1}) except 3-CONS (34.3 Mg ha^{-1}). In 2008, the 3-CONV rotation (22.8 Mg ha^{-1}) was significantly lower than the longer 5- and 6-CONS rotations (28.5–29.8 Mg ha^{-1}) but not the shorter 4-CONV or 3- and 4-CONS rotations (22.8–25.8 Mg ha^{-1}). In 2009 and 2011, similar patterns emerged when the longer 5- and 6-CONS rotations were significantly higher-yielding than the 3- and 4-CONV and 3-CONS rotations (Table 3). Compared to the 3-CONV rotation, the highest-yielding rotation was 59 % higher (4-CONS) in 2005, 31 % higher (5-CONS) in 2008, 34 % higher (5-CONS) in 2009 and 18 % higher (5-, 6-CONS) in 2011. Management contrasts also showed significantly higher (by 15–18 %) marketable yields on the CONS compared to CONV rotations in 2005, 2008, 2009 and 2011 (Table 3).

Table 2 Rotation and management effects on potato parameters averaged over 12 years (2000–2011)

	Days to 50 % Emer.	Plant Density, ha^{-1}	Plant Vigor	Specific Gravity	Deformities	Internal Necrosis	Hollow Heart	French Fry Color[a]	Color Uniformity[b]	Texture[c]
					% Marketable tubers					
Rotation										
3-CONV	31.7	36,140	29	1.0848	6.4	0.9	3.8	3.0	2.9	3.3
4-CONV	32.0	35,830	31	1.0817	6.6	1.4	2.6	3.2	3.0	3.4
3-CONS	32.2	35,910	31	1.0832	5.3	2.2	6.1	3.2	3.0	3.3
4-CONS	32.2	35,520	31	1.0796	7.9	2.0	2.7	3.3	3.1	3.3
5-CONS	32.4	35,840	31	1.0803	6.2	2.8	1.9	3.3	3.2	3.3
6-CONS	32.2	34,980	31	1.0790	7.6	2.1	1.9	3.3	2.9	3.3
P-value	0.75	0.39	0.75	0.13	0.61	0.77	0.26	0.33	0.56	0.95
Management[d]										
CONV	31.8	35,990	30	1.0832	6.5	1.1	3.2	3.1	2.9	3.4
CONS	32.2	35,560	31	1.0805	6.8	2.3	3.1	3.3	3.1	3.3
P-value	0.18	0.22	0.12	0.06	0.80	0.19	0.97	0.06	0.21	0.48

[a] 7 (light) to 1 (dark), based on the USDA color standard: USDA 000=7; 00=6; 0=5; 1=4; 2=3; 3=2; 4=1 (USDA 1988)

[b] 1 (very variable) to 5 (uniform)

[c] 1 (wet) to 4 (mealy)

[d] Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS)

Significant effects for the 12-year average marketable tuber yields (Fig. 2a) showed that the 5-CONS rotation was 18 % higher-yielding (44.5 Mg ha^{-1}) than 3-CONV (37.6 Mg ha^{-1}), and 7–8 % higher than the 4-CONV and 3- and 4-CONS (41.3–41.4 Mg ha^{-1}) rotations. The 6-CONS rotation (41.9 Mg ha^{-1}) was only significantly higher-yielding than 3-CONV. Overall, 12-year average management contrasts revealed that marketable tuber yield on the CONS vs. CONV rotations was significantly higher-yielding by 7 %.

Marketable tuber yield as a percent of total yield (averaged across rotations) ranged from 82 % in 2000 to 95 % in 2003 with a study average of 89 %. Rotation had a significant effect on this parameter in 4 of 12 years (Table 3). In 2006 and 2010, the 3-CONV rotation had significantly less marketable tubers than all other rotations (81 vs. 88–92 % in 2006, and 72 vs. 84–91 % in 2010), while in 2009, both 3- and 4-CONV rotations had significantly less marketable tubers than all others (86–87 % vs. 89–91 %). In 2008, both 3- and 4-CONV rotations had significantly less (84–85 %) marketable tubers than 3-CONS (88 %). Management contrasts showed significantly higher marketable tuber proportions as a percent of total yield on the CONS compared to CONV rotations in the same 4 years as rotation effect was significant: 2006, 2008, 2009, and 2010 (Table 3). Marketable tuber yield as a percent of total yield was not significantly affected by rotation (P=0.26) when averaged over 12 years (Fig. 2b) with values ranging from 87 to 90 %. However, the management contrast for the 12-year average values of this parameter was significant (P=0.02) with CONV rotations at 87.6 % and CONS at 89.4 %.

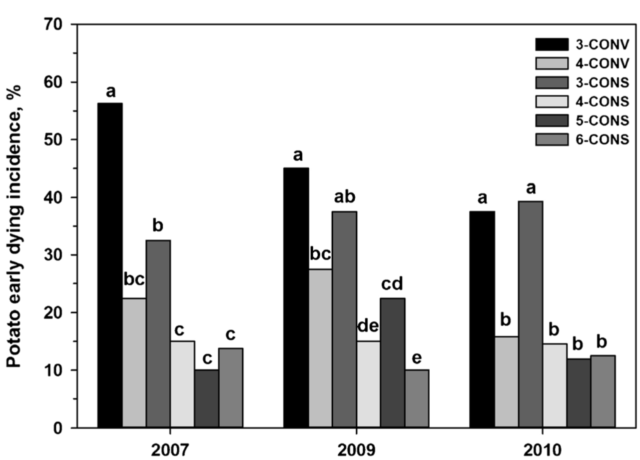

Fig. 1 Effect of rotation on potato early dying (PED) incidence in 2007, 2009 and 2010

Oversize tuber yield as a percent of marketable yield (averaged across rotations) ranged from 9 % in 2001 to 42 % in 2011 with a study average of 21 %. Rotation had a significant effect on this parameter in 3 of 12 years (Table 4). In 2000, the 4-CONS rotation (26 %) was significantly higher than all others (13–18 %) except 3-CONV (20 %). In 2004, the longer rotations showed a significantly higher proportion of oversize tubers (11–12 %) than the 3-CONV and 3-CONS rotations (6 %) while in 2010, all other rotations were significantly higher (29–39 %) than the 3-CONV rotation (10 %). Management contrasts showed a significantly higher proportion of oversize tubers on CONS vs. CONV rotations in 2005 (13 vs. 8 %), 2008 (28 vs. 24 %), and 2010 (34 vs. 19 %). When averaged over 12 years, oversize yield as a percent of

Table 3 Rotation and management effects on marketable tuber yield, 2000–2011

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Marketable tuber yield, Mg ha^{-1}											
Rotation												
3-CONV	46.4	43.1	30.8	49.4	46.6	28.6d	39.2	39.9	22.8c	36.4d	16.2	38.0bc
4-CONV	43.3	54.6	35.7	49.7	45.5	39.4abc	43.6	48.1	23.9bc	43.8bc	28.0	35.6c
3-CONS	43.8	48.7	35.5	53.9	50.3	34.3cd	43.6	48.4	25.8abc	40.4c	25.2	38.2bc
4-CONS	41.9	46.3	28.0	53.3	46.8	45.5a	44.1	47.1	22.8c	47.1ab	26.3	42.1ab
5-CONS	43.7	52.2	34.2	51.7	52.5	36.9bc	42.6	55.7	29.8a	48.8a	24.7	44.7a
6-CONS	42.0	51.5	32.1	52.4	51.4	43.9ab	46.0	44.0	28.5ab	47.8a	24.6	44.7a
P-value	0.96	0.20	0.63	0.99	0.52	0.005	0.71	0.10	0.05	<0.001	0.77	0.009
Management[a]												
CONV	44.8	48.9	33.2	49.5	46.0	34.0b	41.4	44.0	23.3b	40.1b	22.1	36.8b
CONS	42.9	49.7	32.4	52.8	50.2	40.1a	44.1	48.8	26.7a	46.1a	25.2	42.4a
P-value	0.55	0.77	0.79	0.49	0.15	0.01	0.30	0.15	0.04	<0.001	0.51	0.002
	Marketable tuber yield, % of total											
Rotation												
3-CONV	85.4	85.1	85.0	93.4	91.8	87.3	81.5b	89.1	85.1bc	86.4b	72.5b	93.4
4-CONV	81.9	86.7	85.7	93.7	90.7	89.5	88.5a	91.0	84.4c	86.9b	84.7a	90.9
3-CONS	80.5	84.9	91.3	96.2	90.7	89.8	91.8a	93.3	88.3a	89.1a	88.9a	93.9
4-CONS	83.8	84.2	85.7	96.0	92.5	90.9	87.8a	93.0	85.4bc	89.3a	90.8a	92.2
5-CONS	82.6	86.0	90.3	95.7	93.5	86.6	88.3a	93.3	87.0ab	90.8a	84.2a	92.5
6-CONS	79.8	86.6	86.8	94.0	93.5	91.3	90.8a	91.7	86.0abc	90.5a	86.4a	94.7
P-value	0.86	0.79	0.54	0.54	0.31	0.55	0.007	0.57	0.02	<0.001	0.02	0.35
Management[a]												
CONV	83.7	85.9	85.4	93.5	91.2	88.4	85.0b	90.0	84.7b	86.6b	78.6b	92.2
CONS	81.7	85.4	88.5	95.5	92.6	89.6	89.7a	92.8	86.7a	89.9a	87.6a	93.3
P-value	0.51	0.72	0.20	0.12	0.21	0.47	0.003	0.13	0.009	<0.001	0.004	0.27

[a] Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS)

marketable yield was significantly affected by rotation (Fig. 2c). The 4-CONS rotation (24 %) was significantly higher than 3- and 4-CONV, and 3-CONS (19–20 %) but not the 5- and 6-CONS rotations (22–23 %). Additionally the management contrast revealed that the 12-year average for oversize yield as a percent of marketable yield was significantly higher on the CONS (22 %) vs. CONV (19 %) rotations.

Tuber Quality

Averaged across all rotations (Table 4), 2004 had the lowest SG (1.0723) and 2006 the highest (1.0880) with a study average of 1.0818. The rotational effect on SG was significant in 4 of 12 years (2003, 2006, 2009 and 2010). In each of these years, either one or both of the CONV rotations showed significantly higher SG than the CONS rotations. In 3 of the 4 years with significant effects, tubers from the longest 6-CONS rotation had the lowest SG. Management contrasts revealed that CONS rotations had significantly lower SG than CONV rotations in 5 of 12 years (Table 4). The greatest difference occurred in 2010 (CONS, 1.0827; CONV, 1.0909). Averaging SG for the 12 years of the study, the effect of rotation was non-significant (P=0.13) but there was a tendency of decreasing SG with increasing rotation length (Table 2). The management contrast for the 12-year average effect on SG was significant at P=0.06 (very close to the P=<0.05 cutoff) with CONV rotations having a SG of 1.0832 and CONS at 1.0805 (Table 2).

External deformities (across all rotations) ranged from 1 % (2001) to 16 % (2002, 2010) of marketable yield with a study average of 7 %. Only 2 of 12 years (data not shown) exhibited a significant rotation effect (2007, 2009). However, effects were inconsistent with 3-CONS showing significantly less deformities (3 %) than 3-CONV (8 %) in 2007 but significantly more in 2009 (13 vs. 4 %). Only 1 year (2008) showed a significant management contrast when CONS rotations (14 %) showed significantly higher deformities than CONV (9 %). Averaged across 12 years, both rotation and management effects were non-significant (Table 2).

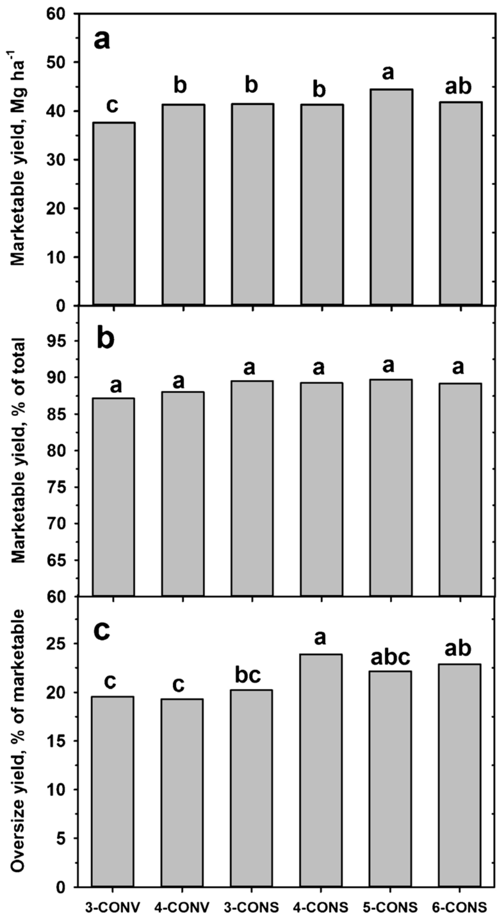

Fig. 2 Effect of rotation on 12-year (2000–11) average (**a**) marketable tuber yield; (**b**) marketable tuber yield as a percent of total yield; and (**c**) oversize tuber yield as a percent of marketable yield

Internal necrosis was not observed in 7 of 12 years (2000, 2002, 2005, 2007–09, 2011) and in remaining years (averaged across rotations) ranged from <1 % (2004) to 13 % (2001, the driest growing season) of marketable tubers (data not shown). Hollow heart was absent in 2 of 12 years (2001, 2005) and in remaining years (averaged across rotations) ranged from <1 % (2003, 2008, 2011) to 15 % (2010) of marketable tubers (data not shown). There was no rotation effect on incidence of internal necrosis in any year. Only 2010 (a wet growing season) showed a rotation effect for hollow heart with 3-CONS significantly higher (43 %) than all others (4–14 %) except 3-CONV (17 %). Management contrasts (CONV vs. CONS) were non-significant for internal necrosis and hollow heart in all individual years. Averaged across 12 years, rotation and management effects were non-significant for both internal necrosis and hollow heart (Table 2).

French Fry Characteristics

Averaged across rotations, French fry colour score ranged from 4.6 in 2001 to 2.3 in 2009 with a study average of 3.2 (data not shown). Rotation was significant in only 1 of 12 years (2005) when fries from 5-CONS were significantly lighter (5.3) than all other rotations (2.8–3.5). Two of 12 years showed management contrasts for French fry color (2001, 2005) with CONS being significantly lighter than CONV in both cases (4.7 vs. 4.2 in 2001; 3.9 vs. 2.8 in 2005). French fry color uniformity ranged from 2.1 in 2000 to 3.8 in 2010, when averaged across rotations, with a study average of 3.0 (data not shown). Rotation showed a significant effect in 2 of 12 years. In 2008, 3-CONS, 4-CONV and 6-CONS were significantly more variable in color (2.3–2.5) than 3-CONV, and 4- and 5-CONS (3.5–3.8). In 2009, 3-CONV (2.3) was significantly more variable than all other rotations (3.0–3.3). Only 1 year (2009) showed a significant management contrast for French fry color uniformity when CONS rotations (3.1) were more uniform than CONV (2.6). Averaged across rotations, French fry texture ranged from 3.0 in 2005 to 3.8 in 2009 with a study average of 3.3. Rotation and management contrasts (CONV vs. CONS) were non-significant for French fry texture in all years (data not shown). Averaged across 12 years, both rotation and management effects were non-significant for all three French fry characteristics (Table 2).

Discussion

Of the four CONS management practices employed in this study, two pertained more directly to potato: zero or reduced tillage where possible in the rotation; and composted cattle manure as a substitute for inorganic fertilizer; while two (fall-seeded cover crops and solid-seeded narrow-row dry bean) likely had minimal direct impact on potato performance. Larkin et al. (2010) reported significant total tuber yield increases of 4 % when winter rye was grown as a cover crop ahead of potato in 2-year rotations in Maine. In our study, however, although cover crops were present in 2 of 3 years on 3-CONS, they did not directly precede potato (Table 1). Cover crops only had one entry point in the 4-, 5-, and 6-CONS rotations (always immediately following potato harvest). Hence their impact on potato, at least in the longer rotations, was somewhat moderated.

There was no detrimental effect of reducing tillage in our study which agreed with Carter and Sanderson (2001) who found that conservation tillage (chisel plowing to 15 cm) in a 3-year rotation (barley–red clover (*Trifolium pratense* L.)–potato) maintained potato productivity and improved soil quality. In addition, they found that switching tillage from fall to spring and maintaining increased residue cover prior to hilling did not adversely affect potato yield. Carter et al. (2009) found tillage (moldboard plowing vs. chisel plowing) was yield-neutral for potato as rotation was the dominant factor influencing productivity. Holmstrom et al. (1999) reported tuber yield 7 % higher and water erosion 90 % lower in a

Table 4 Rotation and management effects on percent oversize tuber yield and specific gravity, 2000–2011

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Oversize tuber yield, % of marketable											
Rotation												
3-CONV	20.0ab	7.3	15.0	30.8	6.3b	5.7	11.3	15.4	27.3	22.6	9.5b	44.4
4-CONV	12.9b	7.7	17.5	30.1	11.1a	10.0	13.5	23.2	20.2	19.2	28.5a	43.5
3-CONS	14.8b	9.0	16.3	29.4	5.8b	9.1	15.8	24.2	27.4	24.3	28.8a	40.4
4-CONS	26.1a	9.2	18.3	40.0	10.5a	16.6	13.1	20.7	27.9	24.6	38.6a	44.2
5-CONS	17.5b	10.5	10.9	36.9	11.7a	12.6	10.0	23.9	27.5	27.7	36.6a	40.0
6-CONS	17.2b	8.1	13.7	34.5	11.0a	15.2	11.6	26.5	30.1	28.0	30.5a	39.7
P-value	0.02	0.73	0.33	0.48	0.008	0.13	0.85	0.45	0.09	0.52	0.03	0.94
Management[a]												
CONV	16.5	7.5	16.3	30.5	8.7	7.9b	12.4	19.3	23.8b	20.9	19.0b	43.9
CONS	18.9	9.2	14.8	35.2	9.8	13.3a	12.6	23.8	28.2a	26.1	33.6a	41.1
P-value	0.27	0.25	0.47	0.23	0.31	0.04	0.93	0.21	0.03	0.11	0.006	0.46
	Specific gravity											
Rotation												
3-CONV	1.0896	1.0799	1.0790	1.0830a	1.0700	1.0877	1.0945a	1.0895	1.0825	1.0915a	1.0935a	1.0879
4-CONV	1.0859	1.0807	1.0737	1.0783b	1.0694	1.0790	1.0888ab	1.0868	1.0809	1.0915a	1.0883ab	1.0806
3-CONS	1.0837	1.0811	1.0812	1.0793ab	1.0768	1.0812	1.0887abc	1.0884	1.0810	1.0875ab	1.0908a	1.0844
4-CONS	1.0849	1.0712	1.0779	1.0789ab	1.0734	1.0783	1.0871bc	1.0706	1.0806	1.0839bc	1.0819bc	1.0868
5-CONS	1.0845	1.0803	1.0761	1.0766b	1.0659	1.0891	1.0864bc	1.0838	1.0791	1.0858b	1.0765c	1.0836
6-CONS	1.0795	1.0767	1.0745	1.0751b	1.0783	1.0777	1.0822c	1.0862	1.0735	1.0800c	1.0816bc	1.0832
P-value	0.17	0.06	0.45	0.03	0.74	0.09	0.05	0.67	0.34	0.002	0.01	0.62
Management[a]												
CONV	1.0878a	1.0803	1.0764	1.0806a	1.0697	1.0833	1.0916a	1.0881	1.0817	1.0915a	1.0909a	1.0843
CONS	1.0832b	1.0774	1.0774	1.0775b	1.0736	1.0816	1.0861b	1.0822	1.0785	1.0843b	1.0827b	1.0845
P-value	0.04	0.16	0.66	0.02	0.50	0.48	0.01	0.45	0.18	0.0002	0.01	0.94

[a] Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS)

chisel plowed vs. moldboard plowed treatment in a 3-year grain–forage–potato rotation. Mundy et al. (1999) found that the success of reducing pre-plant tillage for potato depended on soil type. In a fine sandy loam soil with high organic matter (OM), potato grown under no-till (NT) yielded as high as conventional tillage but in a sandy soil with low OM, potato did not produce well under NT.

In terms of increased potato productivity and reduced PED incidence, our findings supported feedlot manure compost, at an entry point of ~6 months before potato, as a CONS management practice (Table 3, Figs. 1 and 2). In southern Alberta, the location of an intensive beef cattle feedlot industry proximal to the potato growing region provides a ready supply of manure (fresh, stockpiled, composted) as a nutrient management alternative. A survey of potato growers in Idaho noted a significant increase in manure use for potato between 1997 and 2007 as the cost of fertilizer N increased (Pehrson et al. 2011). However, application of fresh manure to potato land is often avoided as it is suspected to provide optimal conditions for pathogens causing common scab [*Streptomyces scabei* (Thaxter) Lambert & Loria], Rhizoctonia (*Rhizoctonia solani* Kühn) and Verticillium wilt (Moore et al. 2011). Olanya et al. (2006) found that addition of 45 Mg ha^{-1} of bedded cow manure or 22 Mg ha^{-1} of compost increased incidence of common scab, Rhizoctonia, black dot [*Collectotrichum coccodes* (Wallr.) S.J. Hughes] and silver scurf [*Helminthosporium solani* Durieu & Mont.] in Maine.

Also, N release from manures during the growing season can extend longer than fertilizer, causing prolonged vegetative growth and delayed tuber bulking (Mikkelsen and Hopkins 2009). This makes the entry point of organic amendments in crop rotations an important consideration. Moore et al. (2011) reported that application of fresh dairy manure and compost 3–5 years ahead of a potato crop, increased total tuber yield by 20 % over a P fertilizer treatment. Curless et al. (2012) recommended liquid dairy manure application at least 18 months prior to planting potato. Rees et al. (2014) compared fall, pre-planting or pre-hilling application of 4 Mg ha^{-1} of fresh broiler poultry manure. Manured treatments averaged 19–34 % increases in marketable yield. However, tuber yields were similar whether manure was applied in fall or pre-hilling. Mallory and Porter (2007) indicated that management practices which improved soil quality also enhanced potato yield stability by reducing the impact of adverse growing conditions. Potato yields in an amended soil system (manure, compost, green manure, supplemental fertilizer) were up to 55 % higher than a non-amended system (synthetic fertilizer only).

In the early growing season, there were few significant rotation effects on days to emergence or plant density. Those that occurred generally favored CONV over CONS rotations in terms of slightly earlier emergence (1–2 days) or higher plant density. Holmstrom et al. (2006) found that potato emergence was not significantly affected by tillage treatment (residue management, zero tillage, zone tillage, conventional tillage).

Verticillium wilt, caused primarily by the soilborne fungus *Vertillicium dahliae* Kleb., is a common limiting factor of potato production in arid and semiarid areas due to its contribution to PED (Davis et al. 2001). The economic impact of PED can be significant, with moderate outbreaks causing 10–15 %, and severe outbreaks up to 50 % yield reductions (Powelson and Rowe 1993). Prior to 2007, PED was not observed, in keeping with reports that it may be absent on land new to potato production (as was this study site in 2000), but invariably develops over time (Rowe and Powelson 2002). For 2-year potato rotations in Maine, PED was not evident until the fourth or fifth rotation cycles, i.e., 8 to 10 years into a study (Larkin et al. 2010). The decreased severity of PED in the longer CONS rotations (4-, 5-, and 6-CONS) may be partly related to compost inputs, as organic amendments have been effective in reducing its impact (Entry et al. 2005; Lazarovits et al. 2008). In line with our results, Molina et al. (2014) reported that 44.5 Mg ha^{-1} (wet wt.) of composted beef cattle manure applied before wheat in Manitoba reduced PED incidence from 57 to 25 % in a following potato crop. Conn and Lazarovits (1999) found that application of chicken, liquid swine or cattle manure led to reduced viability of *V. dahliae* microsclerotia, although the magnitude of reduction was manure and soil specific.

At this study site, Forge et al. (2015) found higher populations of the root lesion nematode *Pratylenchus neglectus* in the 3-year rotations than in the longer 4-, 5- or 6-year rotations from 2007 to 2010. Although *Pratylenchus penetrans* has been shown to interact with *V. dahliae* to cause PED (Rowe and Powelson 2002), other studies (e.g., Davis et al. 2001) have shown no relationship between *P. neglectus*, PED or potato yield. However, Forge et al. (2015) speculated that lower *P. neglectus* pressures in the longer rotations likely contributed to reduced PED intensity, relative to the 3-year rotations. In addition, the significantly higher PED incidence on 3-CONV (38–56 %, Fig. 1) than 4-CONV (16–28 %) may also be due to the crop sequence under 3-CONV (potato after wheat) compared to 4-CONV (potato after dry bean). While both wheat and dry bean can act as *P. neglectus* hosts, the nematode can parasitize and increase rapidly on wheat roots (Riley and Kelly 2002) facilitating the synergistic interaction with *V. dahliae* on the following potato crop. Moreover, even though wheat is a non-host for *V. dahliae*, wheat roots can support low populations of the pathogen (Davis et al. 2000) and act as a disease bridge by maintaining microsclerotia populations between susceptible potato crops.

In 2008, a severe outbreak of potato virus Y (PVY) likely masked PED symptoms. Elite seed was not sourced in 2008, and the seed lot (stored from the previous season) was infected with PVY which was subsequently confirmed in 25-50 % of plants by enzyme linked immunosorbent assay (ELISA). Although aphids and weed hosts are important in PVY transmission, infected seed tubers can act as a major source for the subsequent crop (Nolte et al. 2003). Reasons for the absence of PED in 2011 are unclear but may be related to cultural or edaphic factors known to affect inoculum efficacy of *V. dahliae* and disease severity, such as soil N, P, or electrical conductivity levels (Davis and Everson 1986), or soil OM or sodium concentrations (Davis et al. 2001).

The average marketable tuber yield (across all rotations and years) of 40.8 Mg ha^{-1} was higher than the mean yield (36.6 Mg ha^{-1}) for the province of Alberta (Statistics Canada 2013) during the same time period (2000–11). The two highest-yielding crops (averaged across rotations) were in 2003 (51.7 Mg ha^{-1}) and 2001 (49.4 Mg ha^{-1}) which were drier-than normal growing seasons. Additionally, 2001 (20.3 °C) and 2003 (20.0 °C) ranked as the two warmest Augusts during the 12-year study, in comparison to a 30-year-mean (1971–2000) August air temperature of 17.9 °C.

Of the four lowest-yielding years (averaged across rotations), three (2002, 2005, 2010) were wetter-than-normal while PVY reduced average yield to 25.6 Mg ha^{-1} in 2008, the second lowest of the trial behind 2010 (24.2 Mg ha^{-1}). Also in 2008, three severe hail storms in rapid succession (7, 10, and 15 July) accompanied by strong winds caused canopy damage to all crops including potato. For the above reasons, plant vigor in 2008 was the lowest for the study with a mean value (across rotations) of 16. However, even though overall vigor scores were very low, 2008 was the only year with a significant rotation effect, when 5- and 6-CONS showed significantly higher scores (18–20) than 3-CONV (9) and 4-CONV (14). It is possible that longer rotations with CONS management partly mitigated disease and weather-related stressors.

Significant rotation effects on marketable tuber yield did not become evident until the sixth year of the study (2005) demonstrating that rotation studies demand longer-term commitments. Similar findings were reported for a 12-year potato rotation in Manitoba (Mohr et al. 2011) where the first 4 years (end of first cycle of longest rotations) was deemed the transitional phase and the remaining 8 years, the established phase. In an 11-year study of 2-year potato rotations in Prince Edward Island, yield differences were not apparent until year 6 (Carter et al. 2003).

In Manitoba, Mohr et al. (2011) reported that 3-year [potato–canola (*Brassica napus* L.)–wheat, potato–oat–wheat] and 4-year [potato–wheat–canola–wheat, potato–canola–alfalfa (*Medicago sativa* L.)–alfalfa] rotations maintained their productivity over a 12-year study while 2-year rotations (potato–canola, potato–wheat) showed potato yield declines over time. They concluded that 2-year potato rotations represented a significant management risk to growers. Our results showed that the 5-CONS rotation (potato–wheat–sugar beet–wheat–dry bean) out-performed the 3-CONV rotation by 18 % (Fig. 2a) for marketable yield (12-year average). We believe that a 3-CONV rotation (potato–dry bean–wheat) would represent a risk to growers in terms of lower yield potential and PED. Simply lengthening the rotation to 4 years while maintaining CONV practices increased yield by 10 % (4-CONV vs. 3-CONV). Another option would be to adopt 3-CONS over 3-CONV, which would significantly increase yield (12-year average) by 10 % but still represent a significant shortfall (−7 %) in marketable yield attained by 5-CONS. On average, there was no significant yield effect of imposing CONS practices if the rotation length was 4 years (4-CONS vs. 4-CONV). Also, stretching the potato break by one more year (6-CONS) did not significantly increase marketable yield over 5-CONS.

The significantly higher 12-year average for oversize yield as a percent of marketable yield with CONS (22 %) vs. CONV (19 %) management agreed with the findings of Moore et al. (2011). They reported increased large tubers on compost compared to P fertilizer treatments, suggesting greater tuber bulking potential on soils with manure or compost histories vs. chemical fertilizer. Rees et al. (2014) also found that organic amendment (poultry manure) increased tuber size. Mohr et al. (2011) reported years where longer 3- and 4-year rotations had significantly higher percentages of large tubers than 2-year rotations. However, Carter et al. (2009) found no effect of tillage or rotation treatment on tuber size or number of deformed tubers.

In general, adoption of CONS management practices tended to lower tuber SG which follows findings from other studies especially as they relate to organic amendment addition. Rees et al. (2014) found that manured treatments significantly reduced SG from 1.089 to 1.086 in New Brunswick. Porter et al. (1999) found that while 45 Mg ha^{-1} of beef cattle manure increased total tuber yields by 11–27 %, SG was significantly reduced from 1.076 to 1.071. Curless et al. (2012) reported that tuber dry matter (correlated with SG) was significantly reduced by manure addition, especially if applied close to planting. However, Moore et al. (2011) found no significant effects of compost or manure amendments on tuber SG. Specific gravity is closely linked to N fertility and its interactions with tuber maturity and water availability (Zebarth and Rosen 2007). Bélanger et al. (2002) and Zebarth et al. (2004) reported linear decreases in SG with increasing N rates. Although we allowed for N applied as compost and reduced N fertilizer inputs to 33 % of recommended rates on CONS rotations, soil N levels may not have been fully depleted by late growing season leading to reduced SG. Tillage effects on SG have been inconsistent. Holmstrom et al. (2006) and Ivany et al. (2007) showed no significant effects on tuber SG while Pierce and Burpee (1995) found that reduced tillage increased SG compared with conventional tillage.

An SG range of 1.087–1.092 is considered optimal for local processors in southern Alberta, resulting in good texture, low oil adsorption and improved production efficiency of French fries and chips, and growers may earn a premium for delivering tubers within this range [R. May, McCain Foods (Canada), pers. commun.]. Using these criteria, CONV rotations fell within the ideal range in 5 of 12 years, while CONS rotations were below this range in all 12 years (Table 4). Given that, certain farms in the area have historically produced high SG tubers in the 1.095 to 1.105 range (R. May, pers. commun.). Adoption of CONS management practices may allow such growers to reduce tuber SG.

In previous studies, rotation (Mohr et al. 2011) or additions or timing of manure (Rees et al. 2014) had no significant effect on hollow heart. In our study, external (deformities) or internal (necrosis, hollow heart) tuber defects were generally more influenced by weather conditions than rotation or management. Highest levels (across rotations) of external deformities (2002, 2010) and hollow heart (2010) were associated with wetter-than-normal growing seasons, while highest internal necrosis occurred in a drier-than-normal growing season (2001).

Rotation and management effects on French fry color and color uniformity were minimal, while those on French fry texture were non-existent. However, several instances of darker French fry color with CONV management agreed with Moore et al. (2011) who reported darker French fry color for a control treatment (no fertilizer or manure P) compared to compost, manure or fertilizer treatments, which they attributed to significantly higher glucose concentrations in control tubers. Holmstrom et al. (2006) and Ivany et al. (2007) found no effect of tillage treatment (fall moldboard plowing vs. zone tillage), while Mohr et al. (2011) found no effect of rotations on French fry color.

Other advantages of CONS management were observed in this rotation study in terms of dry bean performance, weed populations, beneficial insects, endophytes, and soil quality. Larney et al. (2015) reported that narrow-row CONS production of dry bean (high-residue system) performed as well as wide-row CONV production (low residue system) with no significant rotation effect on yield. In the last 2 years (2010–

11), in an attempt to reduce harvest losses, narrow-row dry beans were undercut rather than direct combined and this led to significantly higher (25 %) yields with CONS (3311 kg ha^{-1}) vs. CONV management (2651 kg ha^{-1}).

Based on 12 years of weed population and seedbank data, Blackshaw et al. (2015) concluded that implementing a suite of CONS practices posed little risk of increased weed pressures. Bourassa et al. (2008) found that carabid beetle (Coleoptera: Carabidae) activity and density (2003–05) was consistently higher in 3-CONS compared with 3-CONV rotations. Carabids play a role in reducing Colorado potato beetle and aphid populations (Alvarez et al. 2013) as well as weed populations via predation of the weed seedbank (Menalled et al. 2007).

Pageni et al. (2013) found that the size and diversity of endophyte populations isolated from potato roots in 2011 was greater with CONS than CONV management. Endohphytes are microorganisms that live mutually within plants and enhance growth promotion, nutrient uptake, tolerance to abiotic stress, and pathogen inhibition (Ryan et al. 2008). Certain crop sequences favor the build-up of specific bacterial endophyte populations leading to beneficial host-endophyte allelopathies and maintenance of fertile, disease-suppressive soils (Sturz et al. 2000). In addition, Pageni et al. (2014) found that indole acetic acid hormone production was 66 % greater by endophytes isolated from potato grown under CONS vs. CONV management. Also six endophytic isolates from potato grown under CONS management were antagonistic to the potato pathogens *Pectobacterium atrosepticum* (blackleg), *Fusarium sambucinum* (dry rot), and *Clavibacter michiganensis* subsp. *sepedonicus* (ring rot).

Li et al. (2015) found that after 12 years under CONS management, particulate organic matter C and N (labile fractions) increased by >145 %, total C and N by 45–50 %, and fine organic matter C and N (stable fractions) by 20 %. Aggregate stability (a measure of soil resistance to slaking by water) also increased significantly under CONS management. Overall, the 5-year CONS rotation ranked highest for soil quality, with 3- and 4-CONV rotations substantially lower.

In summary, our study suggests that potato yield and quality can benefit from CONS management practices (reduced tillage, cover crops, compost addition) in southern Alberta, which together with other accrued advantages, provides incentive for further adoption of these practices in the region.

Acknowledgments We thank Jim Sukeroff, Dale Reynolds, staff and summer students at the AAFC Vauxhall Sub-station for field assistance. Ron Gregus assisted with potato management. Jennifer Nitschelm (2000–06) and Peter Regitnig (2007–11), Rogers Sugar Ltd./Lantic Inc. (Taber, AB), managed sugar beet husbandry. Funding contributions from the Alberta Agricultural Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers; Lantic Inc., Agriculture and Agri-Food Canada's Matching Investment Initiative and the Pulse Science Cluster are gratefully acknowledged.

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Published September 4, 2015

Conservation Management Practices and Rotations for Irrigated Dry Bean Production in Southern Alberta

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ABSTRACT

Dry bean (*Phaseolus vulgaris* L.) production on the Canadian prairies has traditionally used wide rows, inter-row cultivation, and undercutting at harvest. Recent breeding efforts have produced cultivars with more upright growth which are better suited to solid-seeded narrow-row production systems. A 12 yr (2000–2011) study compared conservation (CONS) and conventional (CONV) management for dry bean in 3- to 6-yr rotations. The CONS rotations included reduced tillage, cover crops, feedlot manure compost, and solid-seeded narrow-row dry bean. Effects of CONS management on plant density were inconsistent with some years showing lower density when seeded into high-residue conditions. On average, there was a 3 d maturity advantage with CONS (103 d) vs. CONV (106 d) management. The CONS rotations showed significantly higher mean incidence (19%) of white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary] than CONV rotations (6%). Averaging across 12 yr, there was no significant rotation effect on yield ($P = 0.19$) showing that CONS production performed as good as CONV production. In the last 2 yr (2010–2011) of the study, in an attempt to reduce harvest losses, CONS dry bean was undercut rather than direct combined. This led to significantly higher (25%) yield with CONS (3311 kg ha^{-1}) vs. CONV management (2651 kg ha^{-1}). Our results provide incentive for more rapid adoption of conservation-oriented soil and crop management practices for dry bean production on the Canadian prairies, including narrow rows, reduced tillage, cover crops, and feedlot manure compost addition.

Since the early 1990s, pulse crop production has increased on the Canadian prairies due to rotational benefits (Miller et al., 2002; Przednowek et al., 2004; Lupwayi and Kennedy, 2007) and greater economic returns compared to cereals (Walburger et al., 2004). Field pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik.), or chickpea (*Cicer arietinum* L.) are replacement options for spring wheat (*Triticum aestivum* L.) or fallow in dryland rotations. Edible dry bean (pinto, great northern, yellow, small red, pink, and black being the most common market classes) are grown under rainfed conditions in humid areas of the prairies (e.g., southern Manitoba), or under irrigation in semiarid areas (e.g., Taber-Vauxhall-Bow Island region of southern Alberta).

In southern Alberta, annual production of dry bean increased approximately fivefold, from 12,000 ha in 1991 to 61,000 ha in 2001(Alberta Agriculture and Rural Development, 2012). However, a row-crop production system that has remained essentially unchanged since the 1950s (McColly, 1958) is used for the majority of irrigated dry bean in the region, that is, wide-row spacing (60–75 cm), inter-row cultivation in the early growing season for weed control, and undercutting at maturity to facilitate harvest. Undercutting severs the plants just below the soil surface, leaving loose stalks and pods for later pick-up by a combine. Smith (1986) found harvest losses of up to 13% between undercutting and combining as the interval between the two operations is weather dependent. Over-ripe pods may shatter in hot or windy conditions or seed quality may deteriorate in wet conditions. Undercutting may also increase wind erosion risk, inasmuch as it leaves unanchored crop residue and loose surface soil.

Narrow-row spacing has been known to increase dry bean yield since at least the 1970s (Eidmann and Adams, 1978; Kueneman et al., 1979). Most of 10 navy bean cultivars evaluated in 19-, 38-, or 76-cm rows yielded highest at the narrowest spacing (Grafton et al., 1988). Even a minor decrease in row spacing from 71 to 56 cm produced yield increases of 300 to 600 kg ha^{-1} (Xu and Pierce, 1998). However it is only relatively recently that narrow-row production has become an agronomic

Published in Agron. J. 107:2281–2293 (2015)
doi:10.2134/agronj15.0062
Received 15 Apr. 2015
Accepted 15 July 2015

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Abbreviations: CHU, corn/crop heat units; CONS, conservation management; CONT, continuous; CONV, conventional management; CT, conservation tillage; DTM, days to maturity; GSP, growing season precipitation; SOM, soil organic matter; ZT, zero tillage.

option as a result of breeding selection for an upright bush-type growth habit, a more open canopy architecture and hence a reduced risk of white mold (Saindon et al., 1995), and integrated weed management approaches (Blackshaw et al., 2000). In addition, Vandenberg et al. (1992) found that direct cutting determinate bush and upright cultivars produced highest yields at 30-cm row spacing while vine cultivars yielded best at 60-cm row spacing. Upright cultivars have improved pod clearance, as a result of less lodging during pod-filling, leading to lower harvest losses compared to prostrate cultivars. With upright pinto bean, Eckert et al. (2011b) found that the lowest pod height was 2.2 cm above the soil surface at 30-cm row spacing which was significantly higher than 1.86 cm for 76-cm row spacing.

Dry bean may be solid seeded with conventional grain drills in narrow rows, which precludes the need for specialized row-crop equipment (Shirtliffe and Johnston, 2002) and facilitates reduced tillage practices. Inter-row cultivation is not an option, reducing tillage intensity even further. At harvest, narrow-row dry bean may be direct cut using a specialized crop lifter (Zyla et al., 2002) or they may be swathed and then combined. Either method leaves standing stubble in narrow rows which offers some protection against wind erosion. Given their reduced tillage options and greater retention of anchored stubble, narrow-row dry bean may be viewed as a conservation management practice compared with conventional wide-row production. However, conservation tillage (CT), widely adopted for dryland cropping, is less common on irrigated land in southern Alberta, even though yield differences between conventional tillage and CT for irrigated crop sequences may be nonsignificant (Hao et al., 2001). Moreover, dry bean are commonly grown in irrigated rotations that include other low-residue producing row crops such as potato (*Solanum tuberosum* L.) or sugar beet (*Beta vulgaris* L.). Even under no-till, Merrill et al. (2006) reported soil surface coverage by residue of 35 to 48% after crop sequences with dry bean and safflower (*Carthamus tinctorius* L.) compared to 89 to 98% for sequences that included spring wheat or barley (*Hordeum vulgare* L.). With a lack of surface residue, unless a fall-seeded cover crop is present, soil may be exposed to wind erosion from September to May (~8 mo). Since irrigation mitigates competition for water with the main crop, Snapp et al. (2005) indicated significant niches within irrigated cropping systems where cover crops are beneficial. The combination of intensive tillage and low-residue production associated with conventional irrigated row crop production, makes maintenance of soil organic matter (SOM) a challenge, especially if row crops are grown in tight rotations at the expense of forages or cereals. One way of replenishing SOM is utilization of composted manure produced in abundance by southern Alberta's beef feedlot industry (Larney et al., 2006).

Given the above background, a 12-yr irrigated rotation study was initiated in 2000 to examine the impact of CONS practices, including narrow-row dry bean production, reduced tillage, cover cropping, and composted manure addition on crop yield and quality, soil quality, and weed and disease pressures. A wide range of soil quality attributes was reported to have been enhanced by CONS management after 12 yr (Li et al., 2015). This paper deals specifically with dry bean agronomic traits and disease incidence in CONV and CONS rotations (3 to 6 yr in length) over 12 yr.

MATERIALS AND METHODS

Experimental Design

The study was conducted from 2000–2011 at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50°03′ N, 112°09′ W, elev. 781 m), near Lethbridge, AB, on an Aridic Cryoll developed on lacustrine and morainal parent materials. Texture (0–15-cm depth) was sandy loam (0.52 kg kg^{-1} sand, 0.34 kg kg^{-1} silt, 0.14 kg kg^{-1} clay). The entire plot area was planted to barley in 1999 and seven rotations established in spring 2000 (Table 1). Dry bean was grown in six rotations under CONV or CONS management: two 3-yr (3-CONV, 3-CONS) and two 4-yr (4-CONV, 4-CONS) rotations, one 5-yr (5-CONS), and one 6-yr (6-CONS) rotation. A seventh continuous wheat (1-CONT) treatment was included. The 3-CONV and 3-CONS rotations had similar crop sequences (dry bean–wheat–potato) as had the 4-CONV and 4-CONS (dry bean–potato–wheat–sugar beet) (Table 1). The 5-CONS rotation comprised two phases of wheat with the three row crops, while 6-CONS included oat (*Avena sativa* L.) which was harvested as silage in July to allow timely seeding of timothy (*Phleum pratense* L.) in late August (Table 1). Each phase of each rotation appeared in each year, resulting in a total of 26 phases (Table 1) in a randomized complete block design with four replicates (104 plots). Individual plots were 10.1 by 18.3 m

Table 1. Outline of rotation treatments over 12 yr (2000–2011), Vauxhall, AB.

Rotation†	Crop sequence	Crop phases	Rotation cycles‡
		no.	no.
1-CONT	wheat	1	12
3-CONV	dry bean–wheat–potato	3	4
4-CONV	dry bean–potato–wheat–sugar beet	4	3
3-CONS	dry bean§–wheat¶–potato§	3	4
4-CONS	dry bean¶–potato§–wheat–sugar beet	4	3
5-CONS	dry bean¶–potato§–wheat–sugar beet¶–wheat	5	2.4
6-CONS	dry bean¶–potato§–oat/(timothy)#–timothy–timothy–sugar beet	6	2

† Integer refers to length of rotation; CONT, continuous; CONV, conventional management; CONS, conservation management.

‡ No. rotation cycles = 12 (yr)/no. crop phases.

§ Fall-seeded cover crop entry point: fall rye [except oat, 2000–2002, on 3-CONS (between dry bean and wheat), 4-, 5-, and 6-CONS].

¶ Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-CONS, 5-CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-CONS, 5-CONS after dry bean, 6-CONS) applied after harvest, except 2003 (postponed to spring 2004 due to wet soil conditions).

Oat harvested as silage in July, timothy direct seeded in late August.

(185 m^2), with a 2.1 m buffer strip between plots. The number of rotation cycles at the end of the 2011 growing season (12 yr) varied from 4 (3-yr rotations) to 2 (6-yr rotation) (Table 1).

Conservation Management Treatments

For the CONS rotations (Table 1), the following four practices were applied as a "package": (i) direct seeding or reduced tillage where possible in the rotation; (ii) fall-seeded cover crops after at least one phase; (iii) composted cattle manure; and (iv) solid seeded narrow-row dry bean. Each of these practices is outlined in further detail below. Conventional management used none of the above practices, and hence the 3- and 4-CONV rotations had more intensive tillage (especially in spring), no cover crops, no organic amendments and dry bean was grown in wide rows, with inter-row cultivation and undercutting at harvest.

Tillage in the fall before dry bean comprised one pass of a double disc harrow with trailed diamond spike harrows for all rotations except 5-CONS which was left in no-till and the wheat stubble from the previous crop shredded with a flail mower. In spring, the wide-row 3- and 4-CONV rotations received one pass of a Triple K spring-tine harrow (Kongskilde Industries Inc., Hudson, IL) as pre-seeding tillage. In contrast, the narrow-row CONS rotations were direct seeded into fall rye (*Secale cereale* L.) residue (3-CONS) desiccated with glyphosate [*N*-(phosphonomethyl) glycine] or shredded wheat stubble (5-CONS), both considered "high-residue", or into undisturbed soil on the 4- and 6-CONS rotations, both considered "low-residue", due to disking the previous fall. Details of tillage practices for crops other than dry bean were provided by Li et al. (2015).

Initially two fall-seeded cover crops were used in the CONS rotations: (i) oat to provide fall cover and then winterkill so as to minimize seeding problems in spring, and (ii) fall rye which did not winterkill, and when successfully established, re-grew in spring, thereby providing protection from wind erosion (Moyer and Blackshaw, 2009), especially before dry bean, which was not seeded until mid-May. Cover crops were used at five entry points (Table 1): twice in 3-CONS (between dry bean and wheat, and between potato and dry bean); once each in 4- and 5-CONS between potato and wheat, and once in 6-CONS between potato and oat.

The only cover crop directly impacting dry bean was the one between potato and dry bean in 3-CONS. Fall rye (cultivar AC Remington) was used at this entry point and seeding date (dictated by timing of potato harvest) ranged from 3 September (2004) to 13 October (2010) (average 25 September, 2000–2010, $n = 11$). In spring, fall rye biomass was sampled (6×0.25 m^2 $plot^{-1}$) between 2 and 20 May (average 12 May, 2002–2011, $n = 10$, not sampled in 2001) or ~2 d before chemical desiccation in preparation for direct seeding dry bean. The remaining four cover crop entry points used oat in fall 2000, 2001, and 2002 (Table 1). However, establishment was largely suboptimal, providing low to nonexistent cover, and the oat cover crop treatment was dropped from the study and fall rye used at all five entry points starting in fall 2003.

Compost, derived from beef feedlot manure, was fall applied (except 2003 when it was postponed by wet conditions until spring) at five entry points in the CONS rotations (Table 1). On the shorter 3-CONS rotation compost was applied at 28 Mg ha^{-1} (fresh wt.) between wheat and potato. In the longer 4-CONS, 5-CONS, and 6-CONS rotations, a higher rate (42 Mg ha^{-1} fresh wt.) was used after dry bean and before potato. The lower rate was also applied at a second entry point in 5-CONS: after sugar beet and before wheat. Compost was sourced from the same feedlot each year and had average concentrations (dry wt., $n = 11$, fall 2000–2010) of 182 g kg^{-1} total C, 15.4 g kg^{-1} total N, and 5.4 g kg^{-1} total P.

Dry bean in CONS rotations (3-, 4-, 5-, 6-CONS) were direct drilled in narrow rows at a target rate of 53 plants m^{-2} with a disc drill (John Deere 1560, Deere and Company, Moline, IL) at 19-cm row spacing (2000–2003), a custom double disc no-till press drill at 23-cm row spacing (2004–2010), or a hoe drill (Model 2200, Versatile Farm Equipment Co., Winnipeg, MB) at 19-cm row spacing (2011). The CONV rotations (3-, 4-CONV) were seeded at a target rate of 29 plants m^{-2} at 60 cm row spacing each year, using a custom small plot disc drill.

Dry Bean Management

An upright short vine Type IIa (indeterminate growth habit) black bean cultivar UI 906 (Myers et al., 1991) was used in the first 4 yr (2000–2003). This was changed to a small red bean cultivar AC Redbond (Mündel et al., 2000), for the remaining 8 yr (2004–2011). AC Redbond was deemed more suited to narrow-row production, being an upright, early-maturing Type IIb cultivar with moderate white mold resistance. All dry bean plots received N fertilizer (as ammonium nitrate, 34–0–0) broadcast before seeding (CONV) or banded below the seed (CONS). The 3-CONV, 3-CONS, and 5-CONS rotations received 90 kg ha^{-1} N, while 4-CONV, 4-CONS, and 6-CONS received 112 kg ha^{-1} N to account for higher N use by the preceding sugar beet crop compared to preceding potato or wheat. Only dry bean grown in 2000–2002 received P (22 kg ha^{-1}) as subsequent soil test levels were considered adequate. Dry bean seed was not inoculated with *Rhizobia* as McKenzie et al. (2001) found no yield response to inoculation in southern Alberta.

Herbicide inputs were similar for CONV and CONS dry bean, except for glyphosate which was used on CONS (narrow-row) rotations only. On 5-CONS, glyphosate was applied (2.5 L ha^{-1}) on wheat stubble in fall 2005, 2007, 2008, and 2010 before dry bean. On 3-CONS, glyphosate (2.5 L ha^{-1}) application date to desiccate fall rye ranged from 4 (2005) to 25 May (2010) with an average of 14 May (2001–2011, $n = 11$) or 8 d before direct drilling narrow-row dry bean. A second application was required on 3-CONS in 2008 and 2009. One application of glyphosate (two in 2002) was also applied pre-seeding on the 4- and 6-CONS rotations except in 2000–2001 and 2005. In 2011, both CONV and CONS dry bean plots received a pre-seeding application of glyphosate. Granular ethalfluralin [***N***-ethyl-N-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)-benzenamine] at 22 kg ha^{-1} was used before all dry bean for grassy weed control (spring applied, 2000, 2004–2011; fall-applied, 2001–2002).

Wide-row CONV treatments were inter-row cultivated once (twice in 2004) in June for weed control except in 2010 and 2011 when adequate weed control achieved with herbicides.

In-crop control of broadleaf weeds on all rotations was managed with bentazon (3-Isopropyl-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide) at 2.25 L ha^{-1}, using one (2000–2003, 2006, 2009–2010), two (2004, 2007–2008, 2011) or three (2005) applications, depending on weed pressures. From 2000–2007, grassy weeds were controlled with one application of sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio) propyl]-3-hydroxy-2-cyclohexen-1-one) at 1.1 L ha^{-1} (except two applications on CONS rotations in 2003). A transition year in 2008 saw one application of sethoxydin (except two on 5-CONS) and one application of imazamox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) at 18.9 g ha^{-1}, a combined grassy weed and targeted broadleaf (e.g., redroot pigweed, *Amaranthus retroflexus* L.) herbicide. For the remainder of the study (2009–2011), sethoxydin was dropped and one application of imazamox used. Diquat (6,7-Dihydrodipyrido [1,2-a:2',1'-c]pyrazinediium dibromide) was used (2.5 L ha^{-1}) as a pre-harvest desiccant each year.

Fungicides included copper hydroxide for bacterial blight (*Xanthomonas axonopodis* pv. *phaseoli* (Smith) Vauterin et al. (Xap) [syn. X. *campestris* pv. *phaseoli* (E.F. Smith) Dye]) control (2000–2004, wettable powder at 2.3–5.6 kg ha^{-1}; 2005–2011, flowable liquid at 1.2–3.2 L ha^{-1}) and vinclozolin [3-(3,5-dichlorophenyl)-5-ethenyl-5-methyl-2,4-oxazolidinedione] at 1.0 to 1.5 kg ha^{-1} (2000–03) or boscalid [2-chloro-*N*-(4′-chloro[1,1′-biphenyl]-2-yl)-3-pyridinecarboxamide] at 0.56 to 0.74 kg ha^{-1} (2004–2011) for white mold control on all rotations. Bacterial blight fungicides were first applied when the crop was >15 cm high (average 6 July, $n = 12$) and as required at ~2 wk intervals depending on seasonal disease pressures: one application in 2002 and 2011; two in 2001 and 2006–2010; three in 2003–2004; and four in 2000 and 2005. White mold fungicides were applied at 30 to 50% flowering (average 24 July, $n = 12$) and repeated (average 6 August, $n = 6$) when the disease persisted in 2001–2002, 2004, 2006, 2009, and 2010.

All crops were irrigated using a wheel-move system to maintain soil water content at >50% field capacity. Plots could be individually irrigated using four quarter circle sprinklers.

Weather Conditions

During each growing season, precipitation and air temperature were monitored at an automated weather station located ~300 m from the plots. Corn/crop heat units (CHU) were calculated from daily maximum and minimum air temperatures as described by Major et al. (1978). Each year, accumulation of daily CHU started on 15 May and ended when an air temperature of ≤–2°C was first recorded in fall. The number of days between the last occurrence of an air temperature <0°C in spring and its first occurrence in fall was counted as frost-free days.

Crop Measurements

Plant density was measured 4 to 5 wk after seeding [average ($n = 12$) 19 June for wide-row, and 21 June for narrow-row] by counting the number of plants in two adjacent 1 m row lengths in each of four quadrants of each plot (2 rows by 1 m by 4 quadrants = *n* plants per 8-m row length). Plant density (plants m^{-2}) was then estimated as $n/8x$, where x = row spacing in meters. Average plant height was measured at approximate maximum biomass production at [average 12 August, $n = 12$] from a representative area of all four quadrants of each plot. Both row spacings were measured on the same day. Plant maturity (except 2003, 2005) was visually assessed over several days in the late growing season and days to maturity (DTM) estimated as the number of days after seeding that 60 to 70% of plants became physiologically ripe, that is, the bottom, first-formed pods were crisp and dried to a buckskin color.

Common bacterial blight is a serious disease in dry bean production regions in Canada including southern Alberta (Bailey et al., 2003). It causes lesions on leaves and pods and reduces yield and seed quality. Incidence was visually assessed late in the growing season (using each entire plot area) and plots ranked as 0% (none), <1% (trace), 1 to 10% (light), 11 to 25% (moderate), 26 to 50% (high), or >50% (very high) of plants infected (Huang and Erickson, 2000). These six disease rankings were then assigned values from zero to five for the purposes of statistical analysis. White mold is another major disease of dry bean in southern Alberta (Huang et al., 1988) where plants develop pale lesions often with white mycelial mats or black sclerotia on the infected tissue. Severe infection can result in premature death. One-hundred and twenty plants (30 adjacent plants by four rows per plot) were visually assessed (on the same day as bacterial blight) for white mold incidence, expressed as (infected plants/total plants) × 100.

At harvest, wide-row dry bean (3-, 4-CONV) were undercut and allowed to further mature in swaths before harvesting with a plot combine. Narrow-row dry bean (3-, 4-, 5-, 6-CONS) were direct cut with a plot combine except in 2003, 2005, 2010, and 2011. Hand-harvesting (6 × 1 m^2 $plot^{-1}$) was performed in 2003 due to high weed populations and in 2005 due to wet soil conditions. In 2010 and 2011, narrow-row dry bean was undercut before combining in an effort to reduce harvest losses associated with direct cutting. This change was made in light of observed harvest losses (intact or cracked pods and seed on ground) in previous years which may have caused an underestimation of narrow-row dry bean performance.

Statistical Analyses

All data were initially tested for outliers (PROC UNIVARIATE) and then analyzed separately by year (PROC MIXED) with rotation as a fixed variable (SAS Institute, 2009). Data were also averaged over 12 yr (PROC MEANS) and analyzed using PROC MIXED. Orthogonal contrasts were used to compare management effects: CONV (mean, 3- and 4-CONV) vs. CONS (mean, 3-, 4-, 5-, and 6-CONS).

RESULTS AND DISCUSSION

Weather Conditions

The 30-yr (1971–2000) normal annual precipitation for Vauxhall is 303 mm of which 240 mm (Fig. 1) or 79% is growing season precipitation (GSP, 1 April–30 September) with 132 mm (44% of annual) in the early growing season (1 April–30 June). There was wide variation in GSP during the 12-yr study period (Fig. 1) from 507 mm (211% of normal) in 2005 to 118 mm (49% of normal) in 2001. In fact, these two growing seasons represented the wettest and driest since records began at Vauxhall in 1953. Other wetter-than-normal growing seasons included 2002 (466 mm, 194% of normal,

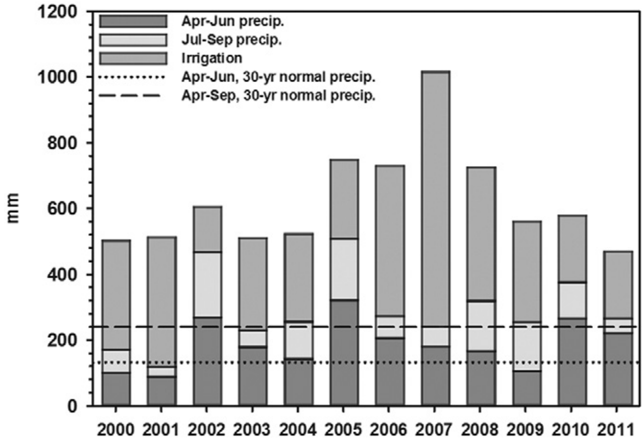

Fig. 1. Precipitation and irrigation amounts during the study period (2000–2011), and 30-yr precipitation normals (1971–2000).

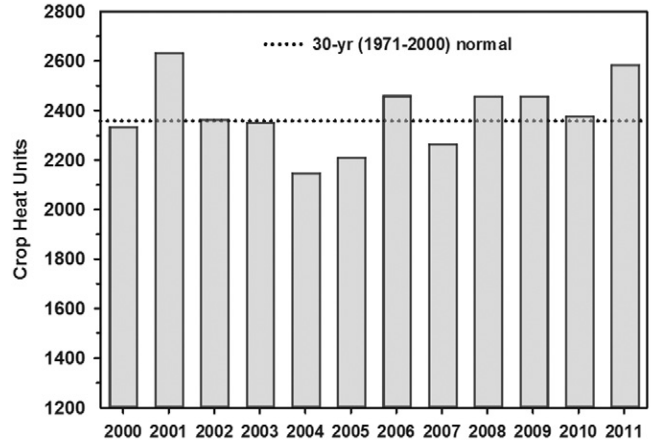

Fig. 2. Crop heat units (CHU) during the study period (2000–2011) compared with the 30-yr normal (1971–2000).

second wettest since 1953) and 2010 (376 mm, 157% of normal, fourth wettest since 1953). Apart from 2001, the only other relatively dry growing season was 2000 (Fig. 1) at 172 mm (72% of normal, fifth driest since 1953). Mean GSP during the study was 290 mm (n = 12) or 21% higher than the 30-yr normal. Growing season evaporation rates during the study varied from 1393 mm in 2009 to 754 mm in 2003 with a mean of 1113 mm (n = 12), very close to the 30-yr normal (1117 mm, 1971–2000).

Excessive rainfall in 2002, 2005, and 2010 led to standing water on low-lying areas of the experiment. Despite pumping off water, some plots were abandoned as plants succumbed to waterlogging. Of the 24 dry bean plots (six rotations by four replicates), two were abandoned in 2002, eight in 2005, and four in 2010. Also June 2011 had 115 mm of precipitation (195% of normal) which led to the abandonment of four dry bean plots due to flooding in 2011. Abandoned plots were treated as missing values in statistical analyses but since no more than two replicates of any rotation were missing in any year, the statistical integrity of the experiment was maintained.

Air temperature data for the trial were expressed in CHU (Fig. 2). The 30-yr (1971–2000) normal value for Vauxhall is 2359 CHU. The season with the lowest CHU was 2004 (2147 CHU, 91% of normal) followed by 2005 (2210, 94%) while the highest was 2001(also the driest season) at 2632 CHU (112% of normal), followed by 2011 (2583 CHU, 109%). A threshold of 1900 CHU is required for successful dry bean production in Alberta (Alberta Pulse Growers, 2014), and all 12 growing seasons easily exceeded this value. The number of frost-free days during the study varied from 105 d in 2009 to 144 d in 2007, with an average (n = 12) of 127 d which was similar to the 30-yr normal (1971–2000) value of 125 d.

Crop Management

On 3-CONS, fall rye biomass yield (Fig. 3) before desiccation ranged from 130 (2004) to 2044 kg ha^{-1} (2006) with an average of 1135 kg ha^{-1} (n = 10). There was a significant linear relationship between the growing period for fall rye (days from fall seeding through winter dormancy to spring sampling) and biomass yield. This was largely dictated by fall seeding date which had a range of 40 d (3 September–13 October) compared to a narrower range of 18 d from earliest to latest spring biomass sampling (2–20 May). Essentially, if rye was well established before soil freeze-up in fall, then biomass yield was higher the following spring. The slope of the relationship showed that biomass production increased by 49 kg ha^{-1} d^{-1} as the growing period extended from 213 (2003–2004) to 242 d (2004–2005).

Seeding dates for wide-row dry bean ranged from 14 to 26 May, and from 16 May to 7 June for narrow-row (Table 2). Seeding dates averaged (n = 12) 18 May for wide-row and 21 May for narrow-row. Balasubramanian et al. (2004) reported higher dry bean yield with mid-May than late-May seeding. As far as logistically possible, seeding dates for wide and narrow rows were kept similar. The greatest differences were 12 d in 2010 (wide, 26 May; narrow, 7 June) and 9 d in 2002 (wide, 18 May; narrow, 27 May) when wet conditions delayed narrow-row seeding.

Annual irrigation amounts (Fig. 1) and timings for dry bean depended on prevailing precipitation and ranged from 140 mm (2002) to 775 mm (2007), with a mean of 333 mm (n = 12). The initial irrigation occurred as early as 4 May (2001) or as late as 20 July (2010) with a mean of 11 June. To allow soil moisture levels to fall below 60% of available water and encourage pod filling, the final irrigation occurred between 31 July (2009) and 25 August (2010) with a mean of 11 August.

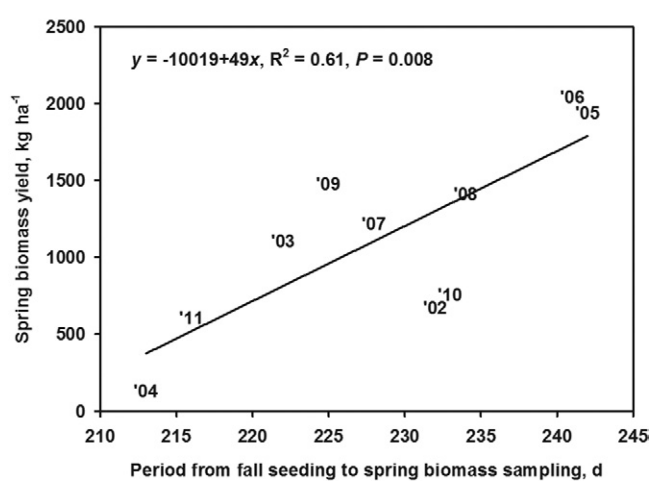

Fig. 3. Relationship between length of growing period and spring biomass yield of fall rye on 3-conservation (CONS) rotation.

Table 2. Seeding and harvest dates for wide- and narrow-row dry bean, 2000 to 2011.

	Seeding date		Harvest date		
			Wide		Narrow
Year	Wide	Narrow	Undercut	Combined	Combined
2000	17 May	17 May	8 Sept.	13 Sept.	13 Sept.
2001	18 May	17 May	29 Aug.	13 Sept.	13 Sept.
2002	18 May	27 May	12 Sept.	25 Sept.	17 Oct.
2003	22 May	28 May	29 Aug.	23 Sept.	8 Sept.†
2004	18 May	17 May	4 Sept.	21 Sept.	21 Sept.
2005	18 May	16 May	8 Sept.	26 Sept.	26 Sept.†
2006	17 May	19 May	23 Aug.	9 Sept.	11 Sept.
2007	17 May	23 May	24 Aug.	10 Sept.	11 Sept.
2008	15 May	20 May	17 Sept.	8 Oct.	8 Oct.
2009	16 May	21 May	8 Sept.	25 Sept.	25 Sept.
2010	26 May	7 June	29 Sept.‡	6 Oct.	6 Oct.
2011	14 May	18 May	6 Sept.‡	22 Sept.	22 Sept.
			12-yr average (2000–2011)		
	18 May	21 May	6 Sept.	21 Sept.	22 Sept.

† Hand-harvested.

‡ Narrow-row dry bean also undercut.

Adding GSP to irrigation (Fig. 1) resulted in total water inputs ranging from 469 mm (2011) to 1016 mm (2007) with a mean of 623 mm (n = 12).

The harvest operation for wide-row dry bean (Table 2) involved undercutting (average 6 September) and combining (average 21 September). Therefore, the average period wide-row dry bean was left in swaths after undercutting was 15 d which varied from 7 d in 2010 to 25 d in 2003 (Table 2). The earliest undercutting of wide-row dry bean occurred in 2006 (23 August) and the latest in 2008 (17 September). These years also had the earliest (9 September) and latest (8 October) combining of wide-row dry bean. The average harvest date for narrow-row dry bean was 21 September (undercutting in 2010–2011 excepted).

Plant Density

There was large year-to-year variation in plant density (Table 3). Wide-row densities varied from only 5 plants m^{-2} on 4-CONV in 2010 (a wet year) to 31 m^{-2} on 4-CONV in 2008. On CONS rotations, plant stand varied from 16 m^{-2} on 3-CONS in 2003 to 75 m^{-2} on 4-CONS in 2000. Densities were generally lower than target densities except in 2000 and 2008 when they were higher (>64 plants m^{-2}). Thinner stands were generally due to either wetter-than normal early growing seasons (e.g., 2002, 2010) or high weed pressures (narrow-row only).

All four CONS rotations had significantly higher plant densities than both CONV rotations (due to a higher seeding rate) in 10 of 12 yr, the two exceptions being 2002 and 2003 (Table 3). In 2002 there was no difference in density (15–17 plants m^{-2}) between narrow-row 3-CONS (direct seeded into desiccated fall rye), 5-CONS (direct seeded into shredded wheat stubble), or the wide-row CONV rotations. As outlined earlier, the 2002 early growing season was wetter-than-normal which decreased plant density under the high-residue conditions of the 3- and 5-CONS rotations. In 2003 the

Table 3. Effect of rotation and management on dry bean plant density, 2000 to 2011.

	Plant density												
Treatment†	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	12-yr mean
	plants m^{-2}												
	Rotation												
3-CONV	21c‡	23c	15b	25ab	30d	28c	22b	18c	30b	27b	8b	22d	23c
4-CONV	20c	24c	17b	30a	29d	29c	22b	16c	31b	29b	5b	23d	23c
3-CONS	71ab	32ab	17b	16c	63b	62a	47a	28ab	68a	62a	32a	40c	44b
4-CONS	75a	35a	30a	22bc	73a	51b	48a	31a	65a	63a	31a	50a	49a
5-CONS	64b	30b	17b	26ab	51c	47b	44a	29a	67a	54a	30a	46ab	42b
6-CONS	64b	37a	31a	24b	69ab	52b	44a	24b	66a	62a	28a	42bc	45b
P value	<0.001	<0.001	<0.001	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Management§												
CONV	21b	23b	16b	28a	30b	28b	22b	17b	30b	28b	6b	22b	23b
CONS	68a	33a	24a	22b	64a	53a	46a	28a	67a	60a	30a	44a	45a
P value	<0.001	<0.001	<0.001	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

† CONV, conventional management; CONS, conservation management.

‡ Within columns, rotation or management values followed by the same letter are not significantly different from each other (P > 0.05).

§ Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS).

wide-row 4-CONV rotation (30 plants m^{-2}) had significantly higher plant density than narrow-row 3-, 4-, and 6-CONS (14–24 plants m^{-2}). This was likely due to higher weed populations in the narrow-row treatments (Blackshaw et al., 2015). Since inter-row cultivation was not possible with narrow rows, weed control based solely on herbicides was a challenge, especially in the early years of the experiment.

There was no difference in plant density between the two wide-row CONV rotations in any year, even though the preceding crop was different: potato on 3-CONV, sugar beet on 4-CONV. Within the narrow-row CONS rotations, there were 4 yr (2006, 2008–2010) when densities on all four rotations (i.e., low- and high-residue conditions) were not significantly different from each other. Blackshaw et al. (2007) found generally no difference in dry bean plant density in narrow rows (23 cm) between conventional and zero tillage (ZT) following wheat, barley, canola (*Brassica napus* L.) or flax (*Linum usitatissimum* L.) in Alberta and in some cases higher density under ZT, which they attributed to improved soil moisture conditions or greater seed-soil contact. Similarly, Deibert and Utter (2002) found that plant populations were not significantly influenced by pre-seeding tillage system (conventional moldboard plowing, chisel plowing, strip tillage, or no till) in North Dakota.

There were instances when the high-residue 3-CONS and 5-CONS treatments resulted in decreased plant densities compared to the low-residue 4- and 6-CONS treatments. This was especially true with higher-than-normal precipitation, as in 2002, which led to significantly lower densities (17 plant m^{-2}) than both 4- and 6-CONS (30–31 m^{-2}). In addition, both 3- and 5-CONS (51–63 plants m^{-2}) were significantly lower than 4-CONS (73 m^{-2}) in 2004, 5-CONS was significantly lower than 4-CONS (64 vs. 75 plants m^{-2}) in 2000, and both 4- and 6-CONS (30 vs. 35–37 m^{-2}) in 2001. Also, the 3-CONS rotation was significantly lower than 6-CONS (16 vs. 24 plants m^{-2}) in 2003 and 4-CONS (40 vs. 50 m^{-2}) in 2011. However, in springs when fall rye biomass was highest (2005, 2006: 1940–2044 kg ha^{-1}), direct-seeding dry bean into the desiccated cover did not depress plant density significantly on the 5-CONS treatment. In contrast, there were a couple of instances of higher plant densities under high-residue conditions, for example, the 3-CONS rotation (62 plants m^{-2}) vs. 4- and 6-CONS (51–52 m^{-2}) in 2005, and 5-CONS (29 plants m^{-2}) vs. 6-CONS (24 m^{-2}) in 2007. Blackshaw (2008) found that despite slower emergence, dry bean density was not significantly affected by cover crops (fall- and spring-seeded rye, barley, and oat) in southern Alberta. Other studies also showed that fall rye (Liebman et al., 1995) or spring barley (Burnside et al., 1993) cover crops did not adversely affect dry bean plant density.

There were 4 yr when plant densities on the 3-CONS (desiccated fall rye) and 5-CONS (shredded wheat stubble) were significantly different from each other. However the trend was inconsistent, with 2 yr showing significantly higher densities on 3- vs. 5-CONS (63 vs. 51 plants m^{-2}, 2004; 62 vs. 47 m^{-2}, 2005) and 2 yr with significantly higher densities on 5- vs. 3-CONS (26 vs.16 plants m^{-2}, 2003; 46 vs. 40 m^{-2}, 2011).

Averaged over 12 yr (Table 3), the wide-row CONV rotations showed significantly lower plant densities (23 plants m^{-2}) as expected, due to a lower seeding rate than the narrow-row CONS rotations (42–49 plants m^{-2}). Within the narrow-row rotations, high-residue 3- and 5-CONS treatments had significantly lower average densities (42–44 plants m^{-2}) than 4-CONS (49 m^{-2}) but not 6-CONS (45 m^{-2}). Management contrasts (CONV vs. CONS) were significant in all years with CONV significantly lower than CONS except in 2003 (as discussed earlier). The 12-yr mean plant density was ~2 times higher with CONS (45 plants m^{-2}) than CONV (23 m^{-2}).

Plant Height

Average plant height (all rotations) varied from 35 cm in 2001 to 52 cm in 2007 (Table 4). A rotation effect was significant in 5 (2001, 2002, 2004, 2005, and 2010) of 12 yr and usually expressed by either one or both of the narrow-row high-residue rotations having shorter plants. Horn et al. (2000) also reported shorter plants with narrower rows. Plants on 3-CONS (desiccated fall rye) and 5-CONS (shredded wheat

Table 4. Effect of rotation and management on dry bean plant height, 2000 to 2011.

	Plant height												
Treatment†	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	12-yr mean
	cm												
	Rotation												
3-CONV	46a‡	34a	39c	45a	45a	35a	46a	53a	35a	46a	52bc	51a	44a
4-CONV	44a	36a	53a	39a	44ab	38a	45a	51a	37a	48a	45d	47a	44a
3-CONS	43a	29b	50ab	46a	41d	39a	47a	51a	35a	48a	51c	51a	44a
4-CONS	43a	38a	52a	47a	43bcd	34a	45a	53a	37a	50a	55ab	50a	45a
5-CONS	45a	38a	46b	47a	42cd	28b	45a	54a	37a	42a	51c	51a	44a
6-CONS	44a	34a	47ab	46a	44abc	39a	41a	52a	36a	49a	55a	49a	45a
P value	0.43	0.005	0.003	0.07	0.02	0.01	0.18	0.15	0.52	0.77	0.003	0.37	0.19
	Management§												
CONV	45a	35a	46a	42b	45a	37a	45a	52a	36a	47a	48b	49a	44a
CONS	44a	34a	49a	46a	43b	35a	44a	53a	36a	47a	53a	50a	44a
P value	0.19	0.61	0.10	0.01	0.002	0.32	0.56	0.58	0.83	0.99	0.002	0.35	0.08

† CONV, conventional management; CONS, conservation management.

‡ Within columns, rotation or management values followed by the same letter are not significantly different from each other ($P > 0.05$).

§ Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS).

stubble) were significantly shorter than 3- and 4-CONV (41–42 vs. 44–45 cm) in 2004 and 4- and 6-CONS (51 vs. 55–56 cm) in 2010. In 2001, 3-CONS plants were significantly shorter than other rotations (29 vs. 34–38 cm) while 5-CONS plants were significantly shorter than 4-CONV and 4-CONS in 2002 (46 vs. 52–53 cm) and all rotations in 2005 (28 vs. 34–39 cm).Overall, plants on CONV rotations were taller than CONS rotations by 2 cm in 2004. However, there were cases where wide-row rotations had shorter plants than narrow row, for example, 3-CONV was significantly shorter than other rotations in 2002 (39 vs. 46–53 cm), while 3-CONV (52 cm) and 4-CONV (51 cm) were both significantly shorter than 6-CONS (55 cm) in 2010. Overall management contrasts showed that plants in CONV rotations were significantly shorter than CONS rotations in 2003 (by 4 cm) and 2010 (by 5 cm). There was no significant effect of rotation or overall management (CONV vs. CONS) on mean plant height over the 12 yr of the study (Table 4).

Days to Maturity

Average DTM ranged from 94 in 2006 and 2007 to 113 in 2002 (Table 5). Of the 10 yr where DTM was assessed, rotation had a significant effect on all but 2 yr (2004, 2008). Within individual rotations, DTM ranged from 92 on the 3-CONS in 2007 to 121 on 4-CONV in 2010. There were 4 yr (2002, 2007, 2009, and 2010) when DTM on all four CONS rotations was significantly lower than both CONV rotations. Within the four CONS rotations, one or both of the high-residue rotations showed significantly delayed maturity in the early part of the study, for example, 5-CONS by 4 to 5 d in 2000 and 4 to 7 d in 2001, and 3-CONS by 1 to 2 d in 2002. In 2006, both 3- and 5-CONS were 2 d later than 6-CONS. However, later in the study, either the above trend was reversed with a high-residue CONS treatment showing earlier maturity than a low-residue one (3-CONS earlier than 4- and 6-CONS by 2 d in 2007 and 5-CONS earlier than 4-CONS by 2 d in 2010), or there was no difference within CONS rotations (2009, 2011). When averaged across all years, the four CONS rotations showed significantly lower DTM than the two CONV rotations, with no significant differences within the four CONS rotations or the two CONV rotations.

Management contrasts revealed significantly lower DTM on CONS than CONV rotations in 8 of 10 yr (Table 5), with no difference in 2004 and a reverse trend in 2001 (CONV 3 d earlier). Maturity advantages with CONS rotations varied from just 1 d in 2006 to 14 d in 2010. On average over 10 yr, there was a 3 d maturity advantage with CONS (103 d) vs. CONV (106 d) management. This could be important in falls with an early killing frost event. Our findings agreed with Deibert (1995) who found that dry bean cultivars matured 7 to 10 d earlier under CT (chisel plowing, strip tillage, no till) than conventional tillage. Our findings differed from those of Blackshaw (2008) who found a 3 to 4 d delay in maturity with fall rye and a 2 d delay with fall-seeded barley or oat cover crops in southern Alberta. Eckert et al. (2011b) found no difference in DTM for upright pinto bean seeded at 30, 46, and 76 cm in North Dakota.

Disease Incidence

For bacterial blight (Table 6), the lowest average ranking (across all rotations) was in 2000 (0: zero incidence) while the highest was in 2008 (3: 11–25% incidence, moderate). The 2008 growing season was characterized by three severe hail storms in rapid succession (7, 10, and 15 July) which were accompanied by strong winds. Canopy damage and subsequent stress may have exacerbated the incidence of bacterial blight on dry bean. The 4-CONS rotation in 2008 was the only one to register a ranking of 4 (26–50% incidence, high) in the study. Three growing seasons (2002, 2005, and 2007) had an average bacterial blight ranking of 2 (1–10% incidence, light). Two of these (2002, 2005) were wetter than normal.

The effect of rotation on bacterial blight was significant in only 2 of 12 yr. In 2008, 4-CONS had a significantly higher ranking (4) than 5-CONS (3) and 3-CONV (2). In 2010, 3-, 4-, and 5-CONS (1) were significantly higher than 3-CONV (0). For management contrasts, only 2010 revealed a significant effect with CONS (1) higher than CONV (0). The latter two cases, although statistically significant, may not be of practical

Table 5. Effect of rotation and management on dry bean maturity, 2000 to 2002, 2004, 2006 to 2011.†

Treatment‡	Days to maturity										
	2000	2001	2002	2004	2006	2007	2008	2009	2010	2011	10-yr mean
					Rotation						
3-CONV	110a§	101cd	116b	110a	96a	96a	105a	107a	119b	108a	105a
4-CONV	110a	99e	118a	114a	95ab	97a	106a	107a	121a	106ab	107a
3-CONS	105b	100de	112c	113a	95ab	92c	105a	102b	107cd	103c	104b
4-CONS	106b	103b	111d	112a	94bc	94b	102a	102b	107c	104bc	103b
5-CONS	110a	107a	110d	113a	95ab	93bc	102a	101b	105d	102c	103b
6-CONS	106b	102c	110d	111a	93c	94b	102a	102b	106d	104bc	103b
P value	<0.001	<0.001	<0.001	0.29	0.004	<0.001	0.06	<0.001	<0.001	0.007	<0.001
					Management¶						
CONV	110a	100b	117a	112a	95a	96a	105a	107a	120a	107a	106a
CONS	106b	103a	111b	112a	94b	93b	102b	101b	106b	103b	103b
P value	<0.001	<0.001	<0.001	0.73	0.01	<0.001	0.009	<0.001	<0.001	<0.001	<0.001

† Maturity was not assessed in 2003 or 2005.

‡ CONV, conventional management; CONS, conservation management.

§ Within columns, rotation or management values followed by the same letter are not significantly different from each other ($P > 0.05$).

¶ Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS).

importance. Also, it was difficult to discern trends between bacterial blight levels and the number of fungicide applications (Table 6).

White mold (Table 7) was not an issue in the first 2 yr (which were also the two driest of the study) with 2000 showing the lowest average incidence (0.3%), followed by 2001 (2%). By 2002, average incidence increased to 10% (a wetter-than-normal year) but dropped to 5% in 2003. The overall highest incidence was 42% in 2010 followed by 34% in 2004. The 2010 growing season was the third wettest (376 mm, 157% of normal) while 2004 had the lowest CHU. White mold incidence ranged from zero (3-CONV, 2001) to 20% (4-CONV, 2004), within the wide-row CONV treatments, and from zero (3- and 6-CONS, 2000) to 89% (4-CONS, 2010) within the narrow-row CONS treatments. In North Dakota, Ramasubramaniam et al. (2008) reported mean annual white mold incidences of 6 to 28% and found that values <20% did not affect yield.

Table 6. Effect of rotation and management on bacterial blight incidence, 2000 to 2011.

	Ranking for bacterial blight incidence†												
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	
	Fungicide applications, no.												
Treatment‡	4	2	1	3	3	4	2	2	2	2	2	1	12-yr mean
						Rotation							
3-CONV	0a§	0a	2a	0a	1a	2a	2a	2a	2c	2a	0b	1a	1a
4-CONV	0a	0a	2a	1a	1a	2a	2a	2a	3ab	2a	1ab	2a	2a
3-CONS	0a	0a	2a	0a	1a	2a	2a	2a	3abc	2a	1a	2a	2a
4-CONS	0a	0a	2a	1a	1a	2a	3a	2a	4a	2a	1a	2a	2a
5-CONS	0a	1a	3a	0a	1a	2a	1a	2a	3bc	2a	1a	2a	2a
6-CONS	0a	1a	2a	1a	1a	2a	2a	2a	3ab	2a	0ab	2a	2a
P value	0.99	0.36	0.50	0.84	0.45	0.65	0.21	0.96	0.05	0.96	0.02	0.50	0.40
						Management¶							
CONV	0a	0a	2a	1a	1a	2a	2a	2a	3a	2a	0b	2a	2a
CONS	0a	1a	2a	1a	1a	2a	2a	2a	3a	2a	1a	2a	2a
P value	0.99	0.55	0.94	0.85	0.13	0.54	0.40	0.87	0.41	0.88	0.02	0.28	0.89

† Rankings: 0 = 0%; 1 = <1%; 2 = 1 to 10%; 3 = 11 to 25%; 4 = 26–50% incidence. Values rounded for display purposes but not for means separation.

‡ CONV, conventional management; CONS, conservation management.

§ Within columns, rotation or management values followed by the same letter are not significantly different from each other (*P* > 0.05).

¶ Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS).

Table 7. Effect of rotation and management on white mold incidence, 2000 to 2011.

	White mold incidence												
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	
	Fungicide applications, no.												
Treatment†	1	2	2	1	2	1	2	1	1	2	2	1	12-yr mean
							%						
						Rotation							
3-CONV	0.4a‡	0c	5c	5a	15b	4c	6c	8c	2c	8b	13c	2b	6c
4-CONV	0.8a	0.2c	3c	2a	20b	4c	12bc	8c	2c	11b	4c	2b	6c
3-CONS	0a	2b	12b	4a	51a	15ab	13bc	35a	10b	52a	82a	10a	23a
4-CONS	0.2a	1b	9b	5a	55a	19a	27a	26b	9b	19b	89a	9a	21a
5-CONS	0.4a	4a	16a	8a	30ab	13b	22ab	28ab	10ab	5b	13c	6ab	13b
6-CONS	0a	2b	12b	8a	33ab	18ab	23ab	29ab	13a	41a	52b	9a	18ab
P value	0.33	<0.001	<0.001	0.06	0.02	<0.001	0.02	<0.001	<0.001	<0.001	0.002	0.01	<0.001
						Management§							
CONV	0.6a	0.1b	4b	4a	18b	4b	9b	8b	2b	9b	9b	2b	6b
CONS	0.1a	2a	12a	6a	42a	16a	21a	30a	11a	29a	59a	8a	19a
P value	0.07	<0.001	<0.001	0.07	0.005	<0.001	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

† CONV, conventional management; CONS, conservation management.

‡ Within columns, rotation or management values followed by the same letter are not significantly different from each other (*P* > 0.05).

§ Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS).

There were only 2 of 12 yr (2000, 2003) when the rotation effect was nonsignificant for white mold incidence (Table 7). In 5 of 12 yr (2001, 2002, 2005, 2007, and 2008), both wide-row CONV rotations had significantly lower incidence than all four narrow-row CONS rotations. White mold incidence on the two CONV rotations was not significantly different in any year whereas 8 of 12 yr (2001–2002, 2005–2010) showed significant differences among the four CONS rotations. Most of the differences were due to one of the high-residue treatments having significantly lower incidence, for example, 3-CONS (desiccated fall rye) was significantly lower than 4-CONS in 2006 (13 vs. 27%) and 6-CONS in 2008 (10 vs. 13%). The 5-CONS rotation (shredded wheat stubble) was significantly lower than 4-CONS in 2005 (13 vs. 19%), 3-CONS and 6-CONS in 2009 (5 vs. 41–52%) and all three other CONS rotations in 2010 (13 vs. 52–89%). Overall (12 yr) mean values with 5-CONS were significantly lower (13%) than 3-CONS (23%) and 4-CONS (21%) but not 6-CONS (18%). Also both CONV rotations had significantly lower white mold incidence when averaged over 12 yr (6%) than CONS rotations (13–23%). However, there were also cases where high-residue CONS treatments led to significantly higher white mold, for example, 5-CONS vs. all other CONS rotations in 2001 (4 vs. 1–2%) and 2002 (16 vs. 9–12%), and 3-CONS vs. 4-CONS in 2007 (35 vs. 26%).

Management contrasts showed a marked difference in white mold incidence between wide- (CONV) and narrow-row (CONS) dry bean, with significant effects in all but 2 yr (2000, 2003). In all cases, white mold increased with CONS management from as little as 2 percentage points in 2001 to as much as 50 percentage points in 2010. Over 12 yr, average incidence was significantly higher with CONS (19%) than CONV management (6%). Pynenburg et al. (2011) reported that high weed pressure in the presence of white mold increased disease severity for dry bean in Ontario. In our study, narrow-row dry bean often had higher weed populations (Blackshaw et al., 2015) than wide-row due to reliance on herbicides for weed control in the absence of inter-row cultivation and this may have contributed to higher white mold incidence.

Peachey et al. (2006) reported that one fungicide application (vinclozolin) allowed snap bean growers in Oregon to use narrow rows without increasing the risk of white mold compared to a control treatment (no fungicide). Our study did not have a control treatment, however, half the study years received one application of white mold fungicide and half received two (Table 6). For the 6 yr with one application, average incidence was 3.4% on wide-row and 11.9% on narrow-row dry bean. For the 6 yr with two applications, average incidence was 8.2% on wide-row and 27.5% on narrow-row. This shows that while a second application did not reduce disease incidence to that of years requiring only one application, foregoing a second application may have resulted in much higher incidence in years where it was justified.

Yield

Dry bean yield (averaged across all rotations) ranged from 943 kg ha^{-1} in 2008 to 3521 kg ha^{-1} in 2011 (Table 8). As mentioned previously, the 2008 crop suffered severe hail damage and bacterial blight. The overall average yield (all years, all rotations) for the trial was 2157 kg ha^{-1}. There was a significant rotation effect on dry bean yield in 8 of 12 yr, the exceptions being 2003 (narrow-row hand-harvested due to high weed pressure), 2004, 2007, and 2010 (Table 8).

The 5-CONS rotation (shredded wheat stubble) was significantly lower-yielding than all other rotations in 2000 (1695 vs. 2040–2157 kg ha^{-1}) and 3- and 4-CONV and 4-CONS in 2001 (1372 vs. 2343–3116 kg ha^{-1}). In 2002 (wetter-than-normal), 3-CONS (desiccated fall rye) was significantly lower-yielding (926 kg ha^{-1}) than the low-residue 4- and 6-CONS treatments (1525–1705 kg ha^{-1}). This agreed with the findings of Liebman et al. (1995) who documented reduced dry bean yield with a fall rye cover crop when early season conditions were cool and wet. The 2005 season was unusual in that three of the narrow-row rotations (3-, 4-, and 6-CONS) were significantly higher yielding than the two CONV rotations (2806–3515 vs. 1319–1726 kg ha^{-1}). This could be explained by harvest weather conditions and harvesting method. The wide-row dry bean was swathed on 8 September. However a total of 120 mm of precipitation fell on the swaths before they were dry enough to combine on 26 September, which may have caused yield losses. In contrast narrow-row dry bean was standing throughout the wet period and was hand harvested on 26 September due to wet soil conditions which would have hindered direct combining. Eliminating risks from weather-related losses while wide-row dry bean are in swaths has been highlighted as an advantage of narrow-row production (Ablett, 1988).

In 2007, 3-, 4-, and 6-CONS (1852–1874 kg ha^{-1}) were all significantly lower yielding than 5-CONS (shredded wheat stubble) and 3- and 4-CONV rotations (2374–2601 kg ha^{-1}) which were not significantly different from each other. In 2008, 3-CONS (desiccated fall rye, 1000 kg ha^{-1}) was not significantly different than 3- and 4-CONV (1089–1420 kg ha^{-1}). In 2009, there was a clear case of both CONV rotations being significantly higher yielding than all four CONS rotations (2329–2484 vs. 1777–1842 kg ha^{-1}).

Management contrasts (Table 8) revealed that 5 of 12 yr showed no significant difference between CONV and CONS management (2000, 2002, 2003, 2004, 2010) and 2 yr with significantly higher yield under CONS management: 2005 (85%) and 2011 (39%). The remaining 5 yr showed significantly lower yield (17–37%) under CONS management (2001, 2006–2009). These were also years where CONS management led to significantly higher white mold incidence (Table 7). Ramasubramaniam et al. (2008) reported a significantly linear relationship between dry bean yield and white mold incidence in North Dakota, with a yield loss of 14 kg ha^{-1} for every 1% point increase in incidence.

In contrast, 2010 provided evidence that white mold pressure had no major effect on yield, for example, 3- and 4-CONS treatments had white mold incidences of 82 to 89% compared to only 4 to 13% on 3- and 4-CONV treatments (Table 7), yet yields were not significantly lower than 3- and 4-CONV treatments (Table 8). Wunsch (2014) found that under high white mold pressures, yields were optimized in narrow rows, and maximizing distance between plants within rows was more important than maximizing row spacing. Lee et al. (2005) reported that plant spacing within rows explained

Table 8. Effect of rotation and management on dry bean yield, 2000 to 2011.

Treatment†	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean 2000–2011	CV 2000–2011	Mean 2000–2009	Mean 2010–2011
	Dry bean yield															
	kg ha^{-1}													%	kg ha^{-1}	
								Rotation								
3-CONV	2096a‡	2834ab	1132bc	2407a	1788a	1319b	2299a	2601a	1089ab	2329a	2576a	3080ab	2139a	33b	2048ab	2940a
4-CONV	2139a	3116a	1523ab	2109a	2198a	1726b	2626a	2374a	1420a	2484a	2335a	2502b	2212a	24c	2186a	2362a
3-CONS	2157a	2140bcd	926c	2582a	2094a	3038a	1743a	1852b	1000abc	1777b	2396a	3992a	2197a	43a	1960bc	3194a
4-CONS	2117a	2343bc	1525ab	2054a	2449a	2806a	2153a	1865b	645c	1804b	2274a	4056a	2128a	40ab	1976b	3103a
5-CONS	1695b	1372d	1109bc	2760a	2070a	1919b	1734a	2547a	764bc	1798b	2847a	3769a	1966a	42a	1789c	3466a
6-CONS	2040a	2043cd	1705a	2180a	2355a	3515a	1730a	1874b	744bc	1842b	3243a	3725a	2223a	45a	2003b	3480a
P value	0.003	0.005	0.03	0.27	0.16	0.002	0.17	0.007	0.01	0.02	0.29	0.05	0.19	<0.001	0.01	0.14
								Management§								
CONV	2118a	2975a	1328a	2258a	1993a	1523b	2463a	2448a	1254a	2406a	2456a	2791b	2196a	29b	2117a	2651b
CONS	2003a	1974b	1316a	2394a	2242a	2820a	1840b	2035b	788b	1805b	2690a	3886a	2128a	43a	1932b	3311a
P value	0.10	<0.001	0.94	0.52	0.12	<0.001	0.02	0.005	0.002	<0.001	0.46	0.003	0.47	<0.001	0.003	0.02

† CONV, conventional management; CONS, conservation management.

‡ Within columns, rotation or management values followed by the same letter are not significantly different from each other ($P > 0.05$).

§ Management contrasts: CONV (mean of 3- and 4-CONV); CONS (mean of 3-, 4-, 5- and 6-CONS).

differences in white mold on soybean [*Glycine max* (L.) Merr.], for example, in narrow (19-cm) rows, incidence was higher at a plant density of 56 vs. 43 m^{-2}, which they attributed to closer plant spacing within the row (9.4 vs. 12.2 cm between plants) at higher densities.

Averaging across all 12 yr, there was no significant rotation effect on yield ($P = 0.19$) showing that narrow-row production under CONS management gave similar yields as wide-row production under CONV management over a long-term period with a range of weather conditions. This supported findings of Blackshaw and Molnar (2008) who reported that with suitable herbicide programs, similar yields were attained when dry bean was seeded directly into stubble or cover crop residues compared with a no-cover control. Also, Blackshaw et al. (2007) found that tillage intensity (conventional vs. ZT) had no significant effect on narrow-row dry bean yield across a range of previous crop stubbles (wheat, barley, canola, flax), years, and sites in Alberta. Deibert (1995) found little difference in dry bean yield between conventional tillage (moldboard plowing) and three CT systems with varying degrees of wheat residue (chisel plowing, strip tillage, or no till) in North Dakota. However, there was a significant rotation effect on the coefficient of variation (CV) of the 12 yr means with 3-, 5-, and 6-CONS showing significantly greater variability in yield (42–45%) than both CONV rotations (24–33%).

A disadvantage of direct harvesting dry bean is the excessive losses due to the cutter bar missing or dissecting pods positioned close to the soil surface (Zyla et al., 2002). Seed losses have been estimated at up to 40% of yield in narrow-row production (Saskatchewan Agriculture, 2009). In North Dakota, Eckert et al. (2011a) found losses of 3 to 8% with conventional harvest (undercutting) and 16 to 32% with direct harvest across a range of cultivars and market classes (black, navy, pinto). Harvest losses were evident after direct cutting narrow-row dry bean in our study, which ostensibly underestimated yield of this system. Assuming AC Redbond weighs 0.34 g seed^{-1}, 30 seeds m^{-2} on the soil surface after harvest represents a yield loss of 102 kg ha^{-1}.

Therefore in the last 2 yr (2010, 2011) of the study, in an attempt to reduce harvest losses associated with direct cutting, narrow-row plots were undercut and raked into swaths which were then combined, resulting in essentially the same harvesting method as wide-row plots. This also reflected changes in grower practices that had evolved over the lifetime of the study, as new or existing narrow-row growers increasingly chose swathing instead of direct combining (Saskatchewan Agriculture, 2009). Given this change in harvest management, the 12 yr mean rotation yields discussed above may not represent a truly accurate comparison between wide- (CONV) and narrow-row (CONS) production. Hence, average yields for the first 10 yr (2000–09) and the last 2 yr (2010–2011) were calculated separately (Table 8). This showed that in fact, significant differences due to rotation occurred in mean yield over the first 10 yr. The 5-CONS rotation (desiccated fall rye) was significantly lower-yielding (1789 kg ha^{-1}) than all other rotations except 3-CONS (1960 kg ha^{-1}) which was significantly lower yielding than 4-CONV (2186 kg ha^{-1}). This disagreed with the findings of Blackshaw (2008) who reported 5 to 13% dry bean yield increases due to inclusion of cover crops, which was largely attributed to a weed suppression effect. There was no significant difference between 3-CONV, 3-CONS, 4-CONS or 6-CONS (1960–2048 kg ha^{-1}). Overall there was a 22% yield difference between the highest and lowest yielding rotations (4-CONV vs. 5-CONS). The management contrast for the first 10 yr mean was also significant with CONV rotations yielding 10% higher than CONS.

There was no significant effect of rotation on the mean yield for the last 2 yr (Table 8), showing that undercutting narrow-row dry bean resulted in similar yields to wide-row. However, the management contrast revealed that narrow-row CONS rotations were significantly higher (25%) than wide-row CONV rotations. Pfiffner et al. (2014) reported an 11% average yield increase with 18 or 36 cm vs. 72 cm rows over 12 site-years in southern Alberta which they attributed to better seedbed utilization. However, they indicated that N inputs may need to be increased by 20% to maximize yield potential under narrow rows. The reversal of the CONV vs. CONS yield trend in last 2 yr showed that the change in harvesting technique, to reduce harvest losses, improved the performance of narrow-row production. Although it is important to maintain treatment consistency in long-term field experiments, this management change toward the end of the study allowed us to capture the true contribution of narrow-row production to dry bean yield as well as reflect ongoing changes in grower practices.

CONCLUDING REMARKS

Our findings suggest that dry bean can be successfully grown with conservation-oriented management practices (such as narrow rows, reduced tillage, cover crops, and compost addition) if steps are taken to minimize harvest losses by swathing rather than direct cutting. Even with direct cutting, narrow-row production was similar to wide-row in the absence of high-residue planting conditions. White mold incidence was significantly higher with CONS management which included narrow rows and this often, but not always, corresponded to lower yields. One issue with narrow-row production is the increased cost of seed inputs since plant densities are normally twice those of conventional wide-row production. However, the indications are that narrow-row dry bean production is currently increasing on the Canadian prairies and our study provides incentive for further adoption of the practice.

ACKNOWLEDGMENTS

We thank Jim Sukeroff, Dale Reynolds, and Vauxhall Substation staff and summer students for field assistance. The input of H.-Henning Mündel (retired) in planning the study is gratefully acknowledged. Dry bean field support was provided by John Braun, Cathy Daniels, and Todd Reid and disease assessment by Scott Erickson. Funding was provided by The Alberta Pulse Growers, the Potato Growers of Alberta, Lantic Inc., the Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster. The China Scholarship Council supported Dr. Lingling Li as a visiting scientist (2012–2013) at the Lethbridge Research Centre.

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NRC Research Press

ARTICLE

Soft white spring wheat is largely unresponsive to conservation management in irrigated rotations with dry bean, potato, and sugar beet

Francis J. Larney, Drusilla C. Pearson, Robert E. Blackshaw, Newton Z. Lupwayi, and Robert L. Conner

Abstract: Historically, soft white spring (SWS) wheat (*Triticum aestivum* L.) has been a crop choice in southern Alberta's irrigation districts. A 12-yr (2000–2011) study compared conservation (CONS) and conventional (CONV) management for SWS wheat in 3–5-yr rotations with dry bean (*Phaseolus vulgaris* L.), potato (*Solanum tuberosum* L.), and sugar beet (*Beta vulgaris* L.). Conservation management incorporated reduced tillage, compost, cover crops, and narrow-row dry bean. Wheat was largely unresponsive to CONS management, with only 2 of 13 parameters showing significant positive effects: greater grain Ca (605 vs. 576 μg g^{-1} on CONV) and S concentrations (1137 vs. 1105 μg g^{-1} on CONV). Two parameters showed significant negative responses to CONS management: shorter plant height (82.8 vs. 84.8 cm on CONV) and higher take-all [*Gaeumannomyces graminis* (Sacc.) Arx & Olivier var. *tritici* Walker] severity (1.34 vs. 1.27 rating on CONV). The remaining nine parameters were unresponsive: plant density, days to maturity, grain yield, grain protein concentration, test weight, kernel hardness, wheat stem sawfly [*Cephus cinctus* Norton (Hymenoptera: Cephidae)] damage, and grain P and K concentrations. With a backdrop of continued decline in irrigated SWS wheat hectarage, we feel our data is relevant to other wheat classes grown under irrigation in southern Alberta.

Key words: soft white spring wheat, rotation, irrigation, soil conservation.

Résumé : Depuis toujours, le blé tendre blanc de printemps (SWS) (*Triticum aestivum* L.) est la culture de prédilection dans les districts irrigués du sud de l'Alberta. Dans le cadre d'une étude de douze ans (de 2000 à 2011), les auteurs ont comparé les pratiques culturales de conservation et classiques du blé SWS, produit en assolement de trois à cinq ans avec le haricot (*Phaseolus vulgaris* L.), la pomme de terre (*Solanum tuberosum* L.) et la betterave sucrière (*Beta vulgaris* L.). Les pratiques de conservation incluaient la réduction du travail du sol, l'usage de compost, des cultures abris et des semis en rangs étroits pour le haricot. Le blé réagit mal aux pratiques de conservation, deux paramètres sur treize seulement ayant enregistré des gains importants, en l'occurrence la concentration de Ca (605 c. 576 μg par g pour les pratiques de culture classiques) et celle de S (1137 c. 1105 μg par g pour les pratiques de culture classiques), plus élevées dans le grain. Deux paramètres ont réagi assez négativement aux pratiques culturales classiques : la taille du plant, qui était plus court (82,8 c. 84,8 cm pour les pratiques de culture classiques), et la plus forte gravité du piétin [*Gaeumannomyces graminis* (Sacc.) Arx & Olivier var. *tritici* Walker] (cote de 1,34 c. 1,27 pour les pratiques de culture classiques). Les neuf paramètres restants n'ont pas réagi : densité de la culture, nombre de jours avant la maturité, rendement grainier, teneur en protéines du grain, poids spécifique, dureté du grain, dommages causés par le cèphe du blé [*Cephus cinctus* Norton (Hymenoptera: Cephidae)] et concentration en P et en K du grain. Face à l'érosion continue de la superficie irriguée consacrée à la culture du blé SWS, les auteurs pensent que ces données pourraient servir aux autres variétés de blé cultivées sous irrigation dans le sud de l'Alberta. [Traduit par la Rédaction]

Mots-clés : blé tendre blanc de printemps, assolement, irrigation, conservation du sol.

Received 5 May 2017. Accepted 26 July 2017.

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Introduction

Canada western soft white spring (CWSWS) is a wheat class with low grain protein concentration (GPC) and high-starch flour with weak dough characteristics, suited to end-uses in cakes, cookies, pastries, and flatbreads (Canadian Grain Commission 2017). Irrigated soft white spring (SWS) wheat was introduced to southern Alberta in the 1930s to secure a local supply for the milling market (Thomas 1995). Production grew slowly, reaching ~40 000 ha by the mid-1970s and peaking at 189 000 ha in 1984 (Fig. 1). However, by 2000, the seeded area of SWS wheat had plummeted dramatically to only 18 000 ha due to low economic returns, changes to consumer dietary preferences, and competition with other wheat classes (Beres et al. 2013). McCallum and DePauw (2008) highlighted limited domestic demand as a reason for the decline of CWSWS wheat, with its end-uses filled by soft white winter wheat from Ontario. Moreover, export prices for SWS wheat were not competitive with net returns from other wheat classes.

While SWS wheat has historically been adapted to the irrigation districts of southern Alberta, it has recently found a niche as a suitable feedstock for ethanol production due to its low GPC and high starch content (Beres et al. 2008, 2013; McKenzie and Pauly 2013). In fact, the rebound in the seeded area of SWS wheat since 2010 (Fig. 1) has been driven by the ethanol market. The growing area has shifted north and east, from its traditional base in the irrigation districts of southern Alberta, to non-irrigated regions of Alberta and Saskatchewan, in proximity to ethanol plants (Beres et al. 2008). In 2015, 111 000 ha of SWS wheat were grown in Alberta and 138 000 ha in Saskatchewan (Fig. 1), with the area under irrigation (7000 ha) representing only 6% of the total area grown in Alberta, compared with ~100% from as recently as 2007.

Despite the above trends, the total area of wheat (of all classes) grown on southern Alberta's ~572 000 ha of irrigated land (Alberta Agriculture and Forestry 2016) has increased over the last two decades (Fig. 2). However, CWSWS, the dominant class under irrigation prior to 1998 (Fig. 2), has been largely displaced by Canada western red spring (CWRS) and Canada western amber durum (CWAD) wheat [*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.]. Those changes were facilitated by the development of shorter cultivars of CWRS, and particularly CWAD, that had sufficient straw strength to preclude lodging under irrigated conditions, and commanded a higher price than SWS wheat (McCallum and DePauw 2008). Even Canada prairie spring and Canada western red winter (CWRW) wheat, which are generally considered non-traditional classes under irrigation, have surpassed SWS wheat area in recent years (Fig. 2).

Compared with rotation studies on dryland wheat, there is a dearth of information on the effects of rotation on SWS wheat, largely because historically it has been a niche crop in southern Alberta's irrigation districts rather than the Canadian prairies as a whole. Even Irrigated Rotation U at Agriculture and Agri-Food Canada's Lethbridge Research and Development Centre, Lethbridge, AB, which dates to 1911 (Dubetz 1983), used CWRS and utility wheats until SWS wheat ('AC Fielder') was first introduced in 1981. Three new 5-yr rotations commenced on Rotation U in 1987 (Nakonechny et al. 2004): alfalfa (*Medicago sativa* L.)–alfalfa–alfalfa–wheat–barley (*Hordeum vulgare* L.), faba bean (*Vicia faba* L.)–wheat–faba bean–wheat–barley, and corn (*Zea mays* L.)–wheat–corn–wheat–barley. Those rotations showed that wheat yield with zero N fertilizer was higher following 3 yr of alfalfa vs. faba bean or corn, likely due to greater N mineralization after alfalfa (Nakonechny et al. 2004). However, with 100 kg ha^{-1} of N fertilizer addition, there was little effect of rotation on wheat yield. In a Lethbridge study comparing conventional and reduced tillage in 4-yr rotations (Hao et al. 2001), SWS wheat ('AC Reed') yield was not significantly different (mean of both phases) between two rotations: wheat–sugar beet–wheat–legumes (dry bean or pea, *Pisum sativum* L.) vs. wheat–wheat–legumes–sugar beet. However, there was a significant effect of preceding crop with wheat following legumes having higher yields than wheat following sugar beet (by 13%) or wheat (by 29%) in 2 out of 3 yr.

The area of potato production increased in southern Alberta in the late 1990s with the opening of two large potato processing plants. Dry bean acreage also expanded during that time, and as those crops are normally rotated with sugar beet, questions arose regarding soil conservation and the maintenance of soil health, as all three of those row crops produce limited crop residue for return to the soil, compared with cereals or forages (Larney et al. 2017*b*). Therefore, a rotation study was initiated in 2000 to compare conventional (CONV) and conservation (CONS) management. The study ran for 12 yr (2000–2011) with CONS management built around four specific practices: (*i*) reduced tillage; (*ii*) compost addition; (*iii*) cover crops; and (*iv*) narrow-row dry bean.

The specific objectives of this study were to assess SWS wheat yield and quality in 3–5 yr irrigated rotations with dry bean, potato, and sugar beet under CONV or CONS soil management over 12 yr. The effects of rotation and soil management on dry bean (Larney et al. 2015), potato (Larney et al. 2016*b*), and sugar beet (Larney et al. 2016*a*) performance and soil quality (Li et al. 2015; Larney et al. 2017*a*; Lupwayi et al. 2017*a*, 2017*b*) have been reported.

Materials and Methods

Experimental design

The study was conducted at the Vauxhall substation of Agriculture and Agri-Food Canada, Vauxhall (50°03′N, 112°09′W, elevation 781 m), AB, on a Brown Chernozemic soil (Soil Classification Working Group 1998). The soil texture was a sandy loam, organic carbon was 12.9 g kg^{-1},

Fig. 1. Areas of Canada western soft white spring wheat grown in Alberta (1972–2016) and Saskatchewan (1991–2016). Sources: 1972–1990 data (Thomas 1995); 1991–2016 data (Statistics Canada 2016).

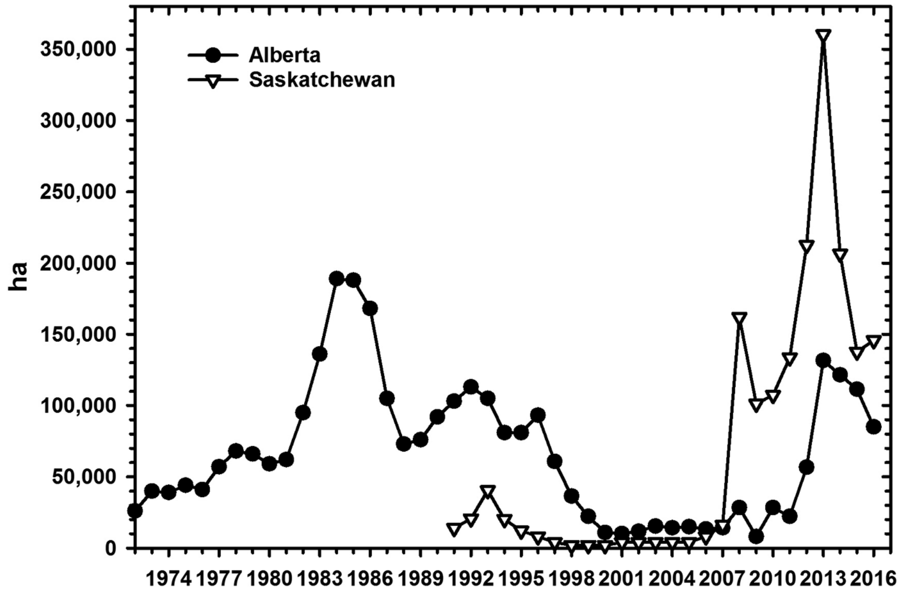
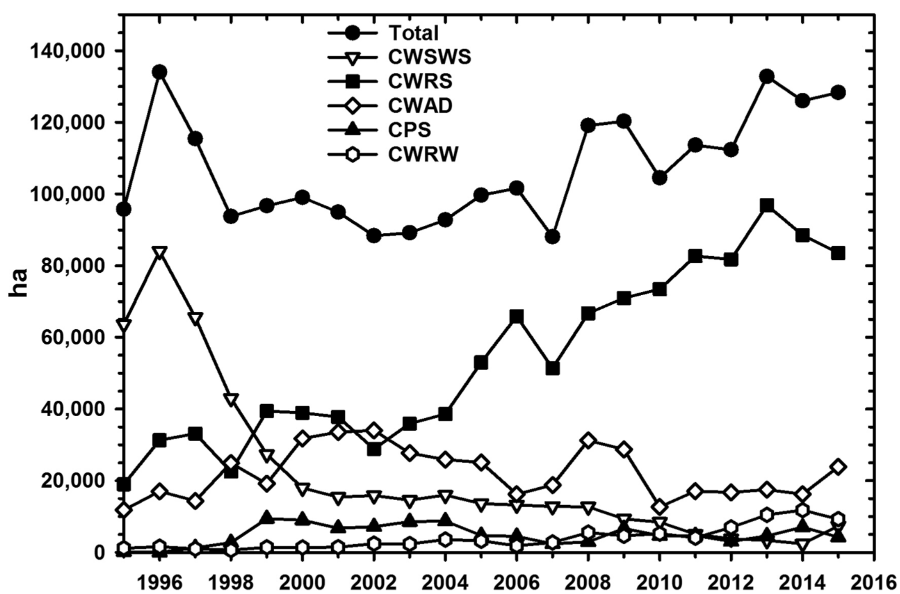


Fig. 2. Areas of total wheat and specific milling classes (CWSWS, Canada western soft white spring; CWRS, Canada western red spring; CWAD, Canada western amber durum; CPS, Canada prairie spring; CWRW, Canada western red winter) grown in Alberta's 13 irrigation districts, 1995–2015. (Adapted from data provided by Basin Management Section, Irrigation and Farm Water Branch, Alberta Agriculture and Forestry, Lethbridge, AB).



and pH was 6.9 (0–15 cm depth). The 30-yr (1971–2000) normal annual precipitation at the site was 303 mm, with 240 mm, or 79%, during the growing season (1 Apr. to 30 Sep.). The 30-yr (1971–2000) normal mean annual air temperature was 5.7 °C and growing season air temperature was 13.8 °C.

In 1999, barley was grown to maturity on the entire plot area and the wheat rotations were established in the spring of 2000 (Table 1). Soft white spring wheat was grown continuously (1-CONT) or under conventional (CONV) or conservation (CONS) management. There were two 3-yr rotations (Table 1) that had similar crop sequences (wheat–potato–dry bean) but different management (3-CONV and 3-CONS); two 4-yr rotations also with similar crop sequences (wheat–sugar beet–dry bean–potato) and different management (4-CONV and 4-CONS), and one 5-yr rotation under CONS management (5-CONS) that had two phases of wheat along with

Table 1. Outline of rotation treatments over 12 yr (2000–2011) in Vauxhall, AB.

Rotation[a]	Crop sequence	Crop phases	Rotation cycles[b]
1-CONT	Wheat	1	12
3-CONV	Wheat–potato–dry bean	3	4
3-CONS	Wheat[c]–potato[d]–dry bean[d]	3	4
4-CONV	Wheat–sugar beet–dry bean–potato	4	3
4-CONS	Wheat–sugar beet–dry bean[c]–potato[d]	4	3
5-CONS	Wheat–sugar beet[c]–wheat–dry bean[c]–potato[d]	5	2.4

[a]Integer refers to length of rotation; CONT, continuous; CONV, conventional management; CONS, conservation management.
[b]Rotation cycles = 12 (yr)/crop phases.
[c]Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-CONS; 5-CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-CONS; 5-CONS after dry bean) applied after harvest, except in 2003 (postponed to spring 2004 due to wet soil conditions).
[d]Fall-seeded cover crop entry point: fall rye [except oat, 2000–2002, on 3-CONS (between dry bean and wheat), 4-, and 5-CONS].

the three row crops (wheat–sugar beet–wheat–dry bean–potato). Henceforth, the two 5-CONS wheat phases will be differentiated by their preceding crop: wheat following sugar beet (5-CONS$_{SB}$) and wheat following potato (5-CONS$_{P}$). This resulted in a total of seven wheat rotation phases: 1-CONT, 3-CONV, 3-CONS, 4-CONV, 4-CONS, 5-CONS$_{SB}$, and 5-CONS$_{P}$. In addition, there was a 6-yr rotation [oat (*Avena sativa* L.)–timothy (*Phleum pratense* L.)–timothy–sugar beet–dry bean–potato] under CONS management, which will not be discussed in this paper as it did not contain SWS wheat.

All phases of each rotation appeared in each year, for a total of 20 phases (Table 1), in a randomized complete block design with four replicates (80 plots). Individual plots were 10.1 m × 18.3 m (185 m^2), with a 2.1-m-wide inter-plot spacing. The number of rotation cycles at the end of the 2011 growing season (12 yr) ranged from 12 (1-CONT) to 2.4 (5-CONS) (Table 1).

Conservation management treatments

Four cultural practices were applied as a "bundle" to the CONS rotations: (*i*) direct seeding or reduced tillage where possible in the rotation; (*ii*) composted cattle manure as a substitute for inorganic fertilizer; (*iii*) fall-seeded cover crops after at least one phase; and (*iv*) solid-seeded narrow-row dry bean. Conventional management used none of those practices, and hence, the CONV rotations had more intensive fall tillage, no organic amendments, no cover crops, and dry bean in traditional wide rows.

Reduced tillage options for wheat in the CONS rotations were limited, as the preceding crops (dry bean on 3-CONV and 3-CONS; potato on 4-CONV, 4-CONS, 5-CONS; and sugar beet on 5-CONS) produced little residue (Larney et al. 2017*b*), which allowed minimum tillage for wheat. In contrast to wheat, reduced tillage options were available on CONS rotations preceding dry bean [direct drilling vs. disking/spring-tine cultivation (Larney et al. 2015)] and potato [chisel plowing and a Dammer Diker® (AG Engineering & Development Co. Inc., Kennewick, WA) vs. moldboard plowing (Larney et al. 2016*b*)]. Fall tillage before wheat was comprised of one pass of a disk harrow on all rotation phases except in 2006, when 4-CONV received two passes. Even 1-CONT (continuous wheat), which had more residue cover than the other rotations (Larney et al. 2017*b*), required only disk harrowing. Spring tillage included one pass of a disk harrow + oscillating harrow (2000, 2009); one (2001–2004, 2011) or two (2005, 2010) passes of a Triple K spring-tine harrow (Kongskilde Industries Inc., Hudson, IL), one pass of a heavy duty cultivator + dead rod (2006–2007), or one pass of a disk harrow followed by one pass of a heavy duty cultivator + dead rod (2008) when surface soil conditions were hard and dry. Details of tillage practices for the other crops grown on the CONV and CONS rotations have been provided, such as dry bean (Larney et al. 2015), potato (Larney et al. 2016*b*), and sugar beet (Larney et al. 2016*a*).

Beef feedlot manure compost was fall-applied (except in 2003, when wet conditions postponed application until spring) at four entry points (three preceding potato, one preceding wheat) on the CONS rotations (Table 1). On the shorter 3-CONS rotation, compost was applied at 28 Mg ha^{-1} (fresh wt.) between wheat and potato. In the longer 4- and 5-CONS rotations, a higher rate (42 Mg ha^{-1} fresh wt.) was used between dry bean and potato. The lower rate (28 Mg ha^{-1}) was also applied at a second entry point (between sugar beet and wheat) in 5-CONS. Compost was sourced from the same feedlot each year and had mean concentrations (dry wt., $n = 11$, fall 2000–2010) of 182 g kg^{-1} total C, 15.4 g kg^{-1} total N, and 5.4 g kg^{-1} total P.

Fall-seeded cover crops were used at four entry points on CONS rotations (Table 1). Three entry points preceded wheat: 3-CONS (between dry bean and wheat); and 4- and 5-CONS (both between potato and wheat). The fourth entry point was on 3-CONS (between potato and dry bean). Oat was used at the three entry points preceding wheat in the initial 3 yr (fall 2000–2002), while fall rye (*Secale cereale* L.) was used on 3-CONS (between potato and dry bean) from the outset of the study. However, oat establishment was poor, providing little or no cover. It was therefore dropped from the study and fall rye used exclusively from the fall of 2003 and onward. Unlike oat, fall rye did not winterkill and regrew in the spring, providing protection from wind erosion (Moyer and Blackshaw 2009). Fall rye was chemically desiccated in spring and soil-incorporated by tillage (3-, 4- and 5-CONS, between dry bean or potato and wheat) or left on the soil surface (3-CONS, between potato and dry bean).

The fourth CONS practice pertained to dry bean only. This involved direct-drilling dry bean in narrow rows (19–23 cm) and direct-cutting at harvest on CONS rotations (Larney et al. 2015). In contrast, dry bean on CONV rotations was planted with conventional tillage in wide rows (60 cm) with soil disturbance by inter-row cultivation in June and undercutting prior to harvest.

Wheat management

Soft white spring wheat was seeded each year with a John Deere 9350 hoe drill at a seeding rate of 134 kg ha^{-1} and a row spacing of 18 cm. The seeding date ranged from 16 Apr. (2004) to 21 May (2010), with a mean of 2 May ($n = 12$). The cultivar 'AC Reed' (Sadasivaiah et al. 1993), which occupied the majority of the SWS acreage at the outset of the study, was grown for the first 6 yr (2000–2005), when it was considered the industry check cultivar for quality. By 2005, 'AC Andrew' (Sadasivaiah et al. 2004) had largely displaced 'AC Reed', accounting for 69% of the seeded SWS wheat area (Pratt 2006). Therefore, following commercial grower practices, 'AC Andrew' was grown for the second 6 yr (2006–2011).

Nitrogen fertilizer (as ammonium nitrate, 34.5–0–0) was broadcast prior to wheat seeding and incorporated by spring tillage. In 2000, wheat phases in each rotation received a rate of 112 kg N ha^{-1}. This rate continued in 2001 and 2002, except for 5-CONS$_{SB}$, which received a lower rate (62 kg ha^{-1}) to account for N in the compost applied in the previous fall after sugar beet. From 2003 to 2011, all wheat received 90 kg N ha^{-1}. As the compost N credit was considered relatively minor, an adjustment was not made for the 5-CONS$_{SB}$ treatment after 2002. Wheat did not receive any fertilizer P, as soil test P levels were considered adequate.

Herbicide inputs (at recommended rates) for in-crop grassy and broadleaf weed control included Achieve Extra Gold (tralkoxydim + bromoxynil + MCPA) from 2000 to 2003. Due to excessive rainfall in 2002 (207 mm in June), barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv.], which favours wet soil conditions, became a problem, which carried over to 2003, especially on the continuous wheat (1-CONT) treatment. To control barnyard grass in 2004, as well as to change herbicides to curtail weed resistance, a tank mix of Horizon (clodinafop) and Target (MCPA + mecoprop + dicamba) was used followed by Puma (fenoxaprop) 8 d later. This herbicide regimen (minus Puma) continued until 2009, changing to Velocity m3 (thiencarbazone + pyrasulfotole + bromoxynil) for the final 2 yr (2010–2011). Reglone (diquat) was used as a preharvest desiccant, except in 2004 and 2007–2008 when crops matured evenly.

All plots were individually irrigated (to maintain soil water at ≥50% field capacity) using four quarter-circle sprinklers on a wheel-move system. Growing season precipitation and air temperature were monitored at an automated weather station located ~300 m from the plots. Wheat harvest took place between 21 Aug. (2000) and 1 Oct. (2010), with a mean harvest date of 8 Sept. ($n = 12$).

Wheat measurements

In all years, plant density was estimated prior to tillering (late May to late June) and based on plant counts from two 1 m row lengths on the four quadrants of each plot (8 m total row length plot^{-1}). Plant height was measured from mid-July to mid-August on four quadrants of each plot at the late milk stage (growth stage 77, Zadoks et al. 1974). Days to maturity (DTM, the number of days from seeding to physiological ripeness) was estimated from visual assessments taken from mid-August to late September.

Wheat was harvested with a plot combine (2 m × 1.25 m wide cuts plot^{-1}). Grain samples were air-dried in cloth bags for ~3 wk before weighing for yield estimation. Grain was cleaned prior to weighing in 2002–2003 to remove barnyard grass seed. Grain protein concentration (13.5% grain moisture basis) was measured on whole-grain subsamples by near-infrared reflectance spectroscopy (NIRS) on a feed and forage analyzer (Model 6500, Foss North America, Eden Prairie, MN). Grain test weight was determined (Canadian Grain Commission 2016) using a 1 L Cox funnel. Kernel hardness [expressed as particle size index, PSI (%)] was estimated by NIRS (all years), as were grain Ca, P, K, and S concentrations (2007–2011 only).

In late July to mid-August, take-all severity was rated on 50 randomly selected plants plot^{-1} using a 1–5 scale (Conner and Kuzyk 1990), based on percent black discolouration of roots and crowns (where 1 = no infection, 2 = <25% infected, 3 = 25%–50% infected, 4 = 51%–75% infected, and 5 = 76%–100% infected). A weighted average was estimated for each plot.

Wheat stem sawfly (WSS) damage was assessed in the last 5 yr (2007–2011) of the study only. After harvest (mid-September to early October), wheat stubble and crowns were removed (~0–7.5 cm soil depth) from four 1 m long row lengths (1 row quadrant^{-1}). The number of severed wheat stems, indicative of WSS cutting, was expressed as a percent of total stems.

Statistical analyses

All data were tested for outliers (PROC UNIVARIATE) prior to analysis by year (PROC MIXED) with rotation as a variable (SAS Institute, Inc. 2010). Orthogonal contrasts compared management effects: CONV (mean of 3-CONV, 4-CONV) vs. CONS (mean of 3-CONS, 4-CONS, 5-$CONS_{SB}$, 5-$CONS_P$), and preceding crop effects: dry bean (mean of 3-CONV, 3-CONV) vs. potato (mean of 4-CONV, 4-CONS, 5-$CONS_P$) on 12-yr averages of wheat parameters. For all comparisons, means were considered significantly different at $P \leq 0.05$.

Results and Discussion

Weather conditions

Growing season (1 Apr. to 30 Sep.) precipitation ranged from 118 mm or 49% of the 30-yr normal (240 mm, 1971–2000) in 2001, to 507 mm (211% of normal) in 2005, with a 12-yr (2000–2011) mean of 290 mm [121% of the 30-yr normal]. The second wettest growing season was 2002 (466 mm, 194% of normal), followed by 2010 (377 mm, 157% of normal). The mean (2000–2011) growing season air temperature (13.8 °C) was equivalent to the 30-yr normal (1971–2000). The warmest growing season was 2006 (15.2 °C), while 2002 was the coolest (12.6 °C). Annual irrigation amounts for wheat depended on prevailing precipitation and ranged from 140 mm (2002) to 724 mm (2007), with a mean of 325 mm ($n = 12$). A large input was required in 2007 due to an extreme mid-season dry spell (21 mm of precipitation between 25 June and 19 Aug.) accompanied by high air temperatures [e.g., a mean July air temperature 3.8 °C warmer than the 30-yr normal (22.2 °C vs. 18.4 °C)]. In comparison, the second highest irrigation water input was 406 mm in 2006.

Plant density, height, and maturity

Across rotations, annual mean plant density ranged from 71 plants m^{-2} in 2005 to 242 plants m^{-2} in 2011 with a study mean of 147 plants m^{-2} (Table 2). The low density in 2005 was due to cool air temperatures following seeding on 25 Apr., culminating in a −8 °C frost on 10 May. Only 4 out of 12 yr showed a significant rotation effect on plant density (Table 2). In 2008, the 1-CONT treatment (139 plants m^{-2}) was significantly lower than all other rotations (180–197 m^{-2}). The remaining 3 yr with significant effects showed inconsistent trends. For example, in 2002, the 5-$CONS_P$ rotation had the highest plant density, significantly so (166 plants m^{-2}) compared with all other rotations (134–149 m^{-2}) except 4-CONS, while 5-$CONS_{SB}$ was the lowest (112 m^{-2}). In 2004, however, the opposite was true, with the highest density (141 plants m^{-2}) on 5-$CONS_{SB}$ and lowest (106 m^{-2}) on 5-$CONS_P$. Moreover, in 2006, both 5-CONS rotations showed significantly lower densities (177–179 plants m^{-2}) than 3-CONS, 4-CONV, and 4-CONS (201–209 m^{-2}). For the 12-yr average plant density, there was a trend ($P = 0.08$) toward higher plant density in the 3-CONV (151 plants m^{-2}) compared with the 5-$CONS_{SB}$ (143 m^{-2}) and 1-CONT (141 m^{-2}) rotations (Table 2). Management (CONV vs. CONS) and preceding crop (dry bean vs. potato) contrasts were both non-significant for 12-yr average plant density (Fig. 3*a*). Yield benefits from higher plant densities (seeding rates) were obtained for irrigated SWS wheat in southern Alberta (McKenzie et al. 2008) and CWRS wheat in the eastern prairies (Lafond and Gan 1999).

Annual mean plant height across rotations ranged from 67 cm in 2005 to 92 cm in 2011, with a study mean of 83 cm (Table 2). The shortest plants occurred in 2005 due to an extremely wet June (284 mm of rainfall, ~5 times the normal of 59 mm), which caused waterlogging and stunted growth. Seven out of 12 yr showed significant rotation effects on plant height (Table 2). Four years showed that monoculture wheat (1-CONT) was significantly shorter than all other rotations, by 6–10 cm in 2001, 8–12 cm in 2008, 5–11 cm in 2009, and 10–15 cm in 2011 (Table 2). The 1-CONT treatment was also significantly shorter than two other rotations in 2003, three others in 2004, and four others in 2010 (Table 2). Plants on 3-CONV were significantly taller (by an average of 9 cm) than five other rotations in 2009, four others in 2003 and 2004, and three others in 2010 (Table 2). In 2008, plants on 4-CONV were significantly taller than 3-CONS and 5-$CONS_{SB}$ (93 vs. 88 cm). Also, three specific pairs of rotations were compared each year: 3-CONV vs. 3-CONS and 4-CONV vs. 4-CONS (different management practices for the same crop sequences), and 5-$CONS_P$ vs. 5-$CONS_{SB}$ (different preceding crops, potato vs. sugar beet). The 3-CONV rotation had significantly taller plants than 3-CONS in 2004 (92 vs. 86 cm) and 2009 (94 vs. 89 cm), while 4-CONV was taller than 4-CONS in 2009 (94 vs. 87 cm). The preceding crop comparison (5-$CONS_P$ vs. 5-$CONS_{SB}$) on plant height was non-significant in all years.

Plant height averaged over 12 yr showed that 1-CONT was significantly shorter (78 cm) than all other rotations (82–86 cm) and 3-CONV was significantly taller than 4-CONS, 5-$CONS_P$, and 5-$CONS_{SB}$ (86 vs. 82–83 cm). Both management (CONV vs. CONS) and preceding crop (dry bean vs. potato) contrasts were significant for 12-yr average plant height (Fig. 3*b*). Wheat on CONV rotations was 2 cm taller (85 vs. 83 cm) than CONS rotations, while wheat grown after dry bean was 3 cm taller than after potato (85 vs. 82 cm), likely due to increased N supply following a legume vs. non-legume crop (O'Donovan et al. 2014).

Across rotations, annual mean DTM ranged from 103 d in 2007 to 130 d in 2005, with a study mean of 115 d (Table 2). The 2007 growing season had the warmest July (22.2 °C vs. 17.9–20.9 °C) of the 12 yr, leading to the shortest DTM. As mentioned previously, 2005 was the wettest growing season (211% of normal), which led to the longest DTM. The 2010 growing season was also wetter-than-normal (157%), leading to the second longest DTM of the study (mean, 127 d).

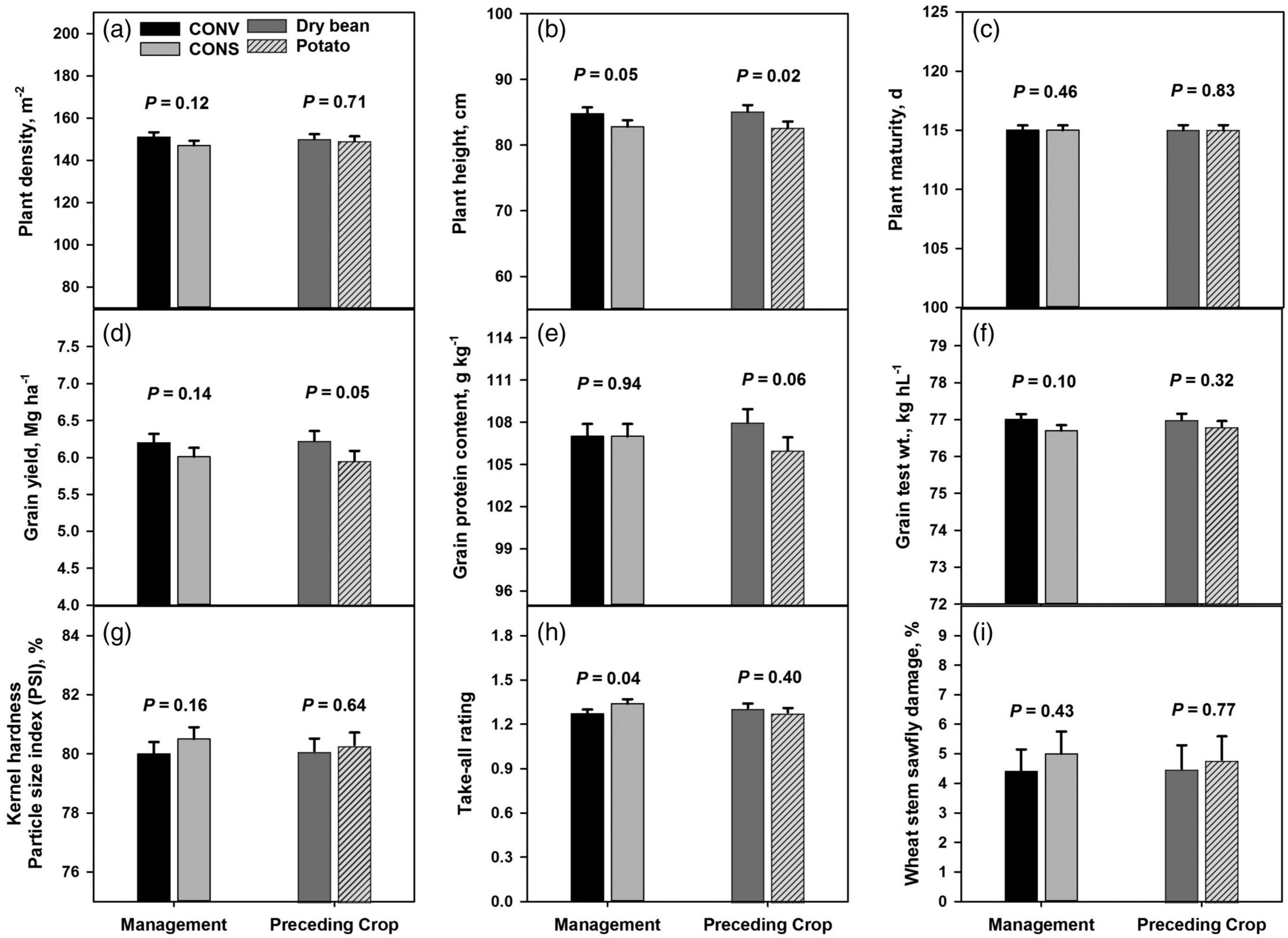
Table 2. Effect of rotation on wheat plant density, height, and maturity from 2000–2011, and 12-yr means.

Rotation	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	12-yr mean
Density (plants m^{-2})													
1-CONT	186	135	149bc	75	136ab	68	192abc	136	139b	119	116	232	141
3-CONV	188	155	140bcd	86	138ab	75	188bc	155	197a	126	119	243	151
3-CONS	187	155	138cd	89	134ab	72	201ab	156	180a	109	99	252	149
4-CONV	204	153	134d	107	120bc	69	206ab	154	192a	126	112	231	150
4-CONS	193	152	154ab	89	124abc	76	209a	158	194a	112	81	237	148
5-CONS$_{\text{P}}$	198	162	166a	92	106c	71	177c	159	191a	108	103	238	149
5-CONS$_{\text{SB}}$	171	157	112e	67	141a	70	179c	156	189a	113	97	263	143
P value	NS	NS	***	NS	*	NS	*	NS	**	NS	NS	NS	NS
Annual mean	189	153	142	86	128	71	193	153	183	116	104	242	147[a]
Height (cm)													
1-CONT	79	78b	71	70d	82c	63	81	84	79c	82d	78c	81b	78c
3-CONV	84	88a	70	81a	92a	74	87	90	91ab	94a	91a	91a	86a
3-CONS	78	88a	70	79ab	86bc	77	86	90	88b	89bc	87ab	94a	84ab
4-CONV	83	85a	71	76abc	85bc	65	84	88	93a	94ab	82bc	95a	84ab
4-CONS	81	85a	71	75bcd	88ab	57	85	89	90ab	87c	76c	94a	82b
5-CONS$_{\text{P}}$	85	85a	68	73cd	87ab	69	85	84	91ab	88c	85ab	91a	83b
5-CONS$_{\text{SB}}$	83	84a	70	74bcd	83bc	65	84	88	88b	88c	90a	97a	83b
P value	NS	*	NS	*	*	NS	NS	NS	***	**	**	**	**
Annual mean	82	85	70	76	86	67	84	88	89	89	84	92	83[a]
Days to maturity (d)													
1-CONT	106	115	113	114	123	130	105	102	114c	113	123	104c	113c
3-CONV	107	116	114	120	129	131	107	104	118a	116	127	108ab	116a
3-CONS	105	116	112	117	126	128	107	105	117ab	115	128	107bc	115ab
4-CONV	107	115	112	118	126	129	105	101	116abc	116	127	108abc	115ab
4-CONS	105	115	112	115	126	131	109	103	116bc	115	129	112a	116ab
5-CONS$_{\text{P}}$	106	116	112	115	125	130	109	104	116abc	116	129	109ab	115ab
5-CONS$_{\text{SB}}$	106	115	113	119	122	132	106	103	119a	114	126	106bc	114bc
P value	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	*	*
Annual mean	106	115	112	117	125	130	107	103	117	115	127	108	115[a]

Note: NS, non-significant; *, significant at $P = 0.01–0.05$; **, significant at $P = 0.001–0.01$; ***, significant at $P < 0.001$. Within columns, means with different lowercase letters are significantly different from each other (least significant difference, $P < 0.05$).

[a]Study mean (all years, all rotations).

Fig. 3. Management (mean of 3- and 4-CONV vs. mean of 3-, 4-, and 5-CONS rotations) and preceding crop [dry bean vs. potato (mean of 3- and 4-CONV vs. mean of 4-CONV, 4-CONS and 5-CONS$_P$)] contrasts, with associated *P* values and standard error bars, for 12 yr (2000–2011) average (*a*) plant density; (*b*) plant height; (*c*) days to maturity; (*d*) grain yield; (*e*) grain protein concentration; (*f*) grain test weight; (*g*) grain kernel hardness; (*h*) take-all rating; and (*i*) 5-yr (2007–2011) average wheat stem sawfly damage.



Only two (2008, 2011) out of 12 yr showed significant rotation effects on DTM (Table 2). In both years, 1-CONT had significantly earlier DTM (by 3–8 d) compared with 3-CONV, 3-CONS, and 5-CONS$_{SB}$ in 2008 (114 vs. 117–119 d) and 3-CONV, 4-CONS, and 5-CONS$_P$ in 2011 (104 vs. 108–112 d). Omitting monoculture wheat (1-CONT), DTM on 4-CONS was significantly shorter (by 2–3 d) than 3-CONV and 5-CONS$_{SB}$ (116 vs. 118–119 d) in 2008, but significantly longer (by 5–6 d) than 5-CONS$_P$ and 3-CONS (112 vs. 106–107d) in 2011. Averaged over 12 yr, DTM on 3-CONV was significantly longer (2–3 d) than 1-CONT and 5-CONS$_{SB}$ (116 vs. 113–114 d), while 1-CONT was significantly shorter (by 2–3 d) than all other rotations except 5-CONS$_{SB}$. O'Donovan et al. (2008) found that increasing seeding rate reduced DTM for barley but did not affect yield. However, in this study, the 3-CONV rotation trended ($P = 0.08$) toward higher plant density (Table 2), yet showed significantly longer DTM than 1-CONT and 5-CONS$_{SB}$. Management (CONV vs. CONS) and preceding crop (dry bean vs. potato) contrasts were both non-significant for 12-yr average DTM (Fig. 3*c*).

Grain yield

Annual mean grain yield across rotations ranged from 3.48 Mg ha^{-1} in 2002 (the second wettest growing season of the study, 466 mm) to 8.06 Mg ha^{-1} in 2001, with a study mean of 5.82 Mg ha^{-1} (Table 3). The wettest growing season (2005, 507 mm) had the second lowest average yield (3.75 Mg ha^{-1}). Those wet seasons led to waterlogging in low-lying areas of the site, which impacted yield. Even though 2001 was the driest growing season (118 mm, 49% of normal), this led to the highest yield, as the balance of water demand was met by timely irrigation.

Significant rotation effects on wheat yield occurred in 10 out of 12 yr (Table 3), the exceptions being the initial year (2000), which would be expected due to no previous rotation history, and 2007. Seven years (2001, 2004, 2006,

Table 3. Effect of rotation on wheat grain yield, protein concentration, and test weight from 2000–2011 and 12-yr means.

Rotation	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	12-yr mean
Grain yield (Mg ha^{-1})													
1-CONT	4.76	5.42b	2.51b	2.30c	5.25b	2.30d	5.03c	5.73	5.70b	4.92c	3.29c	4.28b	4.33c
3-CONV	5.14	8.50a	3.37ab	5.30ab	7.10a	4.53ab	6.54a	6.53	8.56a	7.09a	6.37a	6.73a	6.32a
3-CONS	4.35	8.77a	3.97a	5.51a	6.67a	4.03abc	6.05ab	7.14	8.01a	6.58ab	5.86ab	6.68a	6.15ab
4-CONV	4.78	8.34a	3.90a	4.95ab	6.87a	3.77bcd	6.44ab	6.68	8.09a	6.74ab	5.65b	6.71a	6.08ab
4-CONS	4.39	8.21a	3.91a	4.62ab	6.96a	2.64cd	6.39ab	6.79	8.14a	6.57ab	5.93ab	6.73a	5.93ab
5-CONS$_P$	4.66	8.28a	3.11ab	4.17ab	7.22a	3.38bcd	6.04ab	6.57	8.27a	6.39b	5.77ab	6.58a	5.88b
5-CONS$_{SB}$	5.33	8.92a	3.58a	3.79bc	6.37a	5.63a	5.77b	6.89	7.82a	6.49b	6.32ab	6.54a	6.08ab
P value	NS	***	*	*	**	**	**	NS	***	***	***	**	***
Annual mean	4.77	8.06	3.48	4.37	6.63	3.75	6.04	6.62	7.80	6.40	5.60	6.32	5.82[a]
Grain protein concentration (g kg^{-1})													
1-CONT	103	106	116b	121	103	99	93c	116ab	103cde	100c	96	98	105b
3-CONV	100	109	119b	119	109	110	104b	117a	106bc	105bc	98	93	108ab
3-CONS	100	107	117b	116	104	108	104b	119a	115a	106ab	98	100	108a
4-CONV	103	106	119b	119	108	104	102b	112b	98e	111a	99	100	107ab
4-CONS	95	102	120b	116	108	100	105ab	112b	99de	106abc	100	99	105b
5-CONS$_P$	97	105	125a	120	110	94	108ab	111b	105bcd	103bc	96	102	107ab
5-CONS$_{SB}$	95	111	119b	122	111	110	113a	116ab	111ab	106ab	97	98	109a
P value	NS	NS	*	NS	NS	NS	**	*	***	*	NS	NS	*
Annual mean	99	106	119	119	108	104	104	115	105	105	98	99	107[a]
Grain test weight (kg hL^{-1})													
1-CONT	79.3	78.8c	77.2c	65.8b	72.5	79.1c	76.2a	74.6	76.4b	76.0b	75.0	77.1	75.7c
3-CONV	79.4	79.6ab	79.3a	71.7a	74.7	80.1a	76.3a	76.0	77.5a	76.5ab	76.1	78.7	77.2a
3-CONS	78.7	79.3abc	79.1ab	71.6a	75.0	79.7abc	75.6ab	75.2	76.4b	76.5ab	75.6	78.0	76.7ab
4-CONV	79.7	79.5ab	78.9ab	71.8a	74.3	79.2c	76.4a	75.6	76.9ab	75.2c	76.4	79.3	76.9ab
4-CONS	78.4	79.0bc	78.5ab	70.2a	74.4	79.8abc	75.0b	76.2	76.9ab	76.5ab	76.3	78.4	76.6b
5-CONS$_P$	78.9	79.9a	77.9bc	70.6a	74.4	80.0ab	76.0a	76.4	77.4a	76.2ab	76.1	78.3	76.9ab
5-CONS$_{SB}$	79.0	79.3bc	78.4abc	70.1a	75.0	79.4bc	75.9a	75.3	77.0ab	76.8a	75.8	78.5	76.7ab
P value	NS	*	*	*	NS	*	*	NS	*	**	NS	NS	***
Annual mean	79.0	79.3	78.5	70.3	74.3	79.6	75.9	75.6	76.9	76.2	75.9	78.3	76.7[a]

Note: NS, non-significant; *, significant at $P = 0.01–0.05$; **, significant at $P = 0.001–0.01$; ***, significant at $P < 0.001$. Within columns, means with different lowercase letters are significantly different from each other (least significant difference, $P < 0.05$).

[a]Study mean (all years, all rotations).

and 2008–2011) showed that wheat grown in rotation was significantly higher-yielding, by an average of 23% (2006) to 82% (2010), than monoculture wheat (1-CONT). When monoculture wheat (1-CONT) is disregarded, the rotation effect was non-significant in 5 yr (2001, 2002, 2004, 2008, and 2011) and significant in 5 yr (2003, 2005, 2006, 2009, and 2010) for the remaining 3–5 yr rotations. However, the different management practices but same crop sequence comparisons (3-CONV vs. 3-CONS; 4-CONV vs. 4-CONS) were non-significant in all 5 yr with significant effects, while the preceding crop comparison (5-CONS$_P$ vs. 5-CONS$_{SB}$), was non-significant in 4 out of 5 yr, the exception being 2005, when 5-CONS$_{SB}$ (5.63 Mg ha^{-1}) was significantly higher-yielding than 5-CONS$_P$ (3.38 Mg ha^{-1}). This may have been due to the application of compost prior to 5-CONS$_{SB}$, or more severe waterlogging on 5-CONS$_P$ during the high-rainfall growing season.

Other significant effects revolved around better yield performances by 3-CONV or 3-CONS compared with the 5-CONS$_{SB}$ or 5-CONS$_P$ rotations. The 3-CONV rotation was significantly higher-yielding (by 13%) than 5-CONS$_{SB}$ (6.54 vs. 5.77 Mg ha^{-1}) in 2006 and both the 5-CONS$_{SB}$ and 5-CONS$_P$ rotations (by an average of 10%) in 2009 (7.09 vs. 6.39–6.49 Mg ha^{-1}). Also in 2003, the 3-CONS rotation was significantly higher-yielding (by 45%) than 5-CONS$_{SB}$ (5.51 vs. 3.79 Mg ha^{-1}).

Averaged over 12 yr (Table 3), the grain yield of 1-CONT was significantly lower (4.33 Mg ha^{-1}) than the 3–5-yr rotations (mean, 6.07 Mg ha^{-1}). In addition, the average grain yield was significantly higher (by 7%) on 3-CONV than 5-CONS$_P$ (6.32 vs. 5.88 Mg ha^{-1}). This followed the same trend for plant height, where 3-CONV averaged 3 cm taller than 5-CONS$_P$ (Table 2), which is in agreement with the well-documented positive correlation between plant height and grain yield (Law et al. 1978). The differences among paired comparisons: 3-CONV vs. 3-CONS, 4-CONV vs. 4-CONS (same crop sequence, different management), and 5-CONS$_P$ vs. 5-CONS$_{SB}$ (different preceding crop) were all non-significant for 12-yr average grain yield.

The management contrast (CONV vs. CONS) for the 12-yr average grain yield was non-significant (Fig. 3*d*). In keeping with the preceding crop contrast of taller plant height after dry bean vs. potato, as outlined earlier, wheat after dry bean (Fig. 3*d*) significantly out-yielded wheat after potato (by 5%, 6.23 vs. 5.96 Mg ha^{-1}). Even though most of the N fixed by legumes is removed in the high-protein grain at harvest, residual N from preceding legume crops contributes to subsequent cereal yield. Soon and Lupwayi (2008) reported that wheat following pea had higher grain yield than wheat following barley. Gan et al. (2003) noted that wheat grain yield increased by 7% when grown after pulses [chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), or dry pea] vs. wheat.

Grain quality

Unlike CWRS and CWAD wheats, where high GPC is the aim, low GPC is desirable for SWS wheat, ideally <105 g kg^{-1} for optimum baking quality for the Canadian domestic market (Bole and Dubetz 1986). For growers, the challenge is to apply sufficient N fertilizer and irrigation to achieve optimum yield while maintaining low GPC. Across rotations, annual mean GPC ranged from 98 g kg^{-1} in 2010 to 119 g kg^{-1} in both 2002 and 2003, with a study mean of 107 g kg^{-1} (Table 3). The high GPC in 2002 was associated with the lowest average grain yield of the study (3.48 Mg ha^{-1}), caused by excess moisture (466 mm of growing season precipitation). Five out of the 12 yr showed significant rotation effects on GPC (Table 3): 2002, and four consecutive years (2006–2009) in the second half of the study. The only year when GPC on 1-CONT was significantly lower than all other rotations was 2006 (93 vs. 102–113 g kg^{-1}).

Other significant rotation effects on GPC were somewhat inconsistent (Table 3). In 2002, 5-CONS$_P$ had a significantly higher GPC than all other rotations (125 vs. 116–120 g kg^{-1}), including 5-CONS$_{SB}$. In 2006, the GPC of 5-CONS$_{SB}$ was significantly higher than 3-CONV, 3-CONS, and 4-CONV (113 vs. 102–104 g kg^{-1}). In 2007, the GPC of wheat preceded by dry bean (3-CONV and 3-CONS) was significantly higher (117–119 g kg^{-1}) than wheat preceded by potato (4-CONV, 4-CONS, and 5-CONS$_P$, 111–112 g kg^{-1}), showing that preceding crop overruled the management effect (CONV, CONS) on GPC. In 2008, the GPC of 3-CONS was significantly higher than all other rotations (115 vs. 98–106 g kg^{-1}) except 5-CONS$_{SB}$ (111 g kg^{-1}), including the paired comparison with 3-CONV (106 g kg^{-1}). In 2009, the GPC of 4-CONV was significantly higher than 3-CONV, 5-CONS$_P$, and 1-CONT (111 vs. 100–105 g kg^{-1}).

The rotation effect on the 12-yr average GPC was significant (Table 3), with 3-CONS and 5-CONS$_{SB}$ having significantly higher values than 4-CONS and 1-CONT (108–109 vs. 105 g kg^{-1}). The 12-yr average management contrast (CONV vs. CONS) was non-significant for GPC (Fig. 3*e*); however, the preceding crop contrast trended toward significance ($P = 0.06$), with the GPC of wheat after dry bean higher than that after potato (108 vs. 106 g kg^{-1}). Gan et al. (2003) determined that wheat GPC increased by 11% when grown after pulses (chickpea, lentil, and dry pea) vs. wheat. This was due to the symbiotic N fixation by the pulse crops and its gradual release as mineralizable N, available for wheat uptake, as the residues decomposed during the following growing season.

A high test weight generally indicates sound grain with high flour yield and good milling and baking quality (Finney et al. 1987). Averaged across rotations, annual mean grain test weight ranged from 70.3 kg hL^{-1} in 2003 to 79.6 kg hL^{-1} in 2005, with a study mean ($n = 12$) of 76.7 kg hL^{-1} (Table 3). Seven out of the 12 yr showed significant rotation effects on test weight (Table 3). In 6 out of 7 yr (2006 excepted), 1-CONT had a significantly lower test weight than at least one or up to all six other rotation treatments. The largest difference occurred in 2003, when the test weight was 6 kg hL^{-1} lower on 1-CONT than 4-CONV (65.8 vs. 71.8 kg hL^{-1}). If 1-CONT is disregarded, there were 5 yr when 3-CONV had a significantly higher test weight (by an average of 1.2 kg hL^{-1}) than at least one other rotation: 2002, 2005, 2006, 2008, and 2009 (Table 3). This may have been related to higher plant densities on 3-CONV (Table 2). McKenzie et al. (2011) reported significantly greater test weights at the highest seeding rates for SWS wheat in southern Alberta.

For the paired comparisons of different management practices with the same crop sequences, 3-CONV had a significantly higher grain test weight than 3-CONS in 2008 (77.5 vs. 76.4 kg hL^{-1}), while 4-CONV was significantly higher than 4-CONS in 2006 (76.4 vs. 75.0 kg hL^{-1}) but significantly lower in 2009 (75.2 vs. 76.5 kg hL^{-1}). The preceding crop comparison on 5-CONS was significant in 2001 only, when 5-CONS$_P$ was significantly higher than 5-CONS$_{SB}$ (79.9 vs. 79.3 kg hL^{-1}). Averaged over 12 yr (Table 3), the test weight for 1-CONT was significantly lower than all other rotations by 0.9–1.5 kg hL^{-1}, in keeping with the significantly lower grain yields. Also, 3-CONV was significantly higher than 4-CONS (77.2 vs. 76.6 kg hL^{-1}). Management (CONV vs. CONS) and preceding crop (dry bean vs. potato) contrasts were both non-significant for 12-yr average test weight (Fig. 3*f*). Gan et al. (2003) also reported that preceding crop [chickpea, lentil, dry pea, mustard [*Brassica juncea* (L.) Czern.], canola (*B. napus* L.), or spring wheat] effects on subsequent wheat test weight were non-significant in a Saskatchewan study.

Kernel hardness (expressed as PSI) has important implications for the milling quality of wheat, ranging from 35% to 40% for CWAD, which is considered extra-hard, from 45% to 60% for CWRS, and from 70% to 75% for CWSWS wheat (Lukow 2006). Across rotations, annual mean PSI ranged from 76.5% in 2011 to 85.5% in 2003, with a study mean of 80.4% (data not shown). The rotation effect was non-significant for hardness in all individual years, as well as the 12-yr average (data not shown). In addition, management (CONV vs. CONS) and preceding crop (dry bean vs. potato) contrasts were both non-significant for 12-yr average kernel hardness (Fig. 3g). McKenzie et al. (2008) also reported little effect of management practices such as seeding date and rate on the hardness of SWS wheat. However, higher N rates increased hardness. Nelson et al. (2011*b*) reported that organic production increased hardness compared with conventional production.

Soil, climate, crop type and cultivar, management practices, and postharvest factors can all influence the nutritional quality of crops. Generally, a genetic trade-off exists between grain yield and mineral concentration

Table 4. Effect of rotation, management contrast, and preceding crop contrast on 5-yr mean (2007–2011) Ca, P, K, and S concentrations (μg g^{-1}) in wheat.

	Ca	P	K	S
Rotation				
1-CONT	611a	2739	3202	1105b
3-CONV	566b	2819	3154	1108b
3-CONS	593ab	2863	3146	1167a
4-CONV	586ab	2801	3232	1102b
4-CONS	618a	2856	3218	1124b
5-CONS$_P$	601a	2809	3230	1121b
5-CONS$_{SB}$	607a	2846	3198	1137ab
P value	*	NS	NS	*
Management				
CONV	576b	2810	3193	1105b
CONS	605a	2843	3198	1137a
P value	**	NS	NS	**
Preceding crop				
Dry bean	579b	2841	3150b	1138
Potato	602a	2822	3227a	1116
P value	*	NS	**	NS

Note: NS, non-significant; *, significant at $P = 0.01–0.05$; **, significant at $P = 0.001–0.01$. Within columns, means with different lowercase letters are significantly different from each other (least significant difference, $P < 0.05$).

due to the dilution effect (Fan et al. 2008; i.e., high yield leads to low mineral concentrations). A concerted effort is currently underway to develop cereal crop cultivars with enhanced nutritional value (Graham et al. 2001; Khoshgoftarmanesh et al. 2010). In the last 5 yr of the study (2007–2011), across rotations, average concentrations ranged from 518 (2010) to 671 μg g^{-1} (2011) for Ca, 2269 (2010) to 3276 μg g^{-1} (2011) for P, 2762 (2007) to 3665 μg g^{-1} (2011) for K, and 1031 (2010) to 1184 μg g^{-1} (2008) for S (data not shown). Therefore, three minerals (Ca, P, and S) had the lowest average concentrations in the lowest-yielding and wettest growing season (2010) out of the five measured, while three (Ca, P, and K) were highest in 2011.

The 5-yr average (2007–2011) grain Ca concentration (Table 4) for the 3-CONV rotation was significantly lower than 1-CONT, 4-CONS, 5-CONS$_P$, and 5-CONS$_{SB}$ (566 vs. 601–618 μg g^{-1}). This may have been due to a dilution effect, as 3-CONV achieved the numerically highest grain yield from 2008 to 2011 (Table 3). In addition, the management (CONS, 605 μg g^{-1} > CONV, 576 μg g^{-1}) and preceding crop [after potato, 602 μg g^{-1} > after dry bean, 579 μg g^{-1}) contrasts were both significant. Rotation, management, and preceding crop contrasts were all non-significant for 5-yr average grain P concentration. For grain K concentration, only the preceding crop contrast was significant: wheat after potato (3227 μg g^{-1}) > after dry bean, (3150 μg g^{-1}). For 5-yr average grain S concentration, 3-CONS (1167 μg g^{-1}) was significantly higher

Table 5. Effect of rotation on take-all severity for 2000–2011 and 12-yr means.

Rotation	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	12-yr mean
Take-all severity[a]													
1-CONT	2.1	2.6a	1.3	1.6a	1.3a	1.8a	1.7a	2.3a	1.4a	1.5a	1.7	1.7a	1.7a
3-CONV	2.2	1.5b	1.3	1.2b	1.0b	1.2c	1.4b	1.2b	1.1c	1.1b	1.2	1.2bc	1.3bc
3-CONS	2.3	1.4b	1.1	1.2b	1.0b	1.4bc	1.4b	1.5b	1.2bc	1.1b	1.1	1.2bc	1.3bc
4-CONV	1.9	1.3b	1.2	1.2b	1.0b	1.5b	1.3b	1.2b	1.1c	1.1b	1.2	1.1c	1.2c
4-CONS	2.1	1.5b	1.2	1.3b	1.0b	1.3bc	1.3b	1.2b	1.1bc	1.0b	1.3	1.1bc	1.3c
5-$CONS_P$	1.9	1.5b	1.1	1.4ab	1.0b	1.3bc	1.4b	1.4b	1.1c	1.1b	1.3	1.3b	1.3bc
5-$CONS_{SB}$	2.6	1.5b	1.2	1.3b	1.1b	1.5b	1.5b	1.3b	1.2b	1.3a	1.3	1.2bc	1.4b
P value	NS	***	NS	NS	***	***	**	***	***	**	NS	**	***
Annual mean	2.1	1.6	1.2	1.3	1.1	1.4	1.4	1.4	1.2	1.2	1.3	1.3	1.4[b]

Note: NS, non-significant; **, significant at $P = 0.001–0.01$; ***, significant at $P < 0.001$. Within columns, means with different lowercase letters are significantly different from each other (least significant difference, $P < 0.05$).
[a]Severity rated on a 1–5 scale (Conner and Kuzyk 1990), where 1 = no infection, 2 = <25% infected, 3 = 25%–50% infected, 4 = 51%–75% infected, and 5 = 76%–100% infected.
[b]Study mean (all years, all rotations).

(Table 4) than all other rotations (1102–1124 μg g^{-1}) except 5-$CONS_{SB}$ (1137 μg g^{-1}). Additionally, the management contrast was significant, with CONS (1137 μg g^{-1}) > CONV (1105 μg g^{-1}).

Reported effects of soil management on the mineral composition of wheat are inconsistent. Most involve a comparison of conventional vs. organic wheat production. While our CONS management is not organic, it includes the addition of compost and use of cover crops, common components of organic systems. Organically grown wheat had a significantly higher K concentration than conventionally grown wheat (3218 vs. 3009 μg g^{-1}) in an Alberta study (Nelson et al. (2011*a*). Similarly, significantly higher concentrations of Zn, Fe, and Mg were detected in the organic treatment. Park et al. (2015) noted that the grain P concentration of soft white winter wheat was higher under organic (3302 μg g^{-1}) vs. conventional (2461 μg g^{-1}) production. Reviews by Dangour et al. (2009) and Smith-Spangler et al. (2012) concluded that organically grown crops (not only cereals) had significantly higher P concentrations than conventionally grown crops, with inconsistent differences for Ca, K, Cu, Mg, and Zn concentrations.

Take-all

Take-all is a soil-borne fungal root disease of cereals causing blackening and decay of root tissues, the subcrown internode and crown, often leading to reduced water and nutrient uptake and plant death (Bailey and Irvine 2003). Typical field symptoms include patches of plants with bleached white heads containing few or no seed and brittle roots that are easily pulled from the soil. Take-all development is favoured by moist soil conditions (Paulitz 2006) and is typically found under irrigation in southern Alberta (Conner and Kuzyk 1990).

Across rotations, the annual mean take-all rating was highest (2.1) in the initial year (2000) and lowest (1.1) in 2004, with a study mean of 1.4 (Table 5). The site had been cropped to barley in 1999, and SWS and winter wheat prior to then, rendering initial inoculum levels high in 2000 when SWS wheat followed several years of cereals. However, once wheat was rotated with other crops (dry bean, potato, and sugar beet), the average take-all ratings declined for the remainder of the study. In the 1-CONT treatment, the take-all rating was highest in the initial 2 yr (2.1–2.6) and fluctuated below this level to finish at 1.7 in 2011. Schillinger et al. (2010) reported a take-all decline in continuous wheat in the last years of a 6-yr study due to natural microbial suppression by increased populations of antagonistic *Pseudomonas* spp. that produce antifungal compounds such as 2,4-diacetylphloroglucinol (2,4-DAPG) and phenazine (Weller et al. 2002; Kwak and Weller 2013).

Rotation had a significant effect on take-all rating in 9 out of 12 yr (Table 5), the exceptions being the initial year, 2000 (as expected, as rotations were not yet in place), and 2002 and 2010 (both wetter-than-normal years). In seven (2001, 2004–2008, and 2011) out of the nine significant years, the monoculture wheat (1-CONT) had a significantly higher rating than all the other rotations (Table 5). The largest difference occurred in the second year (2001), with a rating of 2.6 on 1-CONT (the highest in the entire study) compared with 1.3–1.5 for the 3–5 yr rotations. The second largest difference was in 2007, with ratings of 2.3 (1-CONT) vs. 1.2–1.5 (3–5-yr rotations). Continuous wheat leads to a buildup of take-all inoculum, which is reduced by breaks with non-susceptible crops such as dry bean, potato, or sugar beet. Schillinger et al. (2010) reported increased take-all severity in monocrop irrigated wheat, which contributed to lower yields, compared with a winter wheat–spring barley–winter canola rotation. In southern Alberta, Hao et al. (2001) reported a significant reduction in take-all severity (using the same rating scale of 1–5 as the current study) in 3 out of 4 yr when wheat followed sugar beet (1.4–1.6) instead of wheat (1.8–2.1).

In this study, the frequency of wheat in the rotation ranged from 40% (2 out of 5 yr, 5-CONS$_{SB}$ and 5-CONS$_{P}$) to 33% (1 out of 3 yr, 3-CONV and 3-CONS) to 25% (1 out of 4 yr, 4-CONV and 4-CONS). Wheat frequency appeared to play a role in take-all severity. For example, 40% wheat frequencies in 2003 (5-CONS$_{P}$) and 2009 (5-CONS$_{SB}$) were not significantly different than monoculture wheat (1-CONT). Also, 40% wheat frequency (5-CONS$_{SB}$) was significantly higher (1.5 vs. 1.2) than 33% frequency (3-CONV) in 2005. In 2008, 40% frequency (5-CONS$_{SB}$) was significantly higher (1.2 vs. 1.1) than 33% (3-CONV) and 25% (4-CONV) wheat frequencies. In 2009, 40% frequency (5-CONS$_{SB}$) was significantly higher (1.3 vs. 1.1) than 33% (3-CONV, 3-CONS) and 25% frequencies (4-CONV, 4-CONV), while in 2011, 40% frequency (5-CONS$_{P}$) was significantly higher (1.3 vs. 1.1) than 25% frequency (4-CONV).

The comparisons of different management practices with the same crop sequences (3-CONV vs. 3-CONS; 4-CONV vs. 4-CONS) were non-significant. However, for the preceding crop comparison on 5-CONS, 5-CONS$_{P}$ had a significantly lower ratings than 5-CONS$_{SB}$ in 2008 (1.1 vs. 1.2) and 2009 (1.1 vs. 1.3). Accumulation of the antifungal compound 2,4-DAPG produced by *Pseudomonas* spp. varied among plant hosts in a Dutch soil (Bergasma-Vlami et al. 2005), e.g., potato supported a higher threshold density (120 ng 2,4-DAPG g^{-1} of root) than sugar beet (50 ng g^{-1} of root). Even though overall take-all levels were low in our study, this may partly explain the greater take-all suppression when wheat followed potato vs. sugar beet.

Averaged over 12 yr (Table 5), the take-all rating on 1-CONT was significantly higher (1.7) than all other rotations (1.2–1.4). In addition, both 4-CONV and 4-CONS (1.2–1.3) were significantly lower than 5-CONS$_{SB}$ (1.4). The three paired comparisons (3-CONV vs. 3-CONS, 4-CONV vs. 4-CONS, 5-CONS$_{P}$ vs. 5-CONS$_{SB}$) were all non-significant for 12-yr average take-all ratings (Table 5). The management contrast (CONV vs. CONS) for the 12-yr average take-all rating was significant (Fig. 3*h*), with CONV (1.27) lower than CONS (1.34), while the preceding crop contrast was non-significant (Fig. 3*h*).

The higher level of take-all in CONS rotations was in agreement with Moore and Cook (1984), who reported higher disease incidence with no-till. However, other studies have reported lower take-all with reduced tillage intensity (Bailey et al. 1992, 2001; Pankhurst et al. 2002) or no difference (Hao et al. 2001). Clapperton et al. (2001) suggested that reduced tillage fostered greater earthworm [(*Aporrectodea trapezoides* (Duges), *A. tuberculata* (Eisen), and *A. rosea* (Savigny)] activity, which in turn promoted wheat growth and diminished take-all severity. In addition, the presence of fall rye cover crops on the CONS rotations may have increased take-all incidence. Even though fall rye is only mildly affected by take-all, it helps maintain the fungus at a level that can increase take-all damage when wheat is planted during the next season (Rothrock and Cunfer 1991). Cunfer et al. (2006) demonstrated that rye cover crops maintained take-all severity at the same level as continuous wheat. Although compost application has been shown to suppress take-all (Tilston et al. 2005), the opposite effect was evident in our study.

Wheat stem sawfly

Wheat stem sawfly has been a primary insect pest of spring wheat on the Canadian prairies since the crop was first introduced in the late 19th century (Beres et al. 2011*b*). Using a saw-like ovipositor, females lay eggs in the internodes of wheat stems and larvae then feed on internal vascular tissue, which leads to reduced photosynthetic activity and disrupted nutrient flow, resulting in shrivelled kernels. Stem-boring action also cuts stems, which topple or become easily lodged by wind, causing harvest losses.

In the last 5 yr of the study (2007–2011), across rotations, annual mean stem cutting damage by WSS ranged from 1.5% in 2011 to 10.4% in 2010 (a wetter-than normal year), with an overall mean of 5.4% (Table 6). Beres et al. (2007) reported yield losses of ~50–60 kg ha^{-1} at cutting levels of 10%–20% for CWRS cultivars. Rotation effects were significant in 2 out of 5 yr (Table 6). In 2008, 1-CONT had significantly higher damage (12.4%) than all other rotations (2.7%–5.2%) except 5-CONS$_{SB}$ (8.4%). This may be related to the emergence of more WSS adults and potential egg-laying females from previous-year host plants, usually wheat stubble (Beres et al. 2011*b*), under monoculture (1-CONT). In 2011, even though the overall level of WSS damage was low, the 5-CONS$_{SB}$ rotation was significantly higher (2.8%) than the 3-CONV, 4-CONV, 4-CONS, and 5-CONS$_{P}$ rotations (0.3%–1.4%). The 5-yr average for WSS damage was non-significant for rotation (Table 6), management (CONV vs. CONS), and preceding crop (dry bean vs. potato) contrasts (Fig. 3*i*). There was no clear pattern in rotation or management effects on WSS damage, likely because multiple interlinked factors dictate damage potential: tillage and residue management, seeding date, plant density, crop nutrient management (Beres et al. 2011*a*), as well as wild oat (*Avena fatua* L.) and parasitoid pressures (Weaver et al. 2004).

Summary and Conclusions

Not unexpectedly, continuous wheat (1-CONT) performed poorly with shorter plants, lower grain yield (averaging 71% of 3–5 yr rotations) and test weight, and greater take-all severity compared with wheat grown in rotation. Krupinsky et al. (2006) found that spring wheat crop sequence treatments, comprising mostly of non-cereals (legumes, oilseeds), yielded better than continuous wheat, demonstrating the positive impact of crop diversity on cereal crop production. Blackshaw et al. (2015) noted that

Table 6. Effect of rotation on wheat stem sawfly damage from 2007–2011 and 5-yr mean.

Rotation	2007	2008	2009	2010	2011	5-yr mean
Wheat stem sawfly damage (%)						
1-CONT	1.5	12.4a	7.5	12.8	1.6abc	6.8
3-CONV	1.6	3.7bc	—[a]	11.6	1.4bc	3.9
3-CONS	3.0	2.7c	8.9	10.9	2.1ab	5.1
4-CONV	3.5	5.2bc	2.9	11.0	0.3c	4.9
4-CONS	1.6	5.1bc	9.5	9.3	1.0bc	5.2
5-CONS_P	2.5	3.3bc	5.3	8.6	1.1bc	4.2
5-CONS_{SB}	2.9	8.4ab	6.5	8.2	2.8a	5.5
P value	NS	*	NS	NS	*	NS
Annual mean	2.4	5.8	6.8	10.4	1.5	5.4[b]

Note: NS, non-significant; *, significant at $P = 0.01–0.05$. Within columns, means with different lowercase letters are significantly different from each other (LSD, $P < 0.05$).

[a]—, not assessed as fall tillage performed before stubble sampling date.

[b]Overall mean (all years, all rotations).

the 1-CONT treatment had significantly higher weed seed density in the soil seedbank (570 seeds m^{-2}) than all other rotations (183–301 seeds m^{-2}) at the end of the study in 2011. This may have impacted wheat yield, although all rotations received the same herbicide inputs.

Once 1-CONT is disregarded, the effects of remaining rotations were generally inconsistent, except that 3-CONV often performed significantly better than other rotations in individual years or averaged over years. For example, on average, 3-CONV had taller plants, higher grain yield, and higher test weight than at least one other rotation. This is in stark contrast to potato production in the 3-CONV rotation, which Larney et al. (2016*b*) believed would represent a risk to growers in terms of lower yield (e.g., 18% lower marketable yield than 5-CONS, 12-yr average) and incidence of potato early dying.

Wheat was largely unresponsive to CONS management. Looking at the average responses of the 13 wheat parameters measured (12-yr averages for plant density, height, DTM, grain yield, GPC, test weight, kernel hardness, take-all, and 5-yr averages for WSS and grain Ca, P, K, and S concentrations), only two parameters showed significant positive effects from CONS management (i.e., grain Ca and S concentrations), which indicated that increased nutritional benefits could be derived from CONS management. Two showed significant negative effects of CONS management (plant height and take-all rating), while the remaining nine were unresponsive. While SWS wheat may have been largely indifferent to CONS management, the advantages of this system were reported for dry bean (Larney et al. 2015), potato (Larney et al. 2016*b*), and sugar beet (Larney et al. 2016*a*) performance, beneficial insects (Bourassa et al. 2008), bacterial endophytes (Pageni et al. 2013), soil quality (Li et al. 2015; Larney et al. 2017*a*), soil microbial communities (Lupwayi et al. 2017*a*, 2017*b*), and surface residue cover (Larney et al. 2017*b*). In addition, Blackshaw et al. (2015) concluded that implementing a suite of CONS practices posed little risk of increased weed populations in the long term.

Even though SWS wheat was largely unresponsive to 3–5 yr rotations with or without CONS management, the presence of wheat in irrigated rotations, irrespective of milling class, is important and should be maintained. The main reasons are related to wheat's role in returning C to the soil and providing surface residue for protection against wind erosion. Li et al. (2015) reported substantially higher mean (± standard deviation) annual crop C returns to the soil for wheat (4.6 ± 1.4 Mg ha^{-1}) compared with potato (2.3 ± 0.6 Mg ha^{-1}), sugar beet (1.7 ± 0.4 Mg ha^{-1}), or dry bean (1.1 ± 0.3 Mg ha^{-1}) during the 12-yr study. This wheat C is an important energy source for microbial activity, which sustains N and P cycling over the length of a rotation and compensates for crops that do not return as much C to the soil. Larney et al. (2017*b*) reported significantly higher surface residue cover with wheat as the preceding crop (33.7%) compared with narrow-row dry bean (9.7%), which was significantly higher than potato and sugar beet (6.5%–6.7%), which were in turn significantly higher than wide-row bean (3.6%).

Beres et al. (2013) pointed out that as the bioeconomy evolves, opportunities for dual grain markets have emerged, typified by SWS wheat. A SWS wheat grower can now choose to either sell their wheat into a milling market or contract it to an ethanol plant. Even though the area of SWS wheat grown under irrigation has reached historic lows, we believe our data is relevant for other wheat classes (e.g., CWRS, CWRW) grown under irrigation in southern Alberta and normally rotated with dry bean, potato, or sugar beet.

Acknowledgements

We thank J. Sukeroff, D. Reynolds, and staff and summer students at the AAFC Vauxhall substation for field assistance. G. Kereliuk performed wheat grain quality analyses. A. Kuzyk assisted with take-all disease ratings and C. Herle with wheat stem sawfly damage assessment. J. Nitschelm (2000–2006) and P. Regitnig (2007–2011), Rogers Sugar Ltd./Lantic Inc. (Taber, AB), managed sugar beet in the rotations. Funding contributions from the Alberta Agricultural Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster are gratefully acknowledged. R. Graf provided valuable comments on a draft of the manuscript.

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ARTICLE

Sugar beet response to rotation and conservation management in a 12-year irrigated study in southern Alberta

Francis J. Larney, Jennifer J. Nitschelm, Peter J. Regitnig, Drusilla C. Pearson, Robert E. Blackshaw, and Newton Z. Lupwayi

Abstract: Sugar beet (*Beta vulgaris* L.) has a long history as an option for irrigated crop rotations in southern Alberta. A 12-yr (2000–2011) study compared conservation (CONS) and conventional (CONV) management for sugar beet in 4- to 6-yr rotations which also included dry bean (*Phaseolus vulgaris* L.), potato (*Solanum tuberosum* L.), and soft white spring wheat (*Triticum aestivum* L.). Oat (*Avena sativa* L.) and timothy (*Phleum pratense* L.) were included in the longest 6-yr rotation. Conservation management incorporated reduced tillage, cover crops, feedlot manure compost addition, and solid-seeded dry bean. Compared with a 4-yr CONV rotation (52.2 Mg ha^{-1}), sugar beet root yield (averaged over the second 6 yr of the study, 2006–2011) was significantly higher, by 11%, on 4- and 5-yr CONS rotations (57.7–57.9 Mg ha^{-1}), and by 8% on a 6-yr CONS rotation (56.1 Mg ha^{-1}). Sugar beet impurity parameters were significantly affected by rotation in, at most, 3 of 12 yr. However, averaged over the final 6 yr of the study (2006–2011), a significantly higher *K* concentration (impurity) was found with CONS (2108 mg kg^{-1}) vs. CONV (1958 mg kg^{-1}) management. Integrating CONS management practices into sugar beet rotations led to significant yield benefits while effects on sugar beet quality were minimal.

Key words: Sugar beet, rotation, soil conservation, compost, cover crop, irrigation.

Résumé : On cultive depuis longtemps la betterave sucrière (*Beta vulgaris* L.) en assolement avec d'autres cultures irriguées, dans le sud de l'Alberta. Une étude de 12 ans (2000–2011) a permis de comparer les pratiques de conservation (CONS) aux pratiques classiques (CONV) pour la betterave sucrière cultivée en assolements de quatre à six ans avec le haricot (*Phaseolus vulgaris* L.), la pomme de terre (*Solanum tuberosum* L.) et le blé tendre blanc de printemps (*Triticum aestivum* L.), l'avoine (*Avena sativa* L.) et la phléole (*Phleum pratense* L.) s'ajoutant aux précédents dans l'assolement de six ans. Les pratiques de conservation incluaient un travail minimum du sol, l'usage de cultures-abris, l'ajout de fumier composté et la culture dense du haricot. Comparativement à l'assolement de quatre ans en mode CONV (52,2 Mg par hectare), le rendement de la betterave sucrière (moyenne calculée avec le deuxième volet de six ans de l'étude, 2006–2011) dépasse de 11 % le rendement des assolements de quatre et de cinq ans en mode CONS (57,7 à 57,9 Mg par hectare), et celui de l'assolement de six ans en mode CONS de 8 % (56,1 Mg par hectare). Les paramètres de la betterave sucrière liés aux impuretés sont significativement touchés par l'assolement, un maximum de trois années sur douze. Cependant, quand on calcule la moyenne au terme des six dernières années de l'étude (2006–2011), on note une concentration significativement plus élevée de K (impureté) avec le mode de gestion CONS (2 108 mg par kg) qu'avec le mode CONV (1 958 mg par kg). L'intégration des pratiques de conservation à l'assolement de betterave sucrière débouche sur une amélioration sensible du rendement, avec une perte minime au niveau de la qualité de la racine. [Traduit par la Rédaction]

Mots-clés : betterave sucrière, assolement, conservation du sol, compost, culture-abri, irrigation.

Received 5 January 2016. Accepted 29 April 2016.

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Abbreviations: CONS, conservation management; **CONV**, conventional management; **CT**, conservation tillage; **GSP**, growing season precipitation; **SLM**, sugar loss to molasses.

A correction was made to the e-First version of this paper on 5 October 2016 prior to the final issue publication. The current online and print versions are identical and both contain the correction.

Introduction

The history of sugar beet production in southern Alberta can be traced back to the beginning of irrigation farming in the region and the opening of the first sugar beet factory in 1903. There are currently about 200 sugar beet growers in southern Alberta producing the only domestic source of sugar in Canada (Alberta Sugar Beet Growers 2015). With few exceptions, the annual contracted area of sugar beet has remained relatively stable at 12 000–15 000 ha since the mid-1980s, representing an important niche in the local agricultural economy.

Irrigated rotation studies in southern Alberta have generally included sugar beet. The oldest and best-known is 'Irrigated Rotation U' at Agriculture and Agri-Food Canada's Lethbridge Research Centre, which dates to 1911, and is believed to be the oldest continuously irrigated crop rotation in North America (Dubetz 1983). It began as a 10-yr rotation which included 6 yr of alfalfa (*Medicago sativa* L.) followed by 1 yr each of potato, wheat, oat, and barley (*Hordeum vulgare* L.). In 1923 sugar beet replaced potato, and was present until 1986 when three new 5-yr rotations were implemented (Ellert 1995). Manure application has been a part of Irrigated Rotation U since its establishment.

In another rotation study, started at Lethbridge in 1947 (Dubetz and Hill 1964), sugar beet was grown in 1 yr of various 4-, 5-, or 7-yr rotations along with barley, potato, corn (*Zea mays* L.) or alfalfa. Manure was applied in single large doses at 25 Mg ha^{-1} on the 4-yr, 31 Mg ha^{-1} on the 5-yr, and 43 Mg ha^{-1} on the 7-yr rotations. Sugar beet yield was significantly lower on a 4-yr rotation which did not receive manure with no yield differences among other rotations. In comparison, barley and potato yields were not significantly affected by rotation. In a further rotation study initated in 1956, with 4-yr rotations (sweet corn–spring wheat–sugar beet–sugar beet), Dubetz et al. (1975) found positive responses to manure (27 Mg ha^{-1} applied in a single dose after wheat) in the 1st and 2nd yr sugar beet root yields.

While earlier studies focussed on sugar beet responses to rotations that included manure, changes in tillage management, most notably a reduction in tillage intensity, prompted a study (established at Lethbridge in 1994) comparing conventional and reduced tillage in 4-yr rotations (Hao et al. 2001). In 2 of 4 yr, sugar beet yield was significantly higher following dry bean or pea (*Pisum sativum* L) than spring wheat, while the tillage method (moldboard vs. chisel plowing) was nonsignificant for sugar beet yield, as well as sugar concentration, sugar loss to molasses (SLM) or impurities. Moyer et al. (2004) reduced tillage intensity even further, comparing conventional (moldboard plow, cultivator, harrow), minimum (double disc, harrow, glyphosate), and zero tillage (glyphosate) for sugar beet (1998–2000) at Burdett, AB. After dry bean, sugar beet root and extractable sugar yields were similar on all tillage systems. After wheat, sugar beet yields were similar with minimum and conventional tillage, but lower with zero tillage.

In a long-term study in Michigan (Christenson 1997), sugar beet yield in 5- to 6-yr rotations increased when green manures or forage legumes were included compared with a rotation based strictly on cash crops [barley–dry bean–wheat–corn–sugar beet]. Inclusion of sweet clover [*Melilotus officinalis* (L.) Lam.] inter-seeded with oat increased sugar beet yield by 22%, and inclusion of alfalfa increased yield by 16%. Alfalfa grown for 2 yr in a 5-yr rotation (barley–alfalfa–alfalfa–dry bean–sugar beet) increased sugar beet yield by 4% compared with alfalfa 1 yr in 5 (dry bean–wheat–alfalfa–corn–sugar beet). Hurisso et al. (2015) reported that extractable sugar yield was 28%–42% higher in a sugar beet–sugar beet–alfalfa–alfalfa rotation than in 2-yr sugar beet–barley, sugar beet–dry bean, or 3-yr sugar beet–barley–dry bean rotations in Wyoming.

Sugar beet management (e.g., manure addition, tillage or cover crops) aims for a combination of high root yield and high sugar concentration in order to maximize extractable sugar yield (Kenter and Hoffman 2006). However, extractable sugar yield is determined not only by root yield and sucrose concentration, but also by the concentrations of other constituents, so-called root impurities, that impair white sugar recovery. During factory processing, soluble substances such as amino acids, betaine, other nitrogenous compounds, K, and Na, which cannot be eliminated before the sugar is crystallized, increase SLM (Dutton and Huijbregts 2006).

With the arrival of large potato processing plants in southern Alberta in the late 1990s, the area of potato in Alberta doubled from 13 360 ha in 1998 to 26 720 ha in 2003 (Statistics Canada 2013). Dry bean acreage also expanded. Both potato and dry bean are normally rotated with sugar beet, and the expansion in specialty row crops on a limited irrigated land base, led to questions regarding maintenance of soil health as these crops produce limited amounts of crop residue for return to the soil, compared with cereals or forages. By the late 1990s, irrigation farmers were supportive of a new irrigated rotation study on soil conservation practices aimed at improving soil quality for the three most common row crops in the region at the time (sugar beet, potato, and dry bean). Therefore a rotation study was initiated in 2000 with a focus on conservation (CONS) management.

The study ran for 12 yr (2000–2011) with CONS rotations built around four specific management practices: (1) zero or reduced tillage where possible in the rotation; (2) composted cattle manure as a substitute for inorganic fertilizer; (3) fall-seeded cover crops; and (4) solid-seeded narrow-row dry bean. Sugar beet was not present in the 3-yr rotations as a mandatory ≥4-yr rotation is contracted in Alberta (Rogers Sugar Ltd. 2000) for sugar beet cyst nematode (*Heterodera schachtii* Schmidt) control.

Table 1. Outline of sugar beet rotation treatments over 12 yr (2000–11), Vauxhall, Alberta.

Rotation[a]	Crop sequence	Phases	Cycles[b]
4-CONV	Sugar beet–Dry bean–Potato–Wheat	4	3
4-CONS	Sugar beet–Dry bean[c]–Potato[d]–Wheat	4	3
5-CONS	Sugar beet[c]–Wheat–Dry bean[c]–Potato[d]–Wheat	5	2.4
6-CONS	Sugar beet–Dry bean[c]–Potato[d]–Oat/(Timothy)[e]–Timothy[f]–Timothy[g]	6	2

[a]Integer refers to rotation length (yr); CONV, conventional management; CONS, conservation management.
[b]No. of cycles = 12 (yr)/rotation length.
[c]Feedlot manure compost entry point (2000–2010): 28 Mg ha^{-1} fresh wt. (5-CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-CONS; 5-CONS after dry bean; 6-CONS) applied after harvest, except 2003 (postponed to spring 2004 by wet soil conditions).
[d]Fall-seeded cover crop entry point: oat (2000–2002); fall rye (2003–2010).
[e]Oat harvested as silage in July (2000–2011), timothy direct seeded in late August (2000–2010).
[f]First year timothy (2001–2011). Replaced by wheat in 2000 as timothy not planted in August 1999.
[g]Second year timothy (2002–2011). Replaced by wheat in 2000–2001 as timothy not planted in August 1998 or 1999.

Timothy and oat were included in the 6-yr rotation. The effects of rotation and soil management on dry bean (Larney et al. 2015) and potato (Larney et al. 2016) performance and surface soil quality (Li et al. 2015) have already been reported. The specific objectives of this paper are to assess sugar beet yield and quality over 12 yr under CONV and CONS soil management in rotations ranging from 4 to 6 yr in length.

Materials and Methods

Experimental design

The study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50°03′N, 112°09′W, elev. 781 m) on a Brown Chernozemic soil (Soil Classification Working Group 1998). At the 0–15 cm depth, soil texture was sandy loam, soil organic carbon was 12.9 g kg^{-1}, and pH was 6.9. The entire experimental area was planted to barley in 1999 and seven rotations established in spring 2000. Sugar beet was grown in four rotations: one under conventional (CONV) and three under conservation (CONS) management (Table 1). There were two 4-yr (4-CONV, 4-CONS) rotations with similar crop sequences (sugar beet–dry bean–potato–wheat), one 5-yr (5-CONS) rotation (sugar beet–wheat–dry bean–potato–wheat), and one 6-yr (6-CONS) rotation (sugar beet–dry bean–potato–oat–timothy–timothy). In addition, there were three rotations without sugar beet: two shorter 3-yr rotations (potato–dry bean–wheat), one under CONV and one under CONS management, and a continuous wheat treatment. These rotations will not be discussed in this paper.

Each phase of each sugar beet rotation appeared in each year, resulting in 19 phases (Table 1) in a randomized complete block design with four replicates, for a total of 76 plots. Individual plots were 10.1 × 18.3 m (185 m^2), with a 2.1 m inter-plot between plots. The number of rotation cycles after 12 yr (Table 1) ranged from 3 (4-yr rotations) to 2 (6-yr rotation).

Conservation management treatments

The CONS rotations differed from the CONV rotation by the implementation of CONS management practices (Table 1) described in detail by Li et al. (2015) and Larney et al. (2015, 2016). Briefly, four practices were applied as a 'package' to CONS rotations: (1) direct seeding or reduced tillage where possible in the rotation; (2) fall-seeded cover crops after at least one phase; (3) composted cattle manure inputs; and (4) solid seeded narrow-row dry bean.

By the time the experiment was being planned in the late 1990s, fall moldboard plowing was no longer considered the conventional tillage for sugar beet following other row crops (dry bean, potato, soft wheat) in the region, with reduced tillage (heavy-duty cultivator, disking) being widely used instead. Therefore, prior to sugar beet, there were few options for reducing tillage further on the CONS rotations. When following wheat (Table 1), there was no difference in fall tillage between 4-CONV, or 4- and 5-CONS rotations for sugar beet, with all plots receiving one or two passes of a disk harrow. Moreover, on the 6-CONS rotation where timothy preceded sugar beet, fall moldboard plowing (to 25 cm depth) followed by one pass of a disk harrow was the only practical tillage option, commencing in fall 2002 (Table 1), to prevent remnants of timothy sod from interfering with subsequent sugar beet planting in spring.

Spring tillage for all four sugar beet rotations consisted of one or two passes of a heavy-duty or spring-tine cultivator. Hence, this particular CONS management practice (reduced tillage) was not a feature of the CONS rotations for sugar beet. In contrast, reduced tillage options were available preceding dry bean and potato on the CONS rotations. For dry bean (Larney et al. 2015), the CONS rotations included direct drilling vs. disking/shallow spring-tine cultivation on CONV, while for potato (Larney et al. 2016), CONS rotations used chisel plowing and a Dammer Diker® (AG Engineering & Development Co. Inc., Kennewick, WA), a reservoir tillage implement, vs. moldboard plowing on CONV.

Straw-bedded beef feedlot manure compost produced by active aeration (Larney and Olson 2006) was fall-applied (except in 2003 when it was postponed by wet conditions until spring) at four entry points in the CONS rotations (Table 1). In the 4-, 5-, and 6-CONS rotations, a compost rate of 42 Mg ha^{-1} (fresh wt.) was applied between dry bean and potato. In addition, a lower rate (28 Mg ha^{-1} fresh wt.) was applied at a second entry point (between sugar beet and wheat) in 5-CONS. Compost was sourced from the same feedlot each year and had average concentrations (dry wt. ± SE, n = 11, 2000–2010) of 182 ± 14 g kg^{-1} total C, 15.4 ± 1.0 g kg^{-1} total N, and 5.4 ± 0.4 g kg^{-1} total P. Average dry matter content was 0.675 ± 0.024 kg kg^{-1}.

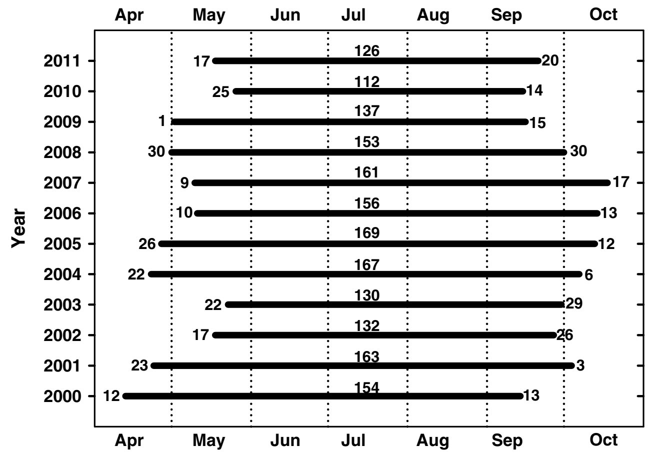
Cover crops were used at three entry points in the CONS rotations (Table 1): between potato and wheat in 4- and 5-CONS, and between potato and oat in 6-CONS. Initially (fall 2000–2002) oat was used as a cover crop (Table 1) to provide fall cover and then winterkill so as to minimize spring seeding problems. However, poor establishment and low to non-existent cover led to its replacement by fall rye (*Secale cereale* L.) from fall 2003 onward. Fall rye did not winterkill and re-grew in March–April, thereby providing protection from wind erosion. In spring, cover crops were either chemically desiccated or soil-incorporated.

The fourth conservation package pertained to dry bean only which was direct drilled in narrow rows (19–23 cm) and direct cut at harvest on CONS rotations (Larney et al. 2015). In contrast, dry bean on 4-CONV was planted with conventional tillage in wide rows (60 cm) with inter-row cultivation and undercutting (soil disturbance) at harvest.

Sugar beet management

Each year commercial sugar beet cultivars were seeded at 3.2 cm depth using the ‘plant-to-stand’ system (Yonts et al. 2001) at 15 cm plant spacing, 56 cm row spacing, and 18 rows plot^{-1}. This resulted in a seeding rate of ~1.8 kg ha^{-1}. Cultivars included HM Bergen (2000–2001), HH-811 (2002), and Beta 1385 (2003–2008). Glyphosate-tolerant (Roundup Ready®) sugar beet first became commercially available in the region in 2009, and in keeping with rapid grower adoption, was used in 2009 (cv. BTS 43RR90) and 2010–2011 (cv. BTS 47RR65). Planting date (Fig. 1) ranged from 12 Apr. (2000) to 25 May (2010) with a mean of 5 May (n = 12). Later planting dates were associated with weather delays, especially in 2003 (22 May) when 97 mm of precipitation occurred between 24 Apr. and 9 May, and 2010 (25 May) when 106 mm occurred between 13 Apr. and 24 May.

Fig. 1. Sugar beet planting dates (April–May), harvest dates (September–October), and length of growing season (d), 2000–2011.



Fertilizer N (as 34-0-0) was broadcast in spring 2000 and 2003–2011 or in fall 2000–2001 and soil-incorporated by spring or fall tillage. Sugar beet planting followed spring fertilizer applications by 2 to 27 d (average = 11 d, n = 10), and fall applications by 200–208 d (n = 2). The N application rate was 112 kg ha^{-1} in the initial year (2000) and when sugar beet followed wheat on 4-CONV, 4- and 5-CONS (2001–2005) and 6-CONS (2001–2002). This was increased to 134 kg ha^{-1} on 4-CONV, and 4- and 5-CONS for the second half of the study (2006–2011). On 6-CONS, sugar beet following timothy was first planted in 2003, and an N rate of 224 kg ha^{-1} was applied to counteract lower soil N levels following a deep-rooted forage. This rate was maintained in 2004, but lowered to 168 kg ha^{-1} N, which was considered adequate for the remainder of the study (2005–2011). The timing of P fertilizer application coincided with N, as above, except in 2000 and 2003 when P fertilizer was not applied. Application rates (as P_2O_5) were 67 kg ha^{-1} (2001–2002), 56 kg ha^{-1} (2004–2005) or 28 kg ha^{-1} (2006–2011).

Inter-row cultivation for weed control was carried out from 2000 to 2008, except in 2006 when weed pressures were low. The number of inter-row cultivations required depended on weed pressures: one (2001), two (2000, 2003–2005) or three (2002, 2007–2008). On average, the first cultivation occurred on 15 June (n = 8), the second on 29 June (n = 7), and the third on 14 July (n = 3). After the introduction of glyphosate-tolerant sugar beet in 2009, inter-row cultivation was no longer necessary. Herbicide inputs (at recommended rates) included fall-applied Roundup (glyphosate) ahead of sugar beet on 4-CONV, and 4- and 5-CONS (wheat stubble, 2000–2010) and 6-CONS (wheat stubble, 2000–2001; timothy sod, 2002–2010). Prior to the introduction of glyphosate-tolerant cultivars, in-crop (planting to mid-July) broadleaf weed control was provided each year (2000–2008) by Nortron® (ethofumesate), Betamix® (phenmedipham/desmedipham), and UpBeet® (trisulfuron methyl) [except 2001]. In addition, Lontrel® (clopyralid) was used in 2001, 2004, and 2006. Poast Ultra® (sethoxydim) was used for in-crop grass weeds from 2000 to 2008, except 2007, when pressure was low. In any given year, the choice, rate, and number of applications of herbicide depended on prevailing weed pressures and weather conditions. From 2009 to 2011, glyphosate was used for all in-crop weed control.

Insecticides used (at recommended rates) included Counter® (terbufos) applied as a band at planting (2001–2005), or Cruiser® (thiamethoxam) applied as a seed treatment (2006–2011), for wireworm (*Limonius* spp.) and sugar beet root maggot (*Tetanops myopaeformis* von Röder) control. One or two applications of Decis® (deltamethrin) were applied in late May–early June in 2000–2001, 2003–2005, and 2007–2009 for cutworm (*Euxoa* spp.) and sugar beet webworm (*Loxostege sticticalis* L.) control.

All crops were irrigated using a wheel-move system. Scheduling was at the discretion of the farm manager in order to maintain soil water (to 100 cm depth) at ≥50% field capacity. Plots could be individually irrigated using four quarter-circle sprinklers. Annual irrigation amounts (Table 2) and timings for sugar beet depended on prevailing precipitation and ranged from 146 mm (2002) to 927 mm (2007), with a mean of 442 mm (n = 12). The reason for high irrigation water inputs in 2007 was due to an extreme mid-season dry spell when only 21 mm of rainfall occurred between 25 June and 19 August. In comparison, the second highest irrigation water input was 660 mm in 2006 (Table 2).

The mean date of the initial irrigation was 11 June (n = 12), occurring as early as 4 May (2001) or as late as 20 July (2010). The final irrigation occurred on a mean date of 5 Sep., falling as early as 21 Aug. (2008) or as late as 28 Sep. (2007). On average, sugar beet plots were irrigated 8 times each growing season, applying 56 mm of water each time. While withholding irrigation 2–3 wk before harvest decreases root moisture content and increases sugar concentration (Rogers Sugar Ltd. 2000), a late irrigation is often applied to facilitate the harvest operation if fall soil conditions are dry. Using a historical weather dataset (1983–2012), Bennett et al. (2014) determined that the net irrigation water requirement for sugar beet at Vauxhall would be >167 mm 90% of the time, >332 mm 50% of the time, and >428 mm 10% of the time. In our study, irrigation amounts were >332 mm 66% of the time (8 yr of 12) but this may be partly due to higher water inputs on experimental plots vs. commercial fields. During each growing season, precipitation and air temperature were monitored at an automated weather station located ~300 m from the plots.

Sugar beet harvest dates (Fig. 1) ranged from 13 Sep. (2000) to 17 Oct. (2007) with a mean of 29 Sep. (n = 12). The length of the sugar beet growing season (Fig. 1) ranged from 112 d (2010) to 169 d (2005), with a mean of 147 d (n = 12). In 2000, and again in the latter years of the experiment (2008–2011), the plots were part of the 'mini-harvest' which consists of research plots that supply the first sugar beet for processing startup at the sugar factory. The 'mini-harvest' occurs in mid- to late-September and precedes the main commercial sugar harvest processing which usually begins 1 Oct. Therefore, harvest dates in these years were generally earlier (e.g., 14–20 Sep. in 2009–2011), resulting in shorter growing seasons (112–137 d). In other years (notably 2004–2007), our plots were not part of the 'mini-harvest' and hence harvest dates were generally later (6–17 Oct.) and growing seasons longer (156–169 d).

Since sugar beet followed second year timothy on 6-CONS (2003–2010), timothy (cv. Climax) biomass yield (6×0.25 m^2 sub-plots) for the first (3 July, n = 9) and second cuts (22 Sep., n = 9) was estimated (after oven-drying at 60 °C for 5 d) for potential implications on subsequent sugar beet performance.

Plant stand, root yield, and quality

In 3 yr (2001, 2007–2008), plant stand (plants ha^{-1}) was estimated 19 June to 1 July on 6 plot-length rows (3 sets of 2 adjacent rows). In the remaining 9 yr (2000, 2002–2006, 2009–2011), plant stand was estimated on 6 rows (as above) after mechanical defoliation with a flail mower, 1–2 d before harvest.

The centre 14 rows of each plot were harvested for root yield, determined by a weigh scale on the harvester. The remaining four rows (outermost two rows on each side) were excluded to minimize edge effects. A subset of six rows (three pairs) was taken for quality analysis conducted at the Rogers Sugar Ltd./Lantic Inc. laboratory, Taber, AB. The location of paired rows varied within plots to avoid crop damage from the wheel-move irrigation system. Sub-sampled beet was washed and weighed to estimate soil tare for correction of overall root yield. Washed beet was passed through a multi-saw rasp to provide brei (macerated roots). A filtered solution was obtained from individual brei samples for determination of sugar concentration by polarimetry using a Sucromat digital automatic saccharimeter (Dr. Kernchen GmbH, Seelze, Germany). Brei impurities were determined by fluorometry (α-amino-N) or flame photometry (Na and K). Sugar loss to molasses (SLM), an estimate of the degree to which impurities impair sugar recovery, was calculated (Reinefeld et al. 1974) as:

$$SLM\left(\text{g kg}^{-1}\right) = \left(3.43 \times \left(Na + K, \text{mg kg}^{-1}\right)\right) + \left(0.94 \times \alpha\text{-amino-}N, \text{mg kg}^{-1}\right) - 3.1 \quad (1)$$

Extractable sugar yield was calculated as:

$$\text{Extractable sugar yield}\left(\text{Mg ha}^{-1}\right) = \text{Root yield}\left(\text{Mg ha}^{-1}\right) \times \left[\frac{\text{Sugar conc.}\left(\text{g kg}^{-1}\right) - \text{SLM}\left(\text{g kg}^{-1}\right)}{1000}\right] \quad (2)$$

Table 2. Growing season (1 Apr.–30 Sep.) precipitation, mean air temperature, and irrigation amount for sugar beet, 2000–2011.

Year	Precipitation (mm)	Air temperature (°C)	Irrigation (mm)
2000	172	14.0	445
2001	118	15.0	546
2002	466	12.6	146
2003	230	14.2	381
2004	256	13.3	406
2005	507	13.4	318
2006	272	15.2	660
2007	241	14.2	927
2008	319	13.1	457
2009	255	13.8	483
2010	376	12.7	203
2011	265	13.7	305
Mean (2000–2011)	290	13.8	440
30-yr normal (1971–2000)	240	13.8	—

Statistical analyses

All data were tested for outliers (PROC UNIVARIATE) prior to analysis by year (PROC MIXED) with rotation as a variable (SAS Institute Inc. 2010). To obtain averages of sugar beet parameters only data from the second 6 yr of the study was used (2006–2011) (i.e., when all rotations had completed one or more full cycles, and were therefore considered to be in an established rotation system). Orthogonal contrasts compared management effects: CONV (4-CONV) vs. CONS (mean of 4-, 5- and 6-CONS) and crop sequence effects: wheat–sugar beet (mean of 4-CONV, 4- and 5-CONS) vs. timothy–sugar beet (6-CONS). In all comparisons, an α level of 0.10 was chosen, rather than the conventional α of 0.05, as explained by Pennock (2004) for conservation-related research.

Results

Weather conditions

The 30 yr (1971–2000) normal annual precipitation for Vauxhall, AB is 303 mm, of which 240 mm or 79% is growing season precipitation (GSP, 1 Apr. to 30 Sep.). There was large variation in GSP during the 12 yr study: from 507 mm (211% of normal) in 2005 to 118 mm (49% of normal) in 2001 (Table 2). In fact, these two growing seasons represented the wettest and driest since records began at Vauxhall in 1953. Mean GSP during the study was 290 mm (n = 12) or 21% wetter than the 30 yr normal. The coolest growing season (1 Apr. to 30 Sep.) was 2002 with a mean air temperature of 12.6 °C (Table 2), while 2006 was warmest (15.2 °C). The study mean (n = 12) growing season air temperature (13.8 °C) was equivalent to the 30 yr normal.

Above-normal GSP in 2002, 2005, and 2010 (Table 2) led to standing water on low-lying areas of the experimental site, necessitating abandonment of some plots due to waterlogging and crop failure. Of the 16 sugar beet plots (4 rotation phases × 4 replications) each year, one was abandoned in 2002 and 2005, and two in 2010. One plot was also abandoned in 2009 due to localized flooding. Abandoned plots were treated as missing values in statistical analyses.

Plant stand

Across all rotations and years, plant stand ranged from 49 420 plants ha^{-1} in 2001 to 91 550 plants ha^{-1} in 2007, with a study average of 67 470 plants ha^{-1} (data not shown). Rotation had a significant effect ($P \leq 0.10$) on stand in only 2 of 12 yr (data not shown). In 2003 and 2010, populations after timothy on 6-CONS were significantly higher than 4-CONV and 4-CONS in 2003 (75 050 vs. 62 180–63 510) and 4- and 5-CONS in 2010 (64 410 vs. 52 820–55 700).

Average plant stand over the second 6 yr of the study (2006–2011) was not affected by rotation (P = 0.69, Table 3). Similarly, contrast analysis revealed that management (CONV vs. CONS) and crop sequence (wheat–sugar beet vs. timothy–sugar beet) effects were also non-significant (Fig. 2*a*).

Root yield

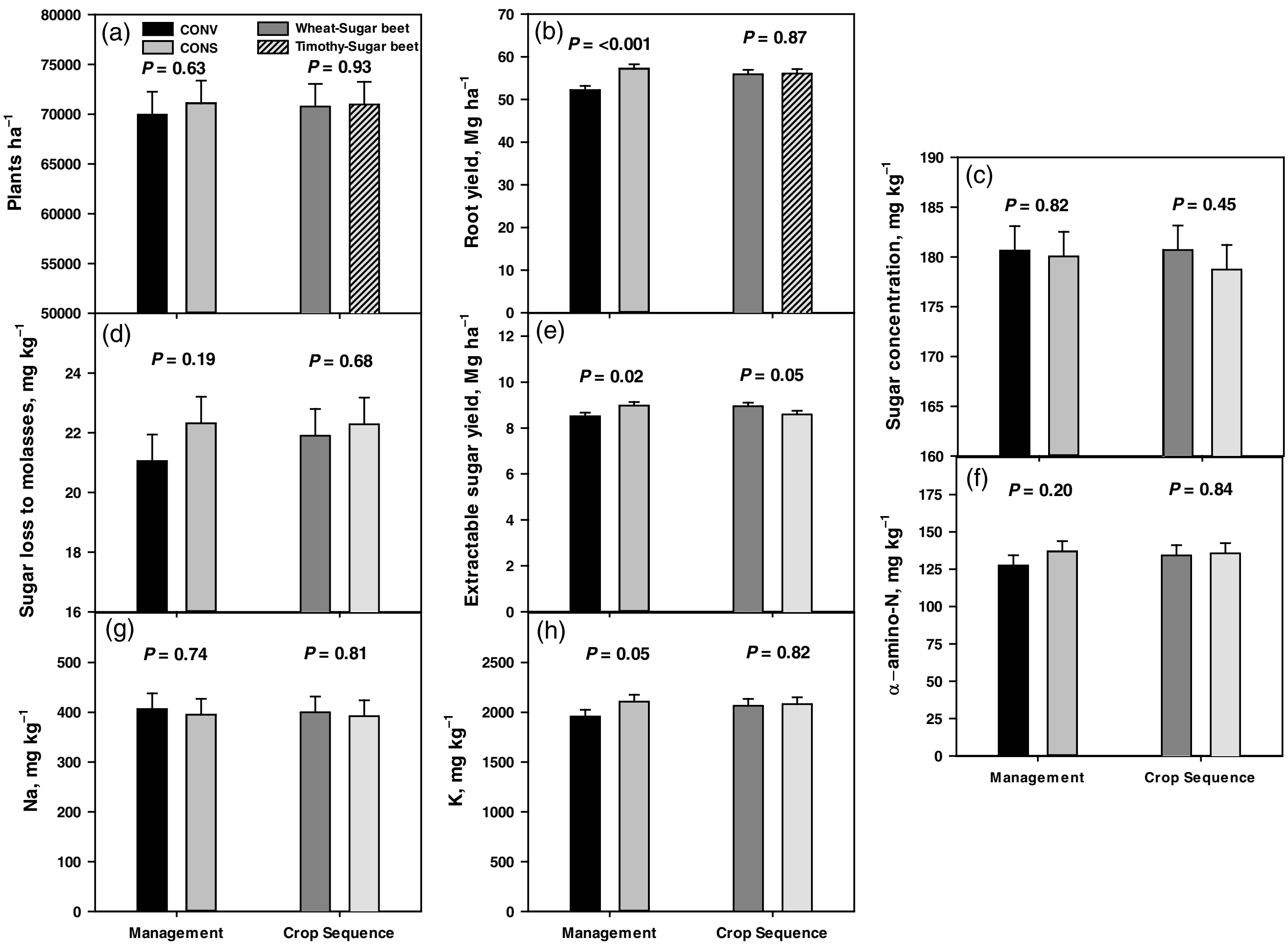
Sugar beet root yield (averaged across rotations) was highest in 2007 (70.7 Mg ha^{-1}) and lowest in 2010 (41.3 Mg ha^{-1}), with a mean (n = 12) of 57.8 Mg ha^{-1}. There was a significant effect of rotation on sugar beet root yield in 4 of 12 yr (Table 4). In those 4 yr (2006, 2009, 2010, 2011), the 5-CONS rotation had 8% (2006) to 19% (2009) significantly higher yields ($P < 0.10$) than the 4-CONV rotation. In addition, 4-CONS was significantly higher than 4-CONV in 2009 and 2011 and 6-CONS significantly higher than 4-CONV in 2009 and 2010. Within the three CONS rotations, 5-CONS was significantly higher (64.6 Mg ha^{-1}) than 4-CONS (59.8 Mg ha^{-1}) in 2006, and significantly higher (63.1 Mg ha^{-1}) than both 4- and 6-CONS (58.4–58.9 Mg ha^{-1}) in 2009 (Table 4).

Table 3. Rotation effects on sugar beet parameters averaged over the second 6 yr cycle (2006–2011).

	Stand (plants ha^{-1})	Sugar conc. (g kg^{-1})	Sugar loss to molasses (g kg^{-1})	α-amino-N (mg kg^{-1})	Na (mg kg^{-1})	K (mg kg^{-1})
Rotation						
4-CONV	69 980[a]	180.6	21.0	127	407	1958
4-CONS	**69 620**	181.4	22.2	135	403	2110
5-CONS	72 720	180.0	22.5	140	391	2132
6-CONS	70 980	178.7	22.3	136	392	2083
SE[b]	2041	2.1	0.8	7	33	59
P-value	0.69	0.84	0.57	0.54	0.97	0.23

[a]Values represent means of $n = 24$ [6 yr (2006–2011) $\times$ 4 replicates yr^{-1}]; means separation not provided since all *P*-values are non-significant (>0.10).
[b]Standard error of rotation LSMEANS ($n = 4$ replicates).

Fig. 2. Management (4-CONV vs. mean of 4-, 5-, and 6-CONS rotations) and crop sequence [Wheat–sugar beet vs. Timothy–sugar beet (mean of 4-CONV, 4- and 5-CONS vs. 6-CONS)] contrasts, with associated *P*-values and standard error bars, for second 6 yr (2006–2011) average (*a*) plant stand; (*b*) root yield; (*c*) sugar concentration; (*d*) sugar loss to molasses (SLM); (*e*) extractable sugar yield; (*f*) α-amino-N concentration; (*g*) Na concentration; and (*h*) K concentration.



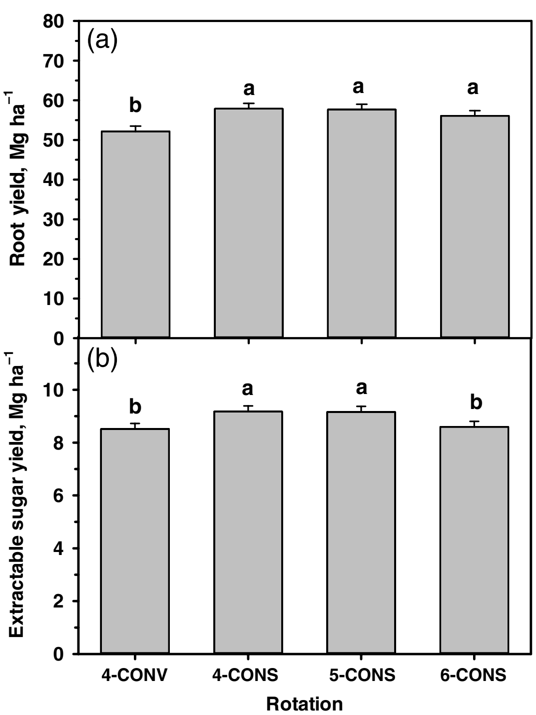
Sugar beet root yield averaged over the second 6 yr of the study (2006–2011) was significantly affected by rotation (Fig. 3*a*). Yield on the 4- and 5-CONS rotations (57.7–57.9 Mg ha^{-1}) was 11% higher, and the 6-CONS rotation (56.1 Mg ha^{-1}) was 8% higher than the 4-CONV rotation (52.2 Mg ha^{-1}). This significant effect was also apparent ($P < 0.001$) in the management contrast analysis where, overall, CONS rotations were

Table 4. Rotation effects on total sugar beet root yield and sugar concentration, 2000–2011.

	Root yield (Mg ha^{-1})											
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Rotation												
4-CONV	62.2	69.3	42.0	63.8	66.7	49.3	59.9b[a]	67.7	49.9	53.1c	38.7b	48.0c
4-CONS	63.1	68.6	44.8	68.0	67.8	46.9	59.8b	73.2	53.6	58.4b	41.1ab	56.8a
5-CONS	65.0	70.2	42.8	62.1	72.3	49.6	64.6a	72.3	49.7	63.1a	43.6a	52.8b
6-CONS	62.0	70.8	42.8	66.7	67.4	46.9	62.4ab	69.5	52.7	58.9b	41.6a	50.4bc
SE[b]	2.0–2.2	2.8	0.7–1.0	2.0–2.3	3.6	4.0–4.6	1.1–1.3	1.7–1.9	2.9	2.0–2.1	1.3–1.4	1.0–1.5
P-value	0.53	0.79	0.27	0.29	0.69	0.94	0.08	0.19	0.26	0.001	0.05	0.008
	Sugar concentration (g kg^{-1})											
Rotation												
4-CONV	159.0	175.6ab	168.1	183.5	188.9	197.5	191.2	199.3a	179.2	183.5a	155.6b	175.1
4-CONS	162.6	182.8a	170.4	175.5	195.5	191.7	191.9	192.1b	177.7	180.9a	162.6a	170.5
5-CONS	161.0	180.3a	171.1	183.0	194.5	193.0	194.6	198.7a	168.7	174.9b	168.4a	175.6
6-CONS	156.4	172.4b	167.2	180.3	195.6	190.4	192.2	193.7b	170.5	169.1b	162.9a	177.7
SE[b]	5.7	4.9	3.3–3.8	3.6–4.0	3.3	5.4–6.0	1.3–1.5	1.9–2.1	4.6	2.3–2.5	3.3–3.5	3.2
P-value	0.72	0.04	0.78	0.30	0.46	0.72	0.41	0.01	0.34	0.003	0.01	0.46

[a]Means separation (means with different letters are significantly different from each other) only provided when *P*-value ≤0.10.
[b]Standard error of rotation LSMEANS; one value presented for balanced designs (n = 4 replicates); range of values presented for unbalanced designs (n < 4 replicates for some rotations) due to abandoned plots and (or) omission of outliers following PROC UNIVARIATE analysis.

Fig. 3. Effect of rotation on second 6 yr (2006–2011) average (± standard error) (*a*) root yield; and (*b*) extractable sugar yield. Bars with the same letters are not significantly different from each other (P > 0.10).



10% higher than CONV (Fig. 2*b*). However, the crop sequence effect was non-significant (P = 0.87, Fig. 2*b*) showing root yield did not differ whether sugar beet followed timothy (6-CONS) or wheat (4-CONV, 4-, 5-CONS).

Sugar beet quality

Sugar concentration

Sugar concentration (averaged over rotations) ranged from 195.9 g kg^{-1} in 2007 to 159.7 g kg^{-1} in 2000, with a mean value (n = 12) of 179.2 g kg^{-1}. Three consecutive years in mid-study (2004–2006) also had average sugar concentrations >190 g kg^{-1}. Two wetter-than-normal years with low yields (2002, 2010) showed lower average sugar concentrations (<170 g kg^{-1}). Significant rotation effects (P < 0.05) on sugar concentration were present in 4 of 12 yr (Table 4). In 2001, significant differences cannot be fully explained as the rotation treatments were very much in transition (and sugar beet followed wheat on all rotations, Table 1) in only the second year of the study. In 2007, 2009, and 2010, there were no consistent trends in significant rotation effects on sugar concentrations (Table 4). Overall, the average sugar concentration in the second half of the study (2006–2011) was not affected by rotation (P = 0.84, Table 3). Contrast analysis showed that management (CONV vs. CONS) and crop sequence (wheat–sugar beet vs. timothy–sugar beet) effects on sugar concentration were also non-significant (Fig. 2*c*).

Sugar loss to molasses

Sugar loss to molasses (averaged across rotations) was lowest in 2005 (15.5 g kg^{-1}) and highest in 2010 (25.9 g kg^{-1}), with a mean (n = 12) of 22.0 g kg^{-1}. Both

Table 5. Rotation effects on sugar loss to molasses (SLM) and extractable sugar yield, 2000–2011.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Sugar loss to molasses, g kg^{-1}											
Rotation												
4-CONV	25.9	26.9a	28.1	20.2	20.6	15.4	20.6	17.1	21.7	20.2b[a]	28.4	18.2
4-CONS	23.6	23.8b	23.5	24.2	19.0	14.8	21.0	20.1	24.5	21.6ab	25.6	19.8
5-CONS	25.6	23.2b	22.7	22.8	19.3	15.1	22.3	21.0	24.7	23.8a	24.4	20.7
6-CONS	25.8	26.6a	25.7	20.6	16.0	16.7	20.3	20.5	26.2	20.6ab	25.4	20.1
SE[b]	2.7	1.6–1.7	1.7–1.9	1.2–1.4	1.2–1.4	1.6–1.8	1.6	1.1	2.0	0.8–1.0	1.4–1.7	0.8–1.0
P-value	0.73	0.04	0.19	0.18	0.19	0.71	0.82	0.12	0.39	0.10	0.34	0.28
	Extractable sugar yield, Mg ha^{-1}											
Rotation												
4-CONV	8.28	10.29	5.87	9.79	11.18	8.87	10.22	11.93	7.82	8.66b	4.91b	7.53
4-CONS	8.74	10.86	6.34	9.72	11.95	8.34	10.22	12.58	8.20	9.30ab	5.57a	8.10
5-CONS	8.75	10.87	5.97	9.93	12.63	8.83	10.54	12.56	7.10	9.57a	6.12a	8.17
6-CONS	8.41	10.27	6.25	10.17	11.85	8.12	10.40	12.04	7.63	8.80b	5.59a	7.12
SE[b]	0.44	0.30	0.28–0.32	0.35	0.40	0.76–0.87	0.27	0.31	0.40	0.32–0.35	0.16–0.19	0.33
P-value	0.75	0.25	0.59	0.81	0.13	0.88	0.63	0.36	0.16	0.05	0.008	0.15

[a]Means separation (means with different letters are significantly different from each other) only provided when *P*-value ≤0.10.
[b]Standard error of rotation LSMEANS; one value presented for balanced designs (n = 4 replicates); range of values presented for unbalanced designs (n < 4 replicates for some rotations) due to abandoned plots and (or) omission of outliers following PROC UNIVARIATE analysis.

extreme years were wetter-than-normal with low root yields. Other years with low SLM values (<20 g kg^{-1}) included 2004, 2007, and 2011, while the first three years of the study (2000–2002) had SLM values >25 g kg^{-1}. The effect of rotation on SLM was significant in only 2 of 12 yr (Table 5). In 2001, 4-CONV and 6-CONS had significantly higher ($P < 0.05$) SLM (26.6–26.9 g kg^{-1}) than 4- and 5-CONS (23.2–23.8 g kg^{-1}), while in 2009, 5-CONS (23.8 g kg^{-1}) was significantly higher than 4-CONV (20.2 g kg^{-1}). Averaged over the second 6 yr of the study (2006–2011), SLM was not affected by rotation (P = 0.57, Table 3), management (CONV vs. CONS, Fig. 2*d*) or crop sequence (wheat–sugar beet vs. timothy–sugar beet, Fig. 2*d*).

Extractable sugar yield

Extractable sugar yield (averaged across rotations) was highest in 2007 (12.3 Mg ha^{-1}) and lowest in 2010 (5.5 Mg ha^{-1}) with a mean (n = 12) of 9.0 Mg ha^{-1}. A significant ($P < 0.05$) rotation effect on extractable sugar yield (Table 5) was present in only 2 yr, late in the study (10th and 11th yr), and closely mirrored effects on root yield (Table 4). In 2009, extractable sugar yield was significantly higher on 5-CONS (9.57 Mg ha^{-1}) than 4-CONV and 6-CONS (8.66–8.80 Mg ha^{-1}), while 4-CONV (4.91 Mg ha^{-1}) was significantly lower than the three CONS rotations (5.57–6.12 Mg ha^{-1}) in 2010. Average extractable sugar yield over the second half of the study (2006–2011) was significantly affected by rotation (Fig. 3*b*). There was essentially no difference between extractable sugar yields on 4- and 5-CONS (9.16–9.18 Mg ha^{-1}) which were higher than 4-CONV (8.60 Mg ha^{-1}) by 8% and 6-CONS (8.51 Mg ha^{-1}) by 7%. Contrast analysis showed that management (CONV vs. CONS) and crop sequence (wheat–sugar beet vs. timothy–sugar beet) effects were both significant (Fig. 2*e*), the only parameter where this occurred, with a 5% extractable sugar yield increase with CONS management and a 4% decrease following timothy vs. wheat.

Impurities

Mean impurity values (n = 12) were 133 mg kg^{-1} for α-amino-N, 372 mg kg^{-1} for Na, and 2128 mg kg^{-1} for K. During the 12 yr study, significant rotation effects ($P < 0.10$) on α-amino-N occurred in 2 yr (2009, 2010), on Na in 3 yr (2001, 2002, 2010), and on K in 2 yr (2003, 2007) [data not shown]. However, rotation effects on impurities were inconsistent. No one rotation stood out as being consistently higher or lower for any impurity parameter. For example, in 2009, 4-CONV (101 mg kg^{-1}) had significantly lower α-amino-N impurities than 6-CONS (171 mg kg^{-1}). However, in 2010, Na concentration on 4-CONV (816 mg kg^{-1}) was significantly higher than the three CONS rotations (496–520 mg kg^{-1}). In 2003, the 6-CONS rotation had significantly lower ($P < 0.10$) K impurities (2138 mg kg^{-1}) than 4-CONS (2436 mg kg^{-1}).

Rotation effects in the second half of the study (2006–2011) were non-significant for impurities (Table 3): α-amino-N (P = 0.54), Na (P = 0.97), and K (P = 0.23). However, contrast analysis showed a significant management effect on K (Fig. 2*h*) with the CONS rotations

(2108 mg kg^{-1}) averaging 8% higher than 4-CONV (1958 mg kg^{-1}). This was not apparent for α-amino-N (Fig. 2*f*) or Na (Fig. 2*g*). The crop sequence (wheat–sugar beet vs. timothy–sugar beet) effect was non-significant (P = 0.72–0.84) for all three impurity parameters (Figs. 2*f*–2*h*).

Discussion

Conservation management practices

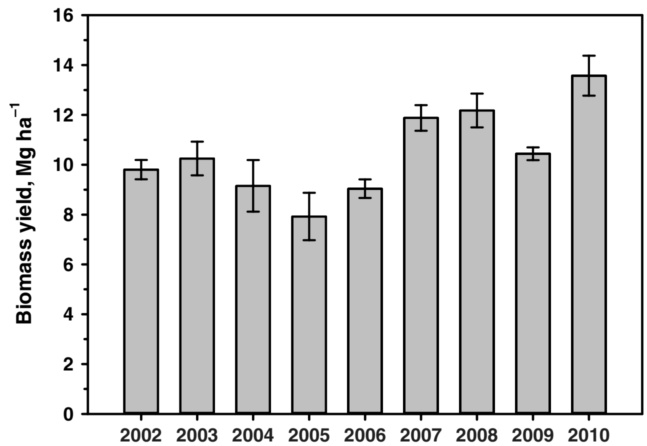
Compared with the other crops in this rotation study (particularly dry bean and potato), there was less opportunity for direct impact of the four CONS management practices on sugar beet performance. The CONS practice of narrow-row production pertained to dry bean only. As discussed previously, the reduced tillage CONS practice was not an option immediately prior to sugar beet as reduced tillage was already the norm for sugar beet on the 4-CONV rotation.

Although tillage system differed on 6-CONS (fall moldboard plowing) vs. 4-CONV, and 4- and 5-CONS (fall disking) for the 2003–2011 growing seasons, a direct tillage comparison was confounded by different crop sequences and rotation lengths (timothy–sugar beet on 6-CONS vs. wheat–sugar beet on 4-CONV and 4- and 5-CONS). Nonetheless, the tillage comparison was generally non-significant which agreed with findings from sugar beet studies conducted locally (Hao et al. 2001; Moyer et al. 2004) or in other growing regions (Koch et al. 2009; Overstreet 2009; Jabro et al. 2010; Stevens et al. 2010). Jabro et al. (2015) found that root yield and adjusted sucrose yield were not significantly affected by depth of tillage (no-till; tillage to 10 cm with a heavy-duty cultivator; or 30 cm with a ripper) in 3 of 4 yr in North Dakota.

However, there were a few instances when significant differences were found between 6-CONS (moldboard plowing) and the other rotations (disking), which may have been due to a tillage effect. In 2009 and 2011, 6-CONS had 7%–11% lower root yield than either the 5-CONS or 4-CONS. Also, 6-CONS had significantly lower sugar concentration (by 3%) than 5-CONS in 2007, and significantly lower extractable sugar yield (by 8%) than 5-CONS in 2009. In addition, 6-CONS had significantly higher α-amino-N (23%–69%) in 2009, which agreed with Halvorson and Hartman (1984) who found that sugar beet quality, in terms of clear juice purity, was better in reduced vs. conventional tillage (CT, rototilling to 15 cm depth) treatments. They attributed this difference to higher levels of soil NO_3-N found under CT. Moldboard plowing (i.e., CT) on 6-CONS may have caused a similar effect.

The results above may also be due to predomination of a crop sequence effect over a tillage effect. Even though the N fertilizer rate was increased by 25% following timothy vs. wheat (168 vs. 134 kg ha^{-1}), this may not have compensated adequately for higher N use by the timothy crop, hence lowering root yield. More accurate N fertility

Fig. 4. Annual biomass yield (± standard error, n = 4) of the second year timothy crop (2002–2010) preceding sugar beet (2003–2011) on the 6-CONS rotation (sugar beet–dry bean–potato–oat–timothy–timothy). Values are summed over first and second cuts.



matching may have occurred following wheat. This explanation is supported by biomass yield of the preceding second year timothy crop (Fig. 4) in 2008 and 2010 (i.e., preceding the 2009 and 2011 sugar beet crops where root yield was significantly lower by 7%–11% on 6-CONS). Fig. 4 shows that 2008 (12.2 Mg ha^{-1}) and 2010 (13.6 Mg ha^{-1}) had the two highest-yielding second year timothy crops of the study. The average second year timothy biomass yield (2002–2010) was 10.5 Mg ha^{-1}, with 2005 showing the lowest yield (7.9 Mg ha^{-1}, Fig. 4). Another possible reason for lower root yield on 6-CONS may have been that the extra 25% N added following timothy may have been insufficient to account for N immobilized by microbial decomposition of timothy residues.

Growing sugar beet after a forage legume (e.g., alfalfa) is often strongly discouraged (e.g., Lamb and Sims 2011) for reasons of increased N mineralization from alfalfa residues during the sugar beet growing season which can promote late-season N uptake and hence impair extractable sugar yield. However, even though timothy residue is less N-rich than alfalfa, N release due to microbial decomposition of timothy residue may have occurred late in the sugar beet growing season, which may have lowered sugar beet performance.

Of the two remaining CONS practices (compost addition, cover crops), their entry points in rotations were such that they had limited direct impact on sugar beet productivity. With organic amendments like compost, synchronization of N release with plant uptake is often a challenge, since N mineralization rates are affected by numerous source, edaphic or environmental factors. An N management plan that drives canopy formation to mid-season closure, maintains the canopy at a moderate size for the rest of the growing season, and exhausts soil

N reserves 4–6 wk before harvest, is recommended for sugar beet (Martin 2001). This ensures that late-season photosynthate is devoted to root and sucrose yield rather than excessive canopy structure. Moreover, excess late-season N has serious negative effects on root purity and therefore sucrose extraction during processing. Thus, late-season flushes of mineralized N from compost or manure can be deleterious to sugar beet quality (Carter and Traveller 1981; Moore et al. 2009).

In our study, the compost application likely did not interfere with N supply or uptake as compost was applied well in advance of the sugar beet crop (e.g., 4- and 5-CONS which received compost in fall 2000 were not planted to sugar beet until 2003, while there was a 5-yr gap between compost application and sugar beet harvest on 6-CONS (Table 1)). Lehrsch et al. (2015*a*) estimated that 20% of compost total N was available for plant uptake in the year following application. Overall our 42 Mg ha^{-1} compost rate (Table 1) supplied (on average) 437 kg ha^{-1} of total N or 87 kg ha^{-1} (20% of total) of available N in the year after application while our 28 Mg ha^{-1} compost rate supplied 291 kg ha^{-1} of total N or 58 kg ha^{-1} of available N. Within 3–5 yr of application, N release from compost would be very low so that effects on sugar concentration or extractability were likely negligible.

In fact, recent research indicated that compost application at an entry point much closer to sugar beet (i.e., 6 mo, or the fall before), and at much higher rates than our study, had no deleterious effects on sugar beet yield and quality. In Idaho, Lehrsch et al. (2015*a*, 2015*b*) applied bulk application rates of up to 128 Mg ha^{-1} (dry wt.) of dairy manure compost, which supplied up to 2175 kg ha^{-1} total N in the fall before sugar beet. They compared N sources of control (no N), urea (202 kg N ha^{-1}), compost (first year rates of 218 and 435 kg estimated available N ha^{-1}), and manure (first year rates of 140 and 280 kg available N ha^{-1}). Averaged across years and organic N rates, sucrose yield was 12.24 Mg ha^{-1} for urea, 11.88 Mg ha^{-1} for compost, and 11.20 Mg ha^{-1} for manure, all statistically equivalent. Doubling the organic N rates for compost and manure increased root yield up to 26% and sucrose up to 21%. They concluded that sugar beet producers could use compost or manure to satisfy crop N needs without sacrificing sucrose yield. In northern Japan, Koga and Tsuji (2009) found that fall- or spring-applied composted dairy manure (20 Mg ha^{-1} fresh wt.) increased root yield by 9% in a reduced tillage (shallow harrowing) system.

Cover crops are important components of sustainable cropping systems (Dabney et al. 2001). They provide surface cover during the vulnerable wind erosion period, which in southern Alberta can extend from fall harvest to spring seeding. They also act as a source of soil fertility and suppress weeds and pests (Moyer and Blackshaw 2009), and scavenge soil nitrate-N remaining after harvest, reducing the risk of leaching to groundwater. Kramberger et al. (2008) found that an Italian ryegrass (*Lolium multiflorum* Lam.) cover crop decreased sugar beet root yield but did not affect sugar concentration, non-sugar impurity concentrations (α-amino-N, Na, K), or white sugar yield. In our study, the impact of the cover crop CONS practice likely exerted minimal direct effects on sugar beet performance, largely because its entry point was 1.5 yr (4-, 5-CONS) or 3.5 yr (6-CONS) prior to sugar beet. A cover crop was unnecessary in falls prior to sugar beet as crop sequences were chosen so that sugar beet followed wheat or timothy (Table 1) resulting in adequate surface residue cover. The cover crop entry points followed potato in CONS rotations (Table 1) as potato was harvested early enough (mean, September 14, n = 12) to allow fall rye seeding and establishment prior to freeze-up. In contrast, mean sugar beet harvest date was 29 Sep., which did not allow for establishment of a fall cover crop after sugar beet.

Sugar beet performance

In southern Alberta, sugar production is maximized at plant populations of 74 000–86 000 plants ha^{-1} (Rogers Sugar Ltd. 2000). Few gaps in the plant stand assure rapid and complete foliage cover, which is required for high radiation interception and thus high root yield and sugar concentration and low impurities (Steven et al. 1986). Five of the 12 yr (2004–2005, 2007–2008 and 2011) attained stands within the optimum range (data not shown). The three poorest stands occurred in 2001 (49 420), 2000 (50 110), and 2009 (51 400 plants ha^{-1}). Stand problems can be caused by a combination of factors that include improper soil preparation, soil crusting, freezing temperatures, blowing soil, inadequate soil water, improper equipment selection or operation, and seedling death from insects, disease or pesticides (Yonts et al. 2001). The poor stand in 2000 was due to a flea beetle (*Psylliodes punctulata* Melsheimer) infestation, while wireworm and cutworm damage coupled with dry seedbed conditions (8 mm of precipitation from 5 Apr. to the first irrigation on 4 May) contributed to a poor stand in 2001.

Our 12 yr average sugar beet root yield (57.8 Mg ha^{-1}) was 8% higher than the average yield (52.9 Mg ha^{-1}) in commercial fields (Laate 2013) during the tenure of the study (2000–2011). The highest ranking root yields (averaged across rotations) were in 2007 (70.7 Mg ha^{-1}) and 2001 (69.7 Mg ha^{-1}). Interestingly, root yields were almost identical in these years even though, as discussed above, they had the highest (2007, 91 550 plants ha^{-1}) and lowest (2001, 49 420 plants ha^{-1}) plant stands. Both years, however, were characterized by the warmest July–August periods of the 12 yr (19.8–19.9 °C), which suggested that the warm temperatures compensated for low plant stand in 2001. In addition, 2001 was the driest growing season of the study (49% of normal), causing no problems with excess rainfall, which reduced plant stand in other years (e.g., 2002, 2010) leading to low yields. Of the four lowest-yielding years, three (2002, 2005, 2010) were wetter-than-normal leading to excess water and yields (averaged across rotations) of 41.3 to 48.2 Mg ha^{-1}. The fourth lowest-yielding year (2008, 51.5 Mg ha^{-1}) experienced three severe hail storms in rapid succession (July 7, 10, and 15), accompanied by strong winds, which caused major canopy damage to all crops.

Significant rotation effects on root yield did not occur until the seventh year (2006) of the study (Table 4), demonstrating that rotation studies demand longer-term commitments for evidence of significant responses. Our results showed positive responses to CONS management with the 5-CONS rotation yielding 8%–19% higher than 4-CONV across 4 yr (2006, 2009–2011). Overall this translated to a 10% higher root yield with CONS (57.2 Mg ha^{-1}) vs. CONV (52.2 Mg ha^{-1}) management, averaged over the second 6 yr of the study. Our results agree with those from older experiments in the region (Dubetz and Hill 1964; Dubetz et al. 1975; Dubetz 1983) regarding the benefits of organic amendments in sugar beet production. Also, Eck et al. (1990) reported higher root yields and sugar concentrations on treatments receiving beef feedlot manure compared with N, P, and K fertilizer in Texas. In a long-term experiment in Sweden, with 4 yr rotations for sugar beet established in 1951, a rotation receiving manure (30 Mg ha^{-1}) once every 4 yr at an entry point 18 mo before sugar beet increased root yield by 8%–18% (Mattsson and Persson 2006). However, in the current study, comparing within CONS rotations only, there was no significant difference in average root yield over the second 6 yr (Fig. 3*a*) between 4- (57.9 Mg ha^{-1}), 5- (57.7 Mg ha^{-1}) or 6-CONS (56.1 Mg ha^{-1}). Once CONS practices were implemented there was no apparent benefit of increasing rotation length, although this may also be partly due to the crop sequence effect on 6-CONS (sugar beet after timothy vs. wheat).

Since extractable sugar yield is a calculated variable that integrates the three measured variables of root yield, sugar concentration, and SLM (eq. 2), it represents grower income from the sugar beet crop. Relationships between the three components of extractable sugar yield (averaged across rotations) were at play in this study. The year with the highest root yield (2007) also had highest sugar concentration (Table 4) and 3rd lowest SLM, which led to highest extractable sugar yield (Table 5). Coincidentally, 2007 also had the highest average plant stand. The 2nd highest extractable sugar yield in 2004 occurred due to a combination of 3rd highest root yield, 2nd highest sugar concentration, and 2nd lowest SLM. Correspondingly, the lowest extractable sugar yield in 2010 coincided with the lowest root yield, 2nd lowest sugar concentration, and highest SLM.

In an irrigation × N rate study with sugar beet, Khan and McVay (2014) found that SLM was the parameter most affected by treatment, with significant responses to year, irrigation, N rate, year × irrigation, and year × tillage. In contrast, our study treatments elicited less obvious effects on SLM, with significant rotation responses in this parameter confined to only 2 of 12 yr (Table 5). A wetter-than-normal year in 2010 forced rotation differences for extractable sugar yield, α-amino-N, and Na, showing lower extractable sugar yield (Table 5) and higher impurities with 4-CONV than the other rotations. Averaged over the last 6 yr, extractable sugar yields on 4- and 5-CONS were significantly higher than 4-CONV by 8% and 6-CONS by 7% (Fig. 3*b*). Therefore, adopting CONS management on 4- and 5-yr rotations would likely lead to higher cash returns. However, unlike root yield, the crop sequence effect (sugar beet after timothy) contributed to significantly lower extractable sugar yield on 6-CONS. Our finding of a significant management effect on K concentration averaged over the final 6 yr (CONS > CONV, Fig. 2*h*) agreed with Artyszak et al. (2014) who found that K was the only impurity parameter that increased when sugar beet followed a white mustard (*Sinapis alba* L.) cover crop vs. CT.

Improved performance with CONS management was not confined to sugar beet in this study. Advantages were also observed with respect to dry bean and potato yields, potato bacterial endophytes, weed populations, beneficial insects, and soil quality. For dry bean yield, Larney et al. (2015) found no significant effect between narrow-row CONS (high residue) and wide-row CONV production (low residue). In the last 2 yr (2010–2011), in an attempt to reduce harvest losses, narrow-row dry bean was undercut rather than direct combined and this led to significantly higher (25%) yields with CONS (3311 kg ha^{-1}) vs. CONV management (2651 kg ha^{-1}). For potato, CONS management led to yield benefits (without negatively impacting tuber quality), e.g., the 5-CONS rotation had significantly higher (by 8%) marketable tuber yield (12 yr average) than the 4-CONV rotation (Larney et al. 2016). Suppression of Verticillium wilt (*Vertillicium dahliae* Kleb.), which contributes to potato early dying, also occurred with CONS management. Pageni et al. (2013) found that the size and diversity of bacterial endophyte populations isolated from potato roots in 2011 was greater with CONS than CONV management. Endophytes live mutually within plants and enhance growth, nutrient uptake, tolerance to abiotic stress, and pathogen inhibition (Ryan et al. 2008).

Based on 12 yr of weed population and seedbank data, Blackshaw et al. (2015) concluded that implementing a suite of CONS practices posed little risk of increased weed pressures. Bourassa et al. (2008) found that carabid beetle (Coleoptera: Carabidae) activity and density (2003–2005) was consistently higher in in the 3-yr CONS vs. CONV rotation. Carabids play a role in reducing Colorado potato beetle (*Leptinotarsa decemlineata*) and aphid populations (Alvarez et al. 2013). Li et al. (2015) found that after 12 yr under CONS management, particulate organic matter C and N (labile fractions) increased by >145%, total C and N by 45%–50%, and fine organic matter C and N (stable fractions) by 20%. Aggregate stability (a measure of soil resistance to slaking by water) also increased significantly under CONS management. Overall, the 5-yr CONS rotation ranked highest for soil quality, with the 4-CONV rotation substantially lower.

Overall, our study indicates that sugar beet can benefit from CONS management (reduced tillage, cover crops, compost addition) in southern Alberta. Sugar beet root yield (averaged over the second 6 yr of the study) was significantly higher, by 11%, on 4- and 5-yr CONS rotations, and by 8% on a 6-yr CONS rotation compared with a 4-yr CONV rotation. Also, a 5% increase ($P = 0.02$) in extractable sugar yield occurred with CONS management. These findings, combined with synchronous advantages for other crops in rotation and soil quality, provide incentive for further adoption of CONS practices on irrigated land in the region.

Acknowledgements

The authors acknowledge the support of the Joint Company-Grower Agricultural Research Committee for Alberta comprised of representatives from Rogers Sugar Ltd/Lantic Inc. and the Alberta Sugar Beet Growers. We thank Jim Sukeroff, Dale Reynolds, and Vauxhall Substation staff and summer students for field assistance. Sugar beet field support was provided by John Laturnus. Funding was provided by The Alberta Pulse Growers, the Potato Growers of Alberta, Rogers Sugar Ltd/Lantic Inc., the Canada-Alberta Sugar Beet Industry Development Fund, the Alberta Environmentally Sustainable Agriculture (AESA) Program, the Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster.

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Submitted to Agroecosystems, Geosciences & Environment: 26-October-2020

Assessing legacy effects of a 12-yr irrigated cropping systems study with a post-hoc bioassay

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Abstract

A healthy soil resource is vital to the continued success of irrigated agriculture in southern Alberta. A 12-yr (2000–11) irrigated cropping systems study was followed with a dry bean (*Phaseolus vulgaris* L.) field bioassay in 2012, to assess legacy effects of preceding management. Specifically, a comparison of conventional (CONV) and conservation (CONS) management (reduced tillage, cover crops, compost addition, narrow-row dry bean) legacies was sought. However, rotational legacies such as preceding phase, length, preceding crop, and interval since previous legume, were also assessed by the fully-phased experimental setup. Only 1 of 18 possible soil management contrasts (CONV vs. CONS, 2000–11) was significant for the dry bean bioassay in 2012, despite overwhelming evidence of improved soil health (microbial biomass C and β-glucosidase activity) under CONS management. Monoculture wheat (*Triticum aestivum* L.) from 2000–11 led to 2 d earlier maturity and higher disease incidence (0.6–2.6 percentage points) in bioassay dry bean. Bioassay dry bean was significantly shorter (4 cm), earlier maturing (2 d), and lower yielding (by 21–35%) with wheat vs. dry bean, potato (*Solanum tuberosum* L.), or sugar beet (*Beta vulgaris* L.) as preceding crops, largely due to volunteer wheat competition. Significantly enhanced bioassay yields (13–17%) with shorter intervals since previous legume demonstrated a ‘legume effect’. Overall, the dry bean bioassay was less effective at assessing soil management legacies (CONV vs. CONS) than rotational legacies such as preceding crop or interval since previous legume.

Abbreviations: 1-CONT, continuous wheat; 3-CONS, 3-yr rotation with conservation management; 3-CONV, 3-yr rotation with conventional management; 4-CONS, 4-yr rotation with conservation management; 4-CONV, 4-yr rotation with conventional management; 5-

CONS, 5-yr rotation with conservation management; 6-CONS, 6-yr rotation with conservation management; CONS, conservation management; CONV, conventional management; MBC, microbial biomass carbon; PAW, plant available water; SOC, soil organic carbon.

1 | INTRODUCTION

In Alberta, 20% of the total agri-food sector gross domestic product is contributed by the irrigation agri-food sector on only 4.7% of the cultivated land base (Paterson Earth & Water Consulting, 2015). As such, conservation of soil resources on irrigated land is of utmost importance. The conservation tillage revolution on the Canadian prairies, initiated in the early 1990s, has proved much more dramatic on dryland than irrigated land. Under irrigation, row crops such as dry bean, potato, and sugar beet may lead to <10% surface residue cover in the following spring (Larney, Pearson, Blackshaw, & Lupwayi, 2017b). In addition, being root crops, potato and sugar beet harvest operations cause major soil disturbance, unconducive to conservation tillage.

Key crop rotation aspects include (i) length, (ii) crop sequence; and (iii) crop choice (Karlen, Varvel, Bullock, & Cruse, 1994). There has been a worldwide trend toward shortening or simplification of crop rotations including monoculture, despite associated yield declines (Bennett, Bending, Chandler, Hilton, & Mills, 2012). Lengthening crop rotations influences diversity and crop frequency and may create more balanced agroecosystems (O'Brien, Hatfield, Dold, Kistner-Thomas, & Wacha, 2020), e.g., by providing natural pest and weed control, and altering the timing and rate of nutrient and water use, thereby enhancing resilience to climatic stressors (Manns & Martin, 2018). Diversity-productivity-stability relationships are becoming increasingly important in rotation and cropping system research, especially as environmental conditions become more uncertain (Gan et al., 2015; Liu, Johnson, Blackshaw, Hossain, & Gan, 2019). Crop sequencing creates preceding–following crop pairs, whereby the preceding crop directly or indirectly affects the following crop (O'Donovan et al., 2014), e.g., disease, pest, or weed pressure, or nutrient carryover, which may have greater impact than the broader rotation effect. Crop choice usually pertains to representation of major crop families, e.g., grain/forage, oilseed, root crop, or pulse/legume. Recently, the virtues of legume inclusion and the associated 'legume effect' have received much attention in crop rotation studies on the Canadian prairies (Gan et al., 2015; St. Luce et al., 2020).

Increased potato hectarage, and the opening of two new processing facilities in southern Alberta in the late 1990s, instigated establishment of an irrigated cropping systems study in 2000, focusing on soil health and conservation issues. The study examined conventional (CONV) vs. conservation (CONS) soil management practices in 3- and 4-yr rotations, and CONS management in longer 5- and 6-yr rotations, for major irrigated crops in the region (dry bean, potato, soft wheat, and sugar beet). Objectives were to optimize crop response, reduce soil erosion, and enhance soil quality. The four CONS management practices were reduced tillage, cover cropping, compost addition, and narrow-row dry bean. A major outcome of the 12-yr study was increased yields of dry bean (Larney, Pearson, Li, Blackshaw, & Lupwayi, 2015), potato (Larney, Pearson, Blackshaw, Lupwayi, & Lynch, 2016), and sugar beet (Larney et al., 2016) with CONS compared to CONV management. Additionally, implementing a suite of CONS practices posed little risk of increased weed pressures (Blackshaw et al., 2015). Soil health parameters were also enhanced by CONS management, including soil organic C (SOC), particulate organic matter C and N, and aggregate stability (Li, Larney, Angers, Pearson, & Blackshaw, 2015; Larney, Pearson, Blackshaw, & Lupwayi, 2017a). Total soil microbial biomass, and that of its components (fungi and bacteria), and β-glucosidase activity were significantly greater under CONS management (Lupwayi, Larney, Blackshaw, Kanashiro, & Pearson, 2017). Averaged over 10 yr (2002–11), residue cover in spring was significantly higher with CONS vs. CONV management, hence lowering wind erosion risk (Larney et al., 2017b).

On completion of the 12-yr study in 2011, dry bean was planted in the thirteenth year (2012) across all treatments. The objective was to use dry bean as a post-hoc field bioassay, to capture and assess the legacy effects of 12 yr of CONV vs. CONS soil management and crop rotation histories. Legacy effects (Larney & Olson, 2018) or soil memory (Janzen, 2016) describe the persistence of past land use actions which have now ceased. Field bioassays have been used to assess legacy effects of other long-term studies. From 1995 to 2000, Smith, Janzen, and Larney (2015) superimposed a 6-yr spring wheat bioassay on a long-term rotation study (established in 1951) with different cropping histories (fallow, forages, or native grasses in rotation; N inputs), to determine the contribution of these parameters to wheat productivity. The presence of fallow in historical rotations had a negative effect on total yield and grain N concentration of bioassay wheat, even with N fertilizer application. Zvomuya, Janzen, Larney, and Olson (2008) used a dryland wheat bioassay in a topsoil-transplant study on uniform subsoil conditions to successfully identify key soil health attributes (total organic C, total N, light fraction C and N, mineralizable C and N, and extractable N and P) related to crop production in southern Alberta.

Classical bioassays estimate the potency of a stimulus on a subject, as measured by a response (Finney, 1947). In our case the stimuli were soil management and crop rotation, the subject was dry bean, and the response was dry bean growth parameters, including grain yield. Specifically, the legacy of CONS soil management was sought, but crop rotation legacies such as preceding phase, length or diversity, preceding crop, and interval since previous legume, were also of interest in the bioassay. We hypothesized that CONS management, longer rotations, and a shorter interval since previous legume would enhance yield parameters of the bioassay dry bean. An additional hypothesis was that CONS management, and longer rotations, would reduce disease pressures of the bioassay dry bean.

2 | MATERIALS AND METHODS

2.1 | Irrigated cropping systems study, 2000–11

The study was conducted on a Brown Chernozem soil at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50° 03′ N, 112° 09′ W, elev. 781 m), in southern Alberta. The Ap horizon texture was sandy loam (0.52 kg kg^{-1} sand, 0.35 kg kg^{-1} silt, and 0.13 kg kg^{-1} clay). Seven rotations were established in spring 2000 (Table 1) and ran for 12 yr (2000–11). The rotations were: continuous wheat (1-CONT); two 3-yr (3-CONV, 3-CONS); two 4-yr (4-CONV, 4-CONS); one 5-yr (5-CONS): and one 6-yr (6-CONS). The 3-CONV and 3-CONS rotations had similar crop sequences (dry bean–wheat–potato), as had 4-CONV and 4-CONS (dry bean–potato–wheat–sugar beet) (Table 1). The 5-CONS rotation interspersed two wheat phases ($wheat_1$, $wheat_2$) with the 3 row crops (dry bean, potato and sugar beet), while 6-CONS included oat (*Avena sativa* L.) and two phases of timothy (*Phleum pratense* L.) with the 3 row crops (Table 1). The experimental design was fully-phased so that all 26 rotation phases (Table 1) appeared in each year in a randomized complete block design with four replicates (n = 104 plots). Individual plots were 10.1 × 18.3 m (185 m^2), with a 2.1 m inter-plot between plots.

The CONS rotations (3-, 4-, 5-, 6-CONS) had four management practices bundled as a package: (i) direct seeding or reduced tillage where possible in the rotation; (ii) fall-seeded cover crops (Table 1) after at least one phase; (iii) composted cattle manure (Table 1) at 12-yr cumulative additions (fresh wt.) of 107 Mg ha^{-1} on 3-CONS, 116 Mg ha^{-1} on 4-CONS, 154 Mg ha^{-1} on 5-CONS; and 77 Mg ha^{-1} on 6-CONS; and (iv) narrow-row (19–23 cm) dry bean. The CONV rotations (3-, 4-CONV) had more intensive tillage (e.g., moldboard plowing prior to potato), no cover crops or compost, and dry bean in wide rows (60 cm), with inter-row cultivation and undercutting at harvest. Details of CONV and CONS practices were reported for dry bean (Larney et al., 2015), potato (Larney, Pearson, et al., 2016), wheat (Larney, Pearson, Blackshaw, Lupwayi, & Conner, 2018), and sugar beet (Larney, Nitschelm, et al., 2016).

The 12 yr study concluded after harvest in fall 2011, with the number of completed rotation cycles ranging from 4 (3-CONV, 3-CONS) to 2 (6-CONS) [Table 1]. In fall 2011, a final set of soil samples was taken for nutrient analyses on all plots (Larney et al., 2017a). Available P levels throughout the study were non-limiting to plant growth (Larney et al., 2017a).

2.2 | Dry bean bioassay, 2012

In preparation for seeding the dry bean bioassay in 2012, the two timothy phases of 6-CONS were terminated (26 Sept. 2011) with glyphosate [*N*-(phosphonomethyl) glycine] and moulboard ploughed (18 Oct. 2011). Regrowth on the oat phase of 6-CONS was also terminated (13 Oct. 2011) with glyphosate. Fertilizer at recommended rates (45 kg ha^{-1} N, 67 kg ha^{-1} P_2O_5, 67 kg ha^{-1} K_2O, 3.4 kg ha^{-1} $ZnSO_4$) was broadcast (31 Oct. 2011) on all plots. Granular ethalfluralin for grassy weed control was applied (1 Nov. 2011) to all plots, and incorporated with a disk harrow.

In spring 2012, glyphosate was applied (11 May) to plots following wheat, to control volunteer wheat from harvest losses in 2011. Pre-seeding tillage (15 May) for dry bean consisted of one pass of a disk harrow and trailed spike and one pass of a spring-tine harrow. An uninoculated great northern dry bean cultivar (Resolute) was seeded (16 May) with a no-till drill in narrow rows (18 cm) at 43 seeds m^{-2}. Narrow-row dry bean was chosen to reflect increased regional adoption over conventional wide-row (60 cm). In-crop weeds were controlled (21 June, 5 July) with bentazon (3-isopropyl-1*H*-2,1,3-benzothiadiazin-4(3*H*)-one 2,2-dioxide) and imazamox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) [5 July]. Volunteer wheat remained an issue following 2011 wheat phases, requiring sethoxydim (2-[(E)-N-ethoxy-C-propylcarbonimidoyl]-5-(2-ethylsulfanylpropyl)-3-hydroxycyclohex-2-en-1-one) application (25 June). Fungicides included copper hydroxide (9, 31 July) for bacterial blight (*Xanthomonas axonopodis* pv. *phaseoli* (Smith) Vauterin et al. (Xap) [syn. X. *campestris* pv. *phaseoli* (E.F. Smith) Dye]), and boscalid (2-chloro-N-(4'-chloro[1,1'-biphenyl]-2-yl)-3-pyridinecarboxamide) [31 July] for white mold.

Plants were counted (9–12 July) in two adjacent 1-m row lengths in four quadrants of each plot to assess density. Plant height was measured (24 July) on representative areas in all four quadrants on each plot. Plant maturity was visually rated (20–27 August), and days to maturity (DTM) estimated as the number of days after seeding when 60-70% of plants were physiologically ripe, i.e., the bottom, first-formed pods were crisp and dried to a buckskin colour. Two 1.2 m-wide strips in each plot were undercut (27 August) and allowed to mature in swaths until harvest (13–17 September) with a plot combine.

White mold (percent of 120 plants infected; 30 adjacent plants × 4 rows plot^{-1}) and bacterial blight (unswathed plot area) incidence were visually rated (29 August). For bacterial blight, plots were ranked as 0% (none), <1% (trace), 1–10% (light), or 11–25% (moderate) of plants infected (Huang & Erickson, 2000). The rankings were assigned values from zero to 3 for statistical analyses. Infection levels of 26–50% (high) or >50% (very high) were not observed.

For microbial biomass C (MBC) and β-glucosidase enzyme activity, dry bean plants were excavated (30–31 July) at approximate peak biomass from four random 0.5-m row lengths plot^{-1}, and shaken vigorously to dislodge loose soil. Soil still adhering to roots was then carefully brushed and recovered as rhizosphere soil. Bulk soil (0–7.5 cm depth) was sampled at four inter-row midpoints plot^{-1}. The rhizosphere or bulk samples from each plot were composited, passed through a 2-mm sieve, and stored at −20 °C. Soil MBC was measured by substrate-induced respiration, and β-glucosidase activity by incubation followed by determination of p-nitrophenol release. More detailed methodological descriptions are provided by Lupwayi et al. (2017).

All plots were individually irrigated using 4 quarter-circle sprinklers on a wheel-move system. Irrigation amounts were 51 mm (12 July), 44 mm (25 July), and 38 mm (2 and 7 August), or 171 mm in total. Volumetric water content (θ) was estimated with a neutron probe, approximately weekly (n = 11) from 11 June to 29 August, on the 32 plots [2 rotations × 4 phases (dry bean, potato, wheat, sugar beet, 2011) × 4 replicates] of the former 4-CONV and 4-CONS rotations. Plant available water (PAW, 0–100 cm depth) was estimated from θ. Precipitation and air temperature were measured at an automated weather station ~300 m from the study site.

2.3 | Statistical analyses

All 2012 dry bean (plant density, height, DTM, yield, white mold, bacterial blight) and soil (MBC, β-glucosidase, PAW) data were analyzed by PROC MIXED with preceding rotation phase (combination of rotation and phase, n = 26, Table 1) as a fixed effect and replicate as a random effect (SAS Institute Inc., 2009).

In addition, *a priori* orthogonal contrasts, using the CONTRAST and ESTIMATE statements in SAS, evaluated the significance of the difference in least square means estimates between specific groups of preceding rotation phases. The contrast groups included CONV vs. CONS management which was confined to preceding 3- and 4-CONV (7 phases) vs. 3- and 4-CONS (7 phases), i.e., only rotations of the same length were compared, considering the absence of 5- and 6-CONV rotations to match 5- and 6-CONS. There were also contrast groups of shorter vs. longer rotations (i) using CONS rotations only (18 preceding 3-, 4-. 5-, and 6-CONS phases), or (ii) confined to preceding phases which grew wheat in 2011, where contrasts between an ultimate ‘short’ rotation (continuous or monoculture wheat, 1-CONT phase) vs. wheat grown in longer 3–4-CONV (2 phases), or 3–5-CONS (4 phases) rotations were possible. Omitting 3 phases in 6-CONS (1 oat, 2 timothy), left 4 preceding crops across 23 preceding rotation phases: 6 phases each of dry bean and potato, 7 of wheat, and 4 of sugar beet (Table 1). This allowed $4(4-1)/2 = 6$ pairwise preceding crop contrasts (preceding crop *x* vs. preceding crop *y*, 2011) across management and rotations.

Lastly, to explore a potential ‘legume effect’, contrasts of shorter vs. longer intervals since previous legume were performed. The fully-phased experimental design of the 12-yr study meant that in the bioassay year (2012), a previous legume (dry bean) was grown on 6 rotation phases in each of 2011 (1 yr interval), 2010 (2 yr interval), and 2009 (3 yr interval). Four phases grew a previous legume in 2008 (4 yr interval), 2 phases in 2007 (5 yr interval), 1 phase in 2006 (6 yr interval), while 1 phase (continuous wheat, 1-CONT) had last grown a legume pre-1999 (>13 yr interval). For ease of interpretation, phases were pooled to provide contrast groups of 1 vs. ≥2 yr, and ≤2 vs. ≥3 yr intervals since previous legume.

3. | RESULTS AND DISCUSSION

3.1 | Bioassay growing conditions

Overall, the 2012 growing season (1 April–30 September) was very similar to the 30-yr (1981–2010) normal, with 268 mm of precipitation (normal, 265 mm), and 14.3 °C mean air temperature (normal, 14.0 °C). However, May–June was 39 mm wetter and 0.6 °C cooler than normal. Although plots following 2011 wheat received a pre-seeding application of glyphosate (11 May) to control early volunteer wheat, the wetter and cooler May–June favoured emergence of a second flush after dry bean seeding. While sethoxydim (25 June) inhibited volunteer wheat competition, visual inspection indicated reduced dry bean growth on the subset of plots following 2011 wheat.

The wetter cooler May–June also meant that an initial irrigation was not required until 12 July. On the 4-CONV and 4-CONS rotations, the 0–100 cm soil layer remained at >60 % of PAW (data not shown) for the entire growing season, indicating that water stress was not an issue (Alberta Agriculture and Forestry 2016). Also, there were no significant differences in PAW (data not shown) for 2012 dry bean previously under CONV vs. CONS management (2000–11), or different preceding crops (dry bean, potato, wheat or sugar beet, 2011).

3.2 | Preceding rotation phase

Dry bean plant density, plant height, days to maturity, yield, and incidence of white mold in 2012 were significantly affected (P <0.05) by preceding rotation phase in 2011 (Figure 1). Density varied from 26 plants m^{-2} following 6-CONS sugar beet, to 37 plants m^{-2} following 6-CONS dry bean (Figure 1a), while plant height ranged from 41 cm following 3-CONV wheat to 51 cm following 3-CONV dry bean (Figure 1b). There was a 5-d dry bean maturity gap between the earliest and latest preceding rotation phases: 4-CONS wheat, 96 d; and 3-CONV dry bean, 4-CONV potato; 101 d (Figure 1c). Dry bean yield ranged from 1884 kg ha^{-1} following 5-CONS $wheat_1$ to 3136 kg ha^{-1} following 3-CONV dry bean (Figure 1d). The average yield of the bioassay was 2547 kg ha^{-1}. Plant height, DTM, and yield in 2012 fell close to average values for narrow-row dry bean in the prior 2000–11 study (Larney et al., 2015).

Fungicide efficacy and environmental conditions led to low white mold pressure on bioassay dry bean, with incidences ranging from zero after 3-CONV wheat, to 4.4% after 4-CONS potato (Figure 1e), and averaging only 1.5%, compared to 19% on narrow-row dry bean during the 2000–11 study (Larney et al., 2015). The preceding rotation phase effect on bacterial blight incidence (Figure 1f) was non-significant ($P = 0.52$), with rankings ranging from 1. to 2.8 (1 ranking = <1%; 2 = 1–10%; 3 = 11–25% incidence). The average ranking was 2 (1–10% incidence), identical to that for narrow-row dry bean in the 12-yr study (Larney et al., 2015).

Soil MBC is a living C fraction and estimate of soil biological activity, while β-glucosidase plays a key role in the hydrolysis and biodegradation of cellulose, and therefore C cycling (Lupwayi et al., 2017). In the 2012 dry bean rhizosphere, preceding rotation phase was significant for MBC ($P = 0.07$, Figure 2a) and β-glucosidase (<0.001, Figure 2c). Both soil health indicators were highest following CONS dry bean, with MBC of 674 mg C kg^{-1} soil on 5-CONS (Figure 2a) and β-glucosidase of 251 mg nitrophenol kg^{-1} soil h^{-1} on 3-CONS (Figure 2c). Both indicators were lowest following 3-CONV potato, with MBC of 394 mg C kg^{-1} soil (Figure 2a); and β-glucosidase of 106 mg nitrophenol kg^{-1} soil h^{-1} (Figure 2c). Larney, Pearson, et al. (2016) reported that averaged over 12 yr (2000–11), potato on the 3-CONV rotation resulted in 16% lower marketable tuber yield than the 5-CONS rotation.

In bulk soil, preceding rotation phase was non-significant (*P* = 0.39, Figure 2b) for MBC, but highly significant (*P* = <0.001) for β-glucosidase (Figure 2d), which was highest (250 mg nitrophenol kg^{-1} soil h^{-1}) following 5-CONS $wheat_2$, and lowest (115 mg nitrophenol kg^{-1} soil h^{-1}) following 4-CONV dry bean.

3.3 | Soil management

All CONV vs. CONS contrasts for dry bean plant density, height, and yield were non-significant (Table 2). Only 1 of 18 (3 CONV vs. CONS contrasts × 6 parameters) possible soil management (2000–11) contrasts was significant: 1 d significantly earlier maturity (99 vs. 100 d) following 4-CONS than 4-CONV rotations (Table 2). Organic amendments, such as compost applied under CONS management in this study, have been shown to control pathogens (*Sclerotinia* spp., *Pythium* spp., *Verticillium dahliae*, *Fusarium* spp., *Phytophthora* spp.) responsible for wilting, damping-off or necrosis in agricultural and horticultural crops (Bonamoni, Antignani, Pane, & Scala, 2007; Termorshuizen et al., 2007). However, soil management was non-significant for white mold and bacterial blight incidence on the dry bean bioassay (Table 2). A growing season with higher white mold pressure than 2012 may have elicited differences.

Of the 6 (3 contrasts × 2 parameters) possible soil management contrasts for MBC in 2012 dry bean rhizosphere or bulk soil, all but one showed significantly greater (by 66–97 mg C kg^{-1} soil; or 14–22%) values following CONS management (Table 3). All 6 possible contrasts were significant for β-glucosidase activity, which was 54–96 mg nitrophenol kg^{-1} soil h^{-1} (36–78%) greater following CONS management. This was in stark contrast to the imperceptible legacy effect of CONS management on dry bean bioassay parameters.

Positive relationships between soil health and crop yield have been reported (Nunes, van Es, Schindelbeck, Ristow & Ryan, 2018). Silva, Babujia, Franchini, Souza, and Hungria (2010) found that MBC was consistently higher under no-till than conventional tillage and associated with higher corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) yields. Soil health metrics linked to labile organic matter correlated well with corn and soybean yields from long-term experiments in North Carolina (van Es & Karlen, 2019).

However, not all relationships between soil health and crop yield have been as conclusive. In the 12-yr study that ran prior to the bioassay, Lupwayi et al. (2018) found quadratic responses showing that MBC >720 mg C kg^{-1} (69% of maximum yield) in wheat rhizosphere soil, or >645 mg C kg^{-1} (66% of maximum yield) in bulk soil, did not elicit further wheat yield increases. On the Canadian prairies, Lupwayi et al. (2015) found that relationships for soil MBC and β-glucosidase activity with canola (*Brassica napus* L.) were regulated by yield magnitude, correlating positively with <4 Mg ha^{-1} yields, but showing no or weak negative correlations with >4 Mg ha^{-1} yields. In southern Alberta, Zvomuya et al. (2008) reported a linear-plateau response of cumulative biomass yield to SOC, with the inflection point at 20 g kg^{-1} SOC. Oldfield, Wood, and Bradford (2020) also found that higher concentrations of SOC led to greater aboveground biomass up to a threshold, after which productivity declined, while indicators of soil health continued to increase linearly with increasing SOC.

While the above findings point to the non-linearity of relationships between specific soil health indicators and crop yield, Roper, Osmond, Heitman, Wagger, and Reberg-Horton (2017) found no correlation between broader soil health tests (i.e., Haney, Cornell) and crop yields in North Carolina. Schmidt, Bowles, and Gaudin (2016) postulated that the lack of correlation between soil health and crop yield was due to the transition from wild ecosystems to modern agriculture, which selected traits that promoted aboveground biomass with more sophisticated crop management and increased nutrient inputs. Hence, root morphology, anatomy, and ecophysiological processes may have undergone substantial genetic and environmental shifts, and traits allowing more efficient foraging and uptake, especially in lower synthetic input environments, may have been lost.

3.4 | Rotation length

Enhancing crop diversity, or the number of species in a rotation, can reduce yield variability resulting from extreme weather, thus increasing total crop production (Gaudin et al., 2015). Extended rotations provide increased opportunities for crop diversity (Smith, Gross, & Robertson, 2008). In our study, the 3-yr rotations had 3 crop species, the 4- and 5-yr rotations had 4 species, while the 6-yr rotation had 5 species. However, increased crop diversity led to reduced crop frequency, e.g., both dry bean and potato frequencies fell from 33% in 3-yr rotations, to 25% in 4-yr rotations, 20% in the 5-yr rotation, and 16.7% in the 6-yr rotation.

Rotation length (shorter vs. longer CONS rotations) in the 2000–11 study was significant for dry bean plant height in the 2012 bioassay, with longer rotations 2–3 cm taller in four comparisons (Table 2). Rotation length was non-significant for dry bean plant density, DTM, yield, white mold or bacterial blight (Table 2). Previous findings have shown that rotational diversity decreased disease pressures (Bailey, Gossen, Lafond, Watson, & Derksen, 2001). However, low levels of white mold in 2012 may have masked the true nature of the rotation length effect.

Days to maturity of dry bean following 12 yr of monoculture wheat (1-CONT) was 2 d significantly earlier than dry bean following 3–4-CONV wheat (96 vs. 98 d). White mold incidence on dry bean was significantly higher following monoculture wheat, by 2.6 percentage points vs. 3- and 4-CONV wheat, and by 2.2 percentage points vs. 3–5-CONS wheat (Table 2). Additionally, the bacterial blight ranking was significantly higher (by 0.6) following monoculture vs. 3–5-CONS wheat (Table 2). These disease trends on dry bean following monoculture wheat agreed with Larney, Pearson, Blackshaw, Lupwayi, & Conner (2018) who reported significantly greater take-all [*Gaeumannomyces graminis* (Sacc.) Arx & Olivier var. *tritici* Walker] incidence in monoculture wheat vs. wheat rotated with dry bean, potato or sugar beet, in 7 of 12 yr in the preceding study (2000–11). Maturity and disease incidence were the only dry bean parameters showing legacies of monoculture wheat, others, including yield, being non-significant (Table 2).

Rotation length (shorter vs. longer CONS rotations, 2000–11) was non-significant for 2012 dry bean rhizosphere MBC (Table 3). However, 3 of 6 contrasts showed shorter rotations led to significantly greater (by 62–88 mg C kg^{-1} soil, or 12–17%) MBC in bulk soil (Table 3). In addition, shorter rotations elicited significantly greater β-glucosidase activity for 2 of 6 contrasts (by 19–34 mg nitrophenol kg^{-1} soil h^{-1}, or 10–18%) in dry bean rhizosphere soil, and for 5 of 6 contrasts (by 16–41 mg nitrophenol kg^{-1} soil h^{-1}, or 8–23%) in bulk soil [Table 3]. These findings suggest an inverse relationship between the number of rotation cycles and the magnitude of MBC and β-glucosidase activity. The shorter 3- and 4-CONS rotations cycled more rapidly, completing 3–4 cycles over the 12-yr duration of the study, compared to 2–2.4 cycles for the 5- and 6-CONS rotations (Table 1). A corollary of this rationale, is the combined frequency of the three row crops (dry bean, potato and sugar beet) in the prior 12-yr rotation: 66–75% frequency in shorter 3–4-CONS rotations vs. 50–60% in longer 5–6-CONS rotations. Under CONS management, the higher combined frequency of row crops in shorter rotations, and concomitant diversity of such systems, supported higher levels of soil health indicators such as MBC and β-glucosidase activity.

There was no significant difference between prior monoculture wheat and CONS rotations (2000–11) for either MBC or β-glucosidase in 2012 dry bean rhizosphere or bulk soil (Table 3). Lupwayi, Larney, Blackshaw, Kanashiro, and Pearson (2017) reported similar findings from 2011 (end of 12-yr rotation) that were attributed to substantial C inputs (Li et al., 2015) from monoculture wheat over the 12-yr timeline, and proved as effective as compost C inputs in sustaining C cycling and hence β-glucosidase activity in CONS rotations. However, monoculture wheat led to 71–79 mg nitrophenol kg^{-1} soil h^{-1}, or 52–56% greater β-glucosidase than prior CONV rotations (Table 3) in rhizosphere and bulk soil. This finding also agreed with Lupwayi et al. (2017), pointing to greater C inputs with monoculture wheat (100% wheat frequency) than 3-CONV (33% wheat frequency), or 4-CONV (25% wheat frequency), which did not receive supplemental C inputs from compost. Similarly, Lupwayi, Lafond, May, Holzapfel, and Lemke (2012) reported that wheat grown after field pea (*Pisum sativum* L.) in a 3-yr pea–wheat–wheat rotation (66% wheat frequency) had greater β-glucosidase activity than that in a 2-yr pea–wheat rotation (50% wheat frequency), in the last 3 yr of a 13-yr field study in Saskatchewan. In southern Ontario, Agomoh et al. (2020) reported that soil health indicators were significantly greater for monoculture winter wheat than winter wheat grown in 2- or 3-yr rotations.

3.5 | Preceding crop (2011)

The experimental design allowed 6 pairwise preceding crop (2011) comparisons (across management and rotation treatments) on 2012 dry bean bioassay parameters (Table 2). Plant density of 2012 dry bean was significantly higher following 2011 wheat vs. dry bean (by 2 plants m^{-2}), or following potato or wheat vs. sugar beet (by 3–4 plants m^{-2}, Table 2). This demonstrated that volunteer wheat following 2011 wheat did not interfere with initial dry bean plant stand in 2012. For plant height, dry bean following wheat was 4 cm shorter than following all other crops (Table 1). This translated into significantly earlier maturity (2 d), and lower yields (445–736 kg ha^{-1}, or 21–35%) [Table 1], for these same comparisons. The poorer performance of dry bean following wheat was largely explained by competition from volunteer wheat. In rotation studies, a distinction is made between crop identity (i.e., current or preceding crop) and temporal cropping system diversification (i.e., crop rotation length) [Meyer, Ott, Götze, Koch, & Scherber, 2019]. In our study, the preceding crop identity exerted as large an influence on the bioassay as overall rotation length, as exemplified by the magnitude of the volunteer wheat issue. Volunteer wheat may also have caused soil fertility issues for dry bean following wheat. Larney et al. (2017a) reported that in fall 2011, rotation and management effects on NO_3-N (0–60 cm depth) were non-significant. However the preceding crop (2011) effect was significant, with wheat (29 kg ha^{-1}) and sugar beet (13 kg ha^{-1}) showing significantly lower NO_3-N than dry bean and potato (61–71 kg ha^{-1}), reflecting deeper rooting and hence greater NO_3-N extraction. Therefore the lower initial soil NO_3-N, coupled with further extraction by volunteer wheat, may have reduced NO_3-N for dry bean following wheat in 2012.

However, dry bean following wheat (0.7%) showed significantly lower (1.2–1.3 percentage points, Table 1) white mold incidence than following dry bean or potato (1.9–2%). Additionally, dry bean following wheat showed significantly lower incidence (0.5 ranking) of bacterial blight than following potato. Miklas, Porter, Kelly, and Myers (2013) reported that greater plant biomass creates denser canopies with less capacity for disease avoidance. This may explain why lower-yielding and less-dense dry bean canopies following wheat showed greater disease avoidance than greater biomass and denser canopies following crops other than wheat.

Dry bean following dry bean was also significantly higher-yielding (292 kg ha^{-1} or 11%) than dry bean following sugar beet (Table 1), even though the benefits of crop rotation compared to monoculture are well documented (Lafond & Harker, 2012). While continuous dry bean is not generally practiced, data for continuous soybean may act as a proxy. Seifert, Roberts, and Lobell (2017) found that soybean yield penalties increased with duration of continuous cropping, from 7.5% for soybean following soybean, to 15% with 5 yr of continuous soybean. However, they also reported that disease pressure was the primary cause of yield penalties. Since the 2012 growing season exhibited low disease pressure, the potential yield penalty for dry bean on dry bean may have been diminished. In addition, the lower yield following sugar beet may have been due to greater root rot (*Rhizoctonia solani*) carryover from sugar beet to dry bean since both crops are hosts (Engelkes & Windels, 1996). In addition, dry bean following dry bean also reduced bacterial blight (0.3 ranking) compared to following potato (Table 1).

In 2012 dry bean rhizosphere soil, MBC following 2011 dry bean or sugar beet was significantly higher (by 55–57 mg C kg^{-1} soil, or 11%) than following 2011 potato (Table 3). However, MBC in bulk soil was significantly higher (by 55 mg C kg^{-1} soil, or 11%) following wheat vs. dry bean. Wheat as a preceding crop in 2011 significantly increased (by 28–33 mg nitrophenol kg^{-1} soil h^{-1}, or 16–19%) β-glucosidase activity compared to dry bean or potato for rhizosphere soil, and compared to dry bean, potato, or sugar beet for bulk soil (by 25–40 mg nitrophenol kg^{-1} soil h^{-1}, or 14–24%). In the 12-yr study, Li et al. (2015) reported mean annual C returns from wheat of 4.6 Mg ha^{-1} vs. 2.3 Mg ha^{-1} for potato, 1.7 Mg ha^{-1} for sugar beet, and only 1.1 Mg ha^{-1} for dry bean. Therefore, greater C returns to soil by wheat, boosted microbial activity and hence MBC, and provided a C-rich substrate for enhanced β-glucosidase enzyme activity. In addition, Lupwayi et al. (2017) found significant correlations between cumulative C inputs (crop residue, compost) and soil MBC and β-glucosidase activity at the end of the 12-yr study.

3.6. | Interval since previous legume

The 1 vs. ≤2 yr since contrast for interval since previous legume ostensibly compared dry bean on dry bean with all other treatments (Table 2), and showed that back-to-back dry bean led to significant effects of 1-cm taller plants, 1-d later maturity, and 407 kg ha^{-1} (17%) higher yield, with no effect on disease incidence. Similarly, ≤2 yr since previous legume, resulted in 1-d later maturity, 318 kg ha^{-1} (13%) higher yield, and higher incidence of white mold (0.7 percentage points), than a longer gap of ≥3 yr. The higher white mold was likely related to higher yield, and hence a denser canopy and lower disease avoidance as outlined above. Enhanced bioassay yields with shorter intervals since previous legume point to the well-documented 'legume effect', related to biological N fixation and improved N cycling when legumes/pulses are included in rotations (Xie, Schoenau, & Warkentin, 2018). Our study demonstrated that the legume effect was evident for at least 2 yr. Grant et al. (2016) showed few effects of field pea, lentil (*Lens culinaris* Medik.), or faba bean (*Vicia faba* L.) on soil NO_3-N supply, crop yield or N accumulation of wheat after 4 yr, and no effects on canola after 5 yr on the Canadian prairies.

Interval since previous legume had no significant effect on dry bean rhizosphere or bulk soil MBC in 2012 (Table 3). However, increasing the interval from 1 to ≥2 yr, led to significantly greater β-glucosidase activity (by 14–21 mg nitrophenol kg^{-1} soil h^{-1}, or 8–13%) in rhizosphere and bulk soil (Table 3). Increasing the interval from ≤2 to ≥3 yr also enhanced activity in bulk soil (by 18 mg nitrophenol kg^{-1} soil h^{-1}, or 11%) [Table 3]. The mechanism of greater C returns to soil, outlined above, likely explained greater β-glucosidase activity as interval since previous legume (lowest annual C input from dry bean, 1.1 Mg ha^{-1}, Li et al., 2015) increased.

4 | SUMMARY AND CONCLUSIONS

Despite the numerous benefits of CONS management reported in the 12-yr (2000–11) irrigated systems study, and corroborated by soil health indicators in 2012, the post-hoc dry bean bioassay largely failed to elicit a response to CONS management. While much recent research has been devoted to the importance of soil health in agroecosystems, transferring superior soil health into positive yield responses has often proved elusive, perhaps because the relationships are complex and often non-linear. In retrospect, a different bioassay crop than dry bean in 2012, or second, or even third successive bioassays in 2013 and 2014, may have teased out yield responses to CONS management, more in line with concomitant soil health benefits. However, this was not feasible within the funding envelope. Moreover, the magnitude of legacy effects of the main study (2000–11) may be expected to diminish with time, such that bioassays conducted two, three or more years since the completion of the main study, may provide limited findings.

The only significant response to longer and more diverse CONS rotations on the bioassay was increased dry bean plant height but this did not translate into yield. Somewhat unexpectedly, shorter CONS rotation led to higher MBC and β-glucosidase activity. This was attributed to the greater number of rotation cycles accrued (3–4 vs. 2–2.4), and greater frequency (and concomitant diversity) of the three row crops (66–75 vs. 50–60%) in shorter vs. longer rotations in the prior 12-yr study. Legacies of monoculture wheat included earlier maturity and increased white mold and bacterial blight incidence of bioassay dry bean. However, monoculture wheat increased β-glucosidase activity in bioassay rhizosphere and bulk soil by >50%, compared to prior CONV rotations, which was attributed to greater cumulative C inputs in the prior rotation study (2000–11).

The legacy effect of preceding crop was amply demonstrated by the volunteer wheat issue, which reduced bioassay dry bean yield. However, wheat as a preceding crop elicited significant positive benefits on microbial soil health indicators, MBC and β-glucosidase activity, compared to other preceding crops (dry bean, potato, sugar beet), which was again attributed to higher C inputs by wheat. The bioassay was also sensitive to interval since previous legume, and demonstrated a positive 'legume effect" on yield that persisted for at least 2 yr.

Legacy effects implicitly recognize the influence of past soil management practices and their persistence into the future, often continuing beyond some expected or perceived temporal endpoint. While a dry bean field bioassay provided an opportunity for assessing legacy effects of a 12-yr cropping systems study, some proved more intangible (e.g., CONV vs. CONS management) than others (e.g., interval since previous legume).

ACKNOWLEDGEMENTS

We thank Jim Sukeroff, Dale Reynolds, Vauxhall Sub-station staff, and summer student Julie Pepneck for field assistance. Scott Erickson conducted dry bean disease ratings. Funding was provided by the Alberta Pulse Growers, the Potato Growers of Alberta, Lantic Inc., the Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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TABLE 1. Outline of rotation treatments over 12 yr (2000-11), Vauxhall, Alberta.

Rotation[a]	Phases	No. phases	No. rotation cycles[b]
1-CONT	Wheat	1	12
3-CONV	Dry bean–wheat–potato	3	4
3-CONS	Dry bean[c]–wheat[d]–potato[c]	3	4
4-CONV	Dry bean–potato–wheat–sugar beet	4	3
4-CONS	Dry bean[d]–potato[c]–wheat–sugar beet	4	3
5-CONS	Dry bean[d]–potato[c]–wheat$_1$–sugar beet[d]–wheat$_2$	5	2.4
6-CONS	Dry bean[d]–potato[c]–oat/(timothy)[e]–timothy–timothy–sugar beet	6	2
	Total	26	

[a]Integer refers to length of rotation; CONT, continuous; CONV, conventional management; CONS, conservation management.

[b]No. rotation cycles = 12 (yr)/no. crop phases.

[c]Fall-seeded cover crop entry point: fall rye (*Secale cereale* L.), except oat, 2000-02, on 3-CONS (between dry bean and wheat), and 4-, 5-, and 6-CONS.

[d]Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-CONS, 5-CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-CONS, 5-CONS after dry bean, 6-CONS) applied after harvest.

[e]Oat harvested as silage in July, timothy direct seeded in late August.

TABLE 2. Management, rotation length, preceding crop, and interval since previous legume contrasts on dry bean plant density, plant height, days to maturity, yield, white mold, and bacterial blight incidence, 2012.

Contrast (Group 1 vs. 2)	No. of phases	Estimate[a]					
		Plant density, m^{-2}	Plant height, cm	Days to maturity	Yield, kg ha^{-1}	White mold, pp[b]	Bacterial blight, ranking
CONV vs. CONS management, 2000–11							
3–4-CONV vs. 3–4-CONS	7 vs. 7	0^{ns}	-1^{ns}	1^{ns}	-28^{ns}	-0.3^{ns}	0^{ns}
3-CONV vs. 3-CONS	3 vs. 3	-1^{ns}	0^{ns}	$<0^{ns}$	-28^{ns}	0.1^{ns}	0^{ns}
4-CONV vs. 4-CONS	4 vs. 4	1^{ns}	-1^{ns}	1**	-27^{ns}	-0.5^{ns}	0^{ns}
Shorter vs. longer rotations, 2000–11							
CONS rotations only							
3–4- vs. 5–6-CONS	7 vs. 11	0^{ns}	−2**	0^{ns}	-39^{ns}	0.1^{ns}	-0.1^{ns}
3- vs. 4–6-CONS	3 vs. 15	1^{ns}	−2*	0^{ns}	-124^{ns}	-0.8^{ns}	-0.2^{ns}
3- vs. 5–6-CONS	3 vs. 11	0^{ns}	−2**	0^{ns}	-118^{ns}	-0.7^{ns}	-0.2^{ns}
3- vs. 6-CONS	3 vs. 6	0^{ns}	−3**	0^{ns}	-207^{ns}	-0.7^{ns}	-0.3^{ns}
4- vs. 5–6-CONS	4 vs. 11	-1^{ns}	-1^{ns}	0^{ns}	21^{ns}	0.6^{ns}	-0.1^{ns}
4- vs. 6-CONS	4 vs. 6	-1^{ns}	-2^{ns}	0^{ns}	-68^{ns}	0.6^{ns}	-0.2^{ns}
Wheat phases, 2011							
1-CONT vs. 3–4-CONV	1 vs. 2	-2^{ns}	3^{ns}	−2*	-171^{ns}	2.6**	0.3^{ns}
1-CONT vs. 3–5-CONS	1 vs. 4	-4^{ns}	1^{ns}	-1^{ns}	25^{ns}	2.2**	0.6*
Preceding crop *x* vs. preceding crop *y*, 2011							
Dry bean vs. potato	6 vs. 6	-1^{ns}	0^{ns}	0^{ns}	196^{ns}	-0.1^{ns}	−0.3*
Dry bean vs. wheat	6 vs. 7	−2*	4***	2***	736***	1.2***	0.1^{ns}
Dry bean vs. sugar beet	6 vs. 4	2^{ns}	0^{ns}	1^{ns}	292*	0.7^{ns}	-0.1^{ns}
Potato vs. wheat	6 vs. 7	-1^{ns}	4***	2***	540***	1.3***	0.5**
Potato vs. sugar beet	6 vs. 4	3**	0^{ns}	0^{ns}	96^{ns}	0.8^{ns}	0.2^{ns}
Wheat vs. sugar beet	7 vs. 4	4***	−4***	−2***	−445***	-0.6^{ns}	-0.2^{ns}
Shorter vs. longer interval since previous legume							
1 vs. ≥2 yr	6 vs. 20	-1^{ns}	1*	1**	407***	0.5^{ns}	-0.1^{ns}
≤2 vs. ≥3 yr	12 vs.	0^{ns}	1^{ns}	1***	318***	0.7**	0.1^{ns}

*, **, ***: significant difference at P <0.10, P <0.05, and P <0.01, respectively; ns, non-significant (P >0.10).
[a]Positive estimate indicates group 1 > group 2; negative estimate indicates group 1 < group 2.
[b]percentage points.

TABLE 3. Management, rotation length, preceding crop, and years since previous dry bean contrasts on soil microbial biomass C (MBC) and β-glucosidase activity, in dry bean rhizosphere and bulk soil, 2012.

Contrast (Group 1 vs. 2)	No. of phases	Estimate[a]			
		Microbial biomass C, mg C kg^{-1} soil		β-glucosidase, mg nitrophenol kg^{-1} soil h^{-1}	
		Rhizosphere	Bulk	Rhizosphere	Bulk
CONV vs. CONS management, 2000–11					
3–4-CONV vs. 3–4-CONS	7 vs. 7	−66**	−81**	−72***	−78***
3-CONV vs. 3-CONS	3 vs. 3	−95**	−97**	−96***	−86***
4-CONV vs. 4-CONS	4 vs. 4	−44^{ns}	−69*	−54***	−71***
Shorter vs. longer rotations, 2000–11					
CONS rotations only					
3–4- vs. 5–6-CONS	7 vs. 11	−10^{ns}	36^{ns}	11^{ns}	16*
3- vs. 4–6-CONS	3 vs. 15	−14^{ns}	62*	18^{ns}	21*
3- vs. 5–6-CONS	3 vs. 11	−15^{ns}	66*	19*	23*
3- vs. 6-CONS	3 vs. 6	7^{ns}	88**	34**	41***
4- vs. 5–6-CONS	4 vs. 11	−6^{ns}	14^{ns}	4^{ns}	10^{ns}
4- vs. 6-CONS	4 vs. 6	17^{ns}	36^{ns}	19^{ns}	27**
Wheat phases, 2011					
1-CONT vs. 3–4-CONV	1 vs. 2	87^{ns}	60^{ns}	79***	71***
1-CONT vs. 3–5-CONS	1 vs. 4	−18^{ns}	−72^{ns}	−13^{ns}	−27^{ns}
Preceding crop *x* vs. preceding crop *y*, 2011					
Dry bean vs. potato	6 vs. 6	55*	−23^{ns}	4^{ns}	−3^{ns}
Dry bean vs. wheat	6 vs. 7	14^{ns}	−55*	−28***	−40***
Dry bean vs. sugar beet	6 vs. 4	−3^{ns}	−36^{ns}	−14^{ns}	−15^{ns}
Potato vs. wheat	6 vs. 7	−41^{ns}	−32^{ns}	−33***	−37***
Potato vs. sugar beet	6 vs. 4	−57*	−13^{ns}	−18^{ns}	−12^{ns}
Wheat vs. sugar beet	7 vs. 4	−16^{ns}	19^{ns}	14^{ns}	25**
Shorter vs. longer interval since previous legume					
1 vs. ≥2 yr	6 vs. 20	25^{ns}	−32^{ns}	−14*	−21**
≤2 vs. ≥3 yr	12 vs. 14	−5^{ns}	−14^{ns}	−10^{ns}	−18**

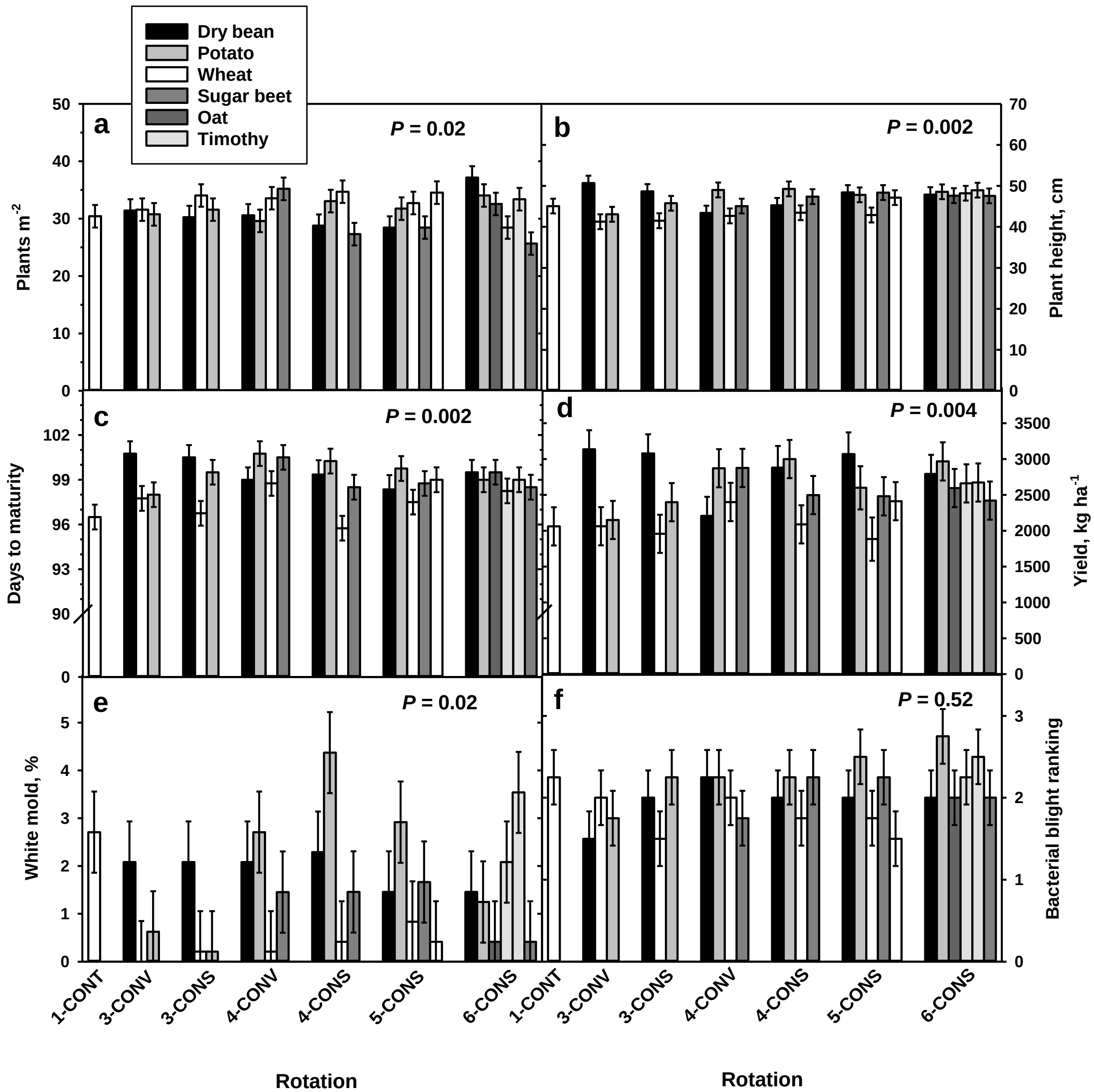
*, **, ***: significant difference at P <0.10, P <0.05, and P <0.01, respectively; ns, non-significant (P >0.10).

[a]Positive estimate indicates group 1 > group 2; negative estimate indicates group 1 < group 2.

Figure captions

Figure 1. Effect of preceding rotation phase (2011) on dry bean (a) plant density; (b) plant height; (c) days to maturity; (d) yield; (e) white mold incidence; and (f) bacterial blight incidence, 2012. Error bars represent standard errors of the means.

Figure 2. Effect of preceding rotation phase (2011) on microbial biomass C of (a) dry bean rhizosphere soil; (b) bulk soil; and β-glucosidase activity of (c) dry bean rhizosphere soil; (d) bulk soil, 2012. Error bars represent standard errors of the means.



Dry bean
Potato
Wheat
Sugar beet
Oat
Timothy
a
P = 0.02
b
P = 0.002
c
P = 0.002
d
P = 0.004
e
P = 0.02
f
P = 0.52
Plants m-2
Plant height, cm
Days to maturity
Yield, kg ha-1
White mold, %
Bacterial blight ranking
1-CONT
3-CONV
3-CONS
4-CONV
4-CONS
5-CONS
6-CONS
Rotation

Figure 1.

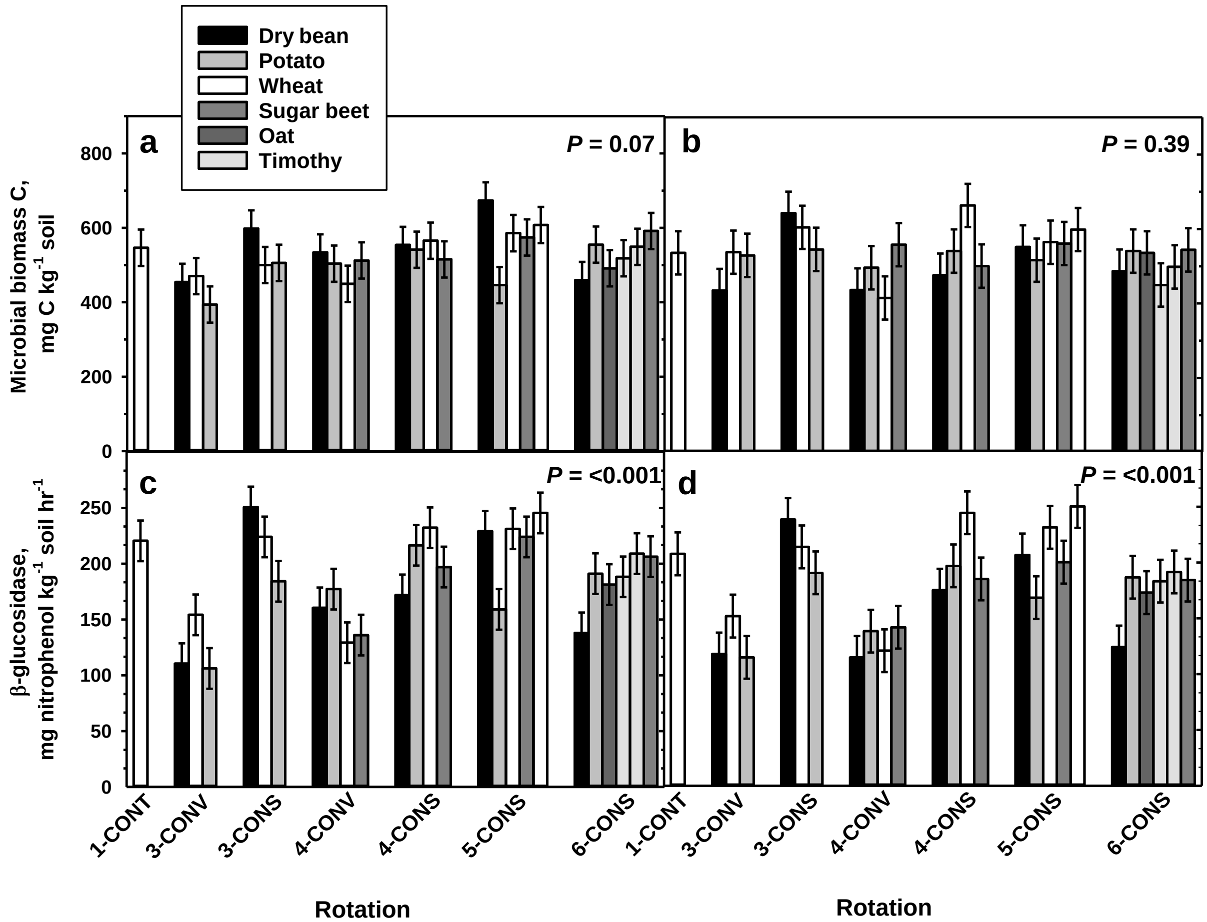

Dry bean
Potato
Wheat
Sugar beet
Oat
Timothy
a
P = 0.07
b
P = 0.39
c
P = <0.001
d
P = <0.001
Microbial biomass C, mg C kg-1 soil
β-glucosidase, mg nitrophenol kg-1 soil hr-1
1-CONT
3-CONV
3-CONS
4-CONV
4-CONS
5-CONS
6-CONS
Rotation

Figure 2.

Published May 29, 2015

Surface Soil Quality Attributes following 12 Years of Conventional and Conservation Management on Irrigated Rotations in Southern Alberta

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Rapid expansion of irrigated row crop production, viz., potato (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), and sugar beet (*Beta vulgaris* L.), in southern Alberta in the late 1990s provided the impetus for a 12-yr (2000–2011) study to evaluate cropping systems that maintained or improved soil quality. The study compared conservation (CONS) and conventional (CONV) management in rotations of 3- to 6-yr duration. Conservation management included reduced tillage, cover crops, feedlot manure compost addition, and solid-seeded narrow-row dry bean production. After 12 yr, particulate organic matter C (POM-C) and N (POM-N) showed >145% increases (POM-C, 2.2–5.8 Mg ha^{-1}; POM-N, 0.20–0.49 Mg ha^{-1}) with CONS management compared with 45 to 50% increases in total organic C and N (TOC, 10.2–15.3 Mg ha^{-1}; TN, 1.06–1.53 Mg ha^{-1}) and 20% increases in fine organic matter (FOM)-C and -N (FOM-C, 8.3–10.1 Mg ha^{-1}; FOM-N, 0.87–1.04 Mg ha^{-1}). Aggregate stability of the pre-wet >1-mm fraction increased significantly from 13% under CONV to 21% under CONS management. Overall, the 5-yr CONS rotation (sugar beet–wheat (*Triticum aestivum* L.)–dry bean–potato–wheat) ranked highest for soil quality (100%), with CONV rotations substantially lower (33–38%). Adoption of CONS management enhanced a wide range of soil quality attributes that could safeguard sustainable expansion of irrigated specialty cropping in southern Alberta.

Abbreviations: AS, aggregate stability; CONS, conservation; CONT, continuous wheat; CONV, conventional; FOM, fine organic matter; MBC, microbial biomass carbon; MBCQ, microbial biomass carbon quotient; SOC, soil organic carbon; SOM, soil organic matter; POM, particulate organic matter; TC, total carbon; TN, total nitrogen; TOC, total organic carbon.

The irrigated land area in southern Alberta's irrigation districts climbed steadily from 280,000 ha in the early 1970s to 560,000 ha in 2013 (Alberta Agriculture and Rural Development, 2014). In 2012, specialty crops (mainly potato, sugar beet, and dry bean) accounted for 18% of the irrigated land area, with 32% of the remainder in forages, 31% in cereals, and 14% in oilseeds. Specialty crops provide diversification of the local agricultural economy in terms of value-added food processing; however, they produce less crop residue biomass, which may compromise soil organic matter (SOM) if they replace forages or cereals in rotations. Potato in particular is recognized as being "hard on the soil." In eastern Canada, conventional potato production has been linked to high erosion rates, soil compaction, and high soil test P due to intensive land preparation and lack of rotation (Boiteau et al., 2014). Rees et al. (2007) reported an 8% decline in

Soil Sci. Soc. Am. J. 79:930–942
doi:10.2136/sssaj2015.02.0051
Received 3 Feb. 2015.
Accepted 25 Mar. 2015.
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soil organic C (SOC) during 10 yr of intensive potato production in New Brunswick.

This combination of issues motivated the establishment of a rotation study in 2000 with a focus on conservation (CONS) management and maintenance of soil quality on irrigated land. By the late 1990s, zero or reduced tillage had been widely adopted in dryland rotations on the Canadian prairies, leading to increased SOM and reduced erosion risk (Larney et al., 1994b). However, adoption on irrigated land was limited, mainly due to the type of crops grown. Potato and sugar beet respond to cultivated seedbeds and, being root crops, harvest operations cause major soil disturbance, not in keeping with zero tillage. However, zero tillage is feasible for dry bean, wheat, or forages grown in rotations with potato or sugar beet.

Cover crops are important components of sustainable cropping systems (Dabney et al., 2001). They provide surface cover during the vulnerable wind erosion period, which on irrigated land in southern Alberta can extend from potato harvest (mid-September) to dry bean seeding some 8 mo later (mid-May). They also act as a source of soil fertility, suppress weeds and pests (Moyer and Blackshaw, 2009), and scavenge soil NO_3–N remaining after harvest, reducing the risk of leaching to groundwater (Ball-Coelho et al., 2004). Because irrigation mitigates competition for water with the main crop, Snapp et al. (2005) indicated significant niches within irrigated cropping systems where cover crops are beneficial. They found fall-seeded rye (*Secale cereale* L.) to be most promising, producing 0.8 to 6 Mg ha^{-1} of biomass across all hardiness zones.

The use of organic amendments, such as livestock manure, is an integral part of conservation management (Larney et al., 2011). As well as adding N, P, and trace elements, manure organic matter improves soil physical properties such as water retention, aggregate stability (AS), and infiltration. This is especially relevant on lighter textured irrigated land where SOM may be depleted by intensive cultivation and lower amounts of crop residue returned to the soil (Grandy et al., 2002; Porter et al., 1999). By the late 1990s, composting had emerged as an alternative handling practice for the large volumes of manure produced by the beef cattle feedlot industry in southern Alberta (Larney et al., 2006), and irrigation farmers were interested in its potential for replenishing SOM and partially substituting for N and P fertilizer inputs.

In the late 1990s, solid-seeded narrow-row dry bean became an option on the Canadian prairies (Blackshaw et al., 1999; Shirtliffe and Johnston, 2002) as plant breeders selected for upright growth, early maturity, and improved pod clearance traits. Solid-seeded dry bean is planted with conventional grain drills in narrow rows (17.5–40 cm), thereby dispensing with interrow cultivation and hence reducing tillage intensity (Blackshaw et al., 2007). At harvest, they can be swathed or direct combined instead of undercut (leaving unanchored stubble), which provides standing stubble in narrow rows and hence some protection against wind erosion.

The development of CONS management, using practices as outlined above, requires knowledge of their impact on soil quality. There are many attributes encompassing a broad range of physical, chemical, and biological properties that can be used to assess soil quality (Bolinder et al., 1999; Li et al., 2011). Soil organic matter is often seen as the most important index of soil quality, encompassing fractions such as total, light fraction, POM, and mineralizable C and N, microbial biomass C (MBC), and soil carbohydrates and enzymes (Gregorich et al., 1994). The various fractions of SOM respond differently to management practices, with the more labile ones (POM, light fraction, and MBC) usually more sensitive than total C (Larney et al., 1997). As such, they are often used as early indicators of soil quality changes (Gregorich et al., 2006). Soil enzymes play an important role in nutrient cycling and are also indices of soil quality (García-Ruiz et al., 2008; He et al., 2010). Phosphatases have received considerable attention due to the importance of P in plant nutrition and the complex nature of soil organic P (Deng and Tabatabai, 1997; Parham et al., 2002). In addition, changes in aggregation have been linked to changes in soil quality related to crop species (Haynes and Beare, 1997), water infiltration (Franzluebbers, 2002), wind erodibility (Larney et al., 1994a), and organic amendments (Sun et al., 1995). Because feedlot manure compost is a relatively new organic amendment in southern Alberta, the response of different SOM fractions and AS to compost addition is not known for irrigated soils in the region. To a large extent, increased AS is triggered by decomposable organic matter (Angers and Carter, 1995), which may be low in mature compost (Annabi et al., 2007).

This study examined the impact of conventional (CONV) and conservation (CONS) rotations for the following crops: potato, sugar beet, dry bean, and soft white spring wheat. Timothy (*Phleum pratense* L.) and oat (*Avena sativa* L.) were included in the longest 6-yr rotation. The CONS rotations were built around four specific management practices: (i) zero or reduced tillage where possible in the rotation; (ii) fall-seeded cover crops; (iii) composted cattle manure as a substitute for inorganic fertilizer; and (iv) solid-seeded narrow-row dry bean. The specific objectives of this study were: (i) to compare the responses of different surface SOM fractions and aggregate stability to 12 yr of CONS vs. CONV management practices under various rotations; and (ii) to elucidate the relationships among aggregation, C inputs (compost and crop), and surface SOM attributes.

MATERIALS AND METHODS

Experimental Design and Management Practices

The study was conducted during 12 yr (2000–2011) at the Vauxhall Substation of Agriculture & Agri-Food Canada (50°3′ N, 112°9′ W, elevation 781 m) on an Orthic Dark Brown Chernozemic soil (Soil Classification Working Group, 1998). The texture of the 0- to 15-cm depth was sandy loam (0.52 kg kg^{-1} sand, 0.34 kg kg^{-1} silt, 0.14 kg kg^{-1} clay), and the pH was 6.9. The 30-yr (1981–2010) normal mean annual precipitation at the site is 352 mm and the air temperature is 5.8°C.

The experiment included seven rotations, established in spring 2000 and managed with either conventional (CONV) or conservation (CONS) management (Table 1): continuous wheat (1-CONT), two 3-yr (3-CONV and 3-CONS) and two 4-yr (4-CONV and 4-CONS) rotations, and one 5-yr (5-CONS) and one 6-yr (6-CONS) rotation. The entire plot area had been planted to barley (*Hordeum vulgare* L.) in 1999. Similar crop sequences occurred in the 3-CONV and 3-CONS rotations (potato–dry bean–wheat) and in 4-CONV and 4-CONS (sugar beet–dry bean–potato–wheat) (Table 1). The 5-CONS rotation included the three row crops interspersed with wheat (sugar beet–wheat–dry bean–potato–wheat), while 6-CONS was the only one with a forage (timothy–timothy–sugar beet–dry bean–potato–oat).

Each phase of each rotation appeared in each year, resulting in 26 rotation phases in a randomized complete block design with four replicates, for a total of 104 plots. Individual plot dimensions were 10.1 by 18.3 m. All crops were grown to maturity, except oat in the 6-CONS treatment, which was harvested as silage in mid- to late July to allow timely planting of timothy in late August. At the end of the 2011 growing season (12 yr), the 3-yr rotations had completed four cycles; the 4-yr rotations, three cycles; the 5-yr rotation, 2.4 cycles; and the 6-yr rotation, two cycles (Table 1).

Tillage Management

As much as possible, tillage intensity was reduced under CONS vs. CONV management. Fall tillage before dry bean was one pass of a disk harrow with harrows for all rotations except 5-CONS, which was left undisturbed and the stubble from the previous wheat crop shredded with a flail mower. In spring, wide-row dry bean plots for 3- or 4-CONV received one or two passes of a Triple K spring-tine harrow (Kongskilde Industries). There was no spring tillage ahead of narrow-row dry bean for the CONS rotations, which were direct seeded into fall rye residue desiccated with glyphosate [*N*(phosphonomethyl)glycine] 7 to 10 d prior (3-CONS), shredded wheat stubble (5-CONS), or undisturbed soil (4-CONS and 6-CONS). In the fall preceding potato (Table 1), the 3- and 4-CONV rotations were moldboard plowed to the 25-cm depth. The 3-CONS rotation received one pass of a chisel plow + packers or disk harrow, while one pass of a Dammer Diker (AG Engineering & Development Co.), a reservoir tillage implement, was used for the 4-, 5-, and 6-CONS treatments. In spring, both CONV and CONS potato plots received two passes of a Triple K spring-tine harrow. Fall tillage before wheat was one pass of a disk harrow (1-CONT), one pass of a heavy-duty cultivator or one to two passes of a disk harrow (CONV) or one pass of a disk harrow (CONS). Tillage before seeding for wheat (Table 1) in spring did not differ between CONS and CONV and was one pass of either a disk harrow, a Triple K, or a heavy-duty cultivator, depending on residue levels.

Sugar beet was not present in the 3-yr rotations because our collaborator (Lantic Inc.) mandates ≥4-yr rotations for sugar beet cyst nematode (*Heterodera schachtii* Schmidt) control. When following wheat (Table 1), there was no difference in fall tillage between CONV and CONS rotations for sugar beet, with all plots receiving one to two passes of a disk harrow. For 6-CONS in 2008, timothy sod was moldboard plowed to 25 cm in fall 2007. Spring tillage for sugar beet (all rotations) consisted of one pass of a Vibra Shank cultivator or Triple K.

For 6-CONS, wheat replaced timothy in 2000–2001 (Table 1) because timothy would have to be planted in August 1999 to allow a first-year crop in 2000 or a second-year crop in 2001. Tillage for oat followed that for wheat for the CONS rotations above, while timothy was direct seeded into oat stubble in August 2006 and remained for the 2007 and 2008 growing seasons.

Cover Crops

Two cover crops were used for the CONS rotations only, oat and fall rye, with entry points detailed in Table 1. Oat was selected to provide fall cover and then winterkilled to avoid seeding problems in the following spring. Fall rye was chosen because it did not winterkill, and if successfully established in fall, regrew as the soil warmed in early spring. However, fall establishment of

Table 1. Rotation histories of wheat or oat plots sampled in 2011, showing cover crop and compost entry points.

	Rotation history‡											
Rotation†	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1-CONT	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}
3-CONV	{P	DB	W}	{P	DB	W}	{P	DB	W}	{P	DB	W}
3-CONS	{P§	DB¶	W#}	{P§	DB§	W#}	{P§	DB§	W#}	{P§	DB§	W}
4-CONV	{SB	DB	P	W}	{SB	DB	P	W}	{SB	DB	P	W}
4-CONS	{SB	DB††	P¶	W}	{SB	DB††	P§	W}	{SB	DB††	P§	W}
5-CONS	P¶	W}	{SB#	W	DB††	P§	W}	{SB#	W	DB††	P§	W}
6-CONS	{W(T1)	W(T2)	SB	DB††	P§	O}	{T1	T2	SB	DB††	P§	O}

† 1-CONT, continuous wheat; 3- and 4-CONV, 3- and 4-yr conventional rotation, respectively; 3-, 4-, 5-, and 6-CONS, 3-, 4-, 5-, and 6-yr conservation rotations, respectively.

‡ W, wheat; P, potato; DB, dry bean; SB, sugar beet; T1, 1st-yr timothy (seeded in previous August); T2, 2nd-yr timothy; W(T1), wheat replaced T1 because T1 was not feasible in 2000 (startup year); W(T2), wheat replaced T2 because T2 was not feasible in 2001; O, oat. Rotation cycles are delineated within braces.

§ Fall rye cover crop planted after harvest and desiccated (3-CONS, before dry bean) or tilled (3-CONS before wheat; 4-, 5-, 6-CONS) the following spring.

¶ Oat cover crop planted after harvest and winterkilled.

\# Compost applied at 28 Mg ha^{-1} (fresh wt.) after harvest.

†† Compost applied at 42 Mg ha^{-1} (fresh wt.) after harvest (except 2003 postponed until spring 2004 due to wet soil conditions).

oat was suboptimal, with low to nonexistent cover, and after an especially poor performance in 2002, it was dropped and only fall rye was used from fall 2003 onward. The 3-CONS rotation had the greatest proportion of fall-seeded cover crops (8 of 12 yr, Table 1), with lesser proportions in the 4- and 5-CONS (3 of 12 yr) and 6-CONS (2 of 12 yr) treatments.

Compost Addition

Straw-bedded beef cattle feedlot manure compost produced by active aeration (Larney and Olson, 2006) and sourced from the same feedlot was fall applied (except 2003, Table 1) for the CONS rotations only. A rate of 42 Mg ha^{-1} (fresh weight) was applied after dry bean and before potato for the 4-, 5-, and 6-CONS rotations. The shorter 3-CONS rotation received a lower rate (28 Mg ha^{-1}, fresh weight) after wheat and before potato. This lower rate was also applied at a second entry point in the 5-CONS rotation: after sugar beet and before wheat.

Compost was sampled from the spreader and analyzed to determine inputs of C, N, and P on individual plots. Water content was determined on ~0.5 kg of compost oven dried at 60°C for 5 d. Oven-dried subsamples were coarsely ground (<2 mm) and finely ground (<150 μm) for total C and N by flash combustion in an elemental analyzer (NA-1500, CE Instruments). Total P was determined colorimetrically after wet digestion. The compost had average concentrations (dry weight basis ± SE, n = 8, 2001–2005, 2007–2009, Table 1) of 183 ± 18 g kg^{-1} total C, 15.0 ± 0.9 g kg^{-1} total N, and 5.8 ± 0.6 g kg^{-1} total P, and a C/N ratio of 12.1 ± 0.7.

Narrow-Row Dry Bean

The fourth conservation management practice was specific to dry bean. The CONV rotations were seeded in wide rows (60 cm) with a custom small-plot disk drill at 29 plants m^{-2}, and CONS rotations were seeded in narrow rows (19–23 cm) with a John Deere 1560 no-till disk drill (2000–2003), a custom double-disk no-till press drill (2004–2010), or a Versatile 2200 hoe drill (2011) at 53 plants m^{-2}. Wide-row dry bean for the 3- and 4-CONV rotations were interrow cultivated (late June–early July) for weed control, except in 2010 when herbicides provided adequate control for 3-CONV. Interrow cultivation was not performed on CONS rotations. Harvest of wide-row dry bean involved undercutting, causing soil disturbance, and pickup with a plot combine. Narrow-row dry bean was direct cut with a plot combine or hand harvested, causing no soil disturbance.

Crop Management

Dry bean plots received spring applications of 90 kg ha^{-1} N for 3-CONV and 3- and 5-CONS, and 112 kg ha^{-1} N for 4-CONV and 4- and 6-CONS. Fertilizer P was not applied to dry bean because plant-available soil P was considered adequate. Dry bean was not inoculated with *Rhizobia* due to a lack of yield response on local soils (McKenzie et al., 2001). Plots going into potato for 3- and 4-CONV were fertilized (123 kg ha^{-1} N, 67 kg ha^{-1} P_2O_5, and 67 kg ha^{-1} K_2O) in the previous fall except in 2000, when they were fertilized in spring. Potato plots in CONS rotations received a lower rate of N (37 kg ha^{-1}) and zero P to account for N and P in the compost. Wheat (and oat for 6-CONS) received 90 to 112 kg ha^{-1} N. Sugar beet received 112 to 134 kg ha^{-1} N and 28 to 67 kg ha^{-1} P_2O_5 when following wheat (Table 1). When sugar beet followed timothy for 6-CONS in 2008, the N rate was increased to 168 kg ha^{-1} to compensate for greater N uptake by the preceding 2 yr of timothy. First-year timothy in 2006 (Table 1) received 112 kg ha^{-1} N in spring and 112 kg ha^{-1} N after the first cut in July. Second-year timothy received 145 kg ha^{-1} N in spring 2007 and 78 kg ha^{-1} N after the first cut.

Pre-seeding, in-crop, and post-harvest herbicides were used as required for weed control. All crops were irrigated using a wheel-move system to maintain soil water content at ≥50% field capacity. Plots could be individually irrigated using four quarter-circle sprinklers. Annual irrigation amounts (average weighted by the number of plots for each crop) ranged from 140 mm in 2002 to 813 mm in 2007, with a mean of 395 mm (n = 12). During the 12 growing seasons, water use by potato, sugar beet, and timothy was 25 to 30% higher than dry bean or wheat. Each fall, mature crops were harvested for yield and quality assessment. For the 6-CONS rotation, oat biomass was measured in July 2005 (milky dough stage) and timothy biomass (2006 and 2007) in July (first cut) and September (second cut). Fall rye cover crops were sampled for biomass yield before tillage or desiccation in spring.

Carbon Inputs

Carbon inputs to the soil during the 12-yr study were calculated for all seven rotations. The 1-CONT and CONV rotations had C inputs from crops only, while the CONS rotations included C inputs from both crops and compost. Crop C inputs were calculated based on yield (dry bean, potato, wheat, and sugar beet) or biomass (oat, timothy, and fall rye cover crop) using relative C allocation coefficients, which express C inputs to the soil as a proportion of the net primary productivity (Janzen et al., 2003; Bolinder et al., 2007). Compost C inputs were estimated from the dry weights of compost applied to each plot and compost C concentrations.

Soil Sampling and Analyses

A subset of 7 phases × 4 replicates (28 plots) was sampled at the end of the 12-yr experiment (5 Oct. 2011) to explore rotation and management effects on soil quality. The subset included wheat phases from six rotations—1-CONT, 3-CONV, 3-CONS, 4-CONS, 4-CONV, and 5-CONS (the phase between potato and sugar beet only)—and the oat phase from 6-CONS. This sampling protocol resulted in a uniform group of plots (all planted to cereals in 2011) with different management histories from 2000–2010 (Table 1).

Ten to 15 soil subsamples were taken in each of the 28 plots with a hand-held auger (0–7.5-cm depth), combined (~500 g total), and stored at 4°C before analyses. Soil sampling was restricted to a surface soil layer because the primary soil management issues on irrigated land in the region relate to reduced soil erosion and increased water infiltration by improved surface soil aggregation and SOM attributes. Total C (TC) and N (TN) were measured by dry combustion (CNS-1000 analyzer, Leco Corp.) on 5 g of air-dried soil (<0.5 mm). The TC was corrected for inorganic C measured by the method of Amundson et al. (1988) to obtain total organic C (TOC). An additional 5- to 10-g subsample was separated into particulate (>53 μm) and fine mineral-associated (<53 μm) size fractions by sieving after shaking with 50 mL of deionized water and five glass beads (6-mm diam.) for 16 h on a reciprocal shaker. The material <53 μm was dried at 40°C and weighed before determination of fine mineral-associated organic matter C (FOM-C) and N (FOM-N) by CNS analyzer as above. Particulate-associated C (POM-C) and N (POM-N) were estimated by subtracting the content of FOM-C and FOM-N from the whole soil TOC and TN. Microbial biomass C was determined on 20-g samples after 24 h chloroform fumigation and extraction of C with 0.25 mol L^{-1} K_2SO_4 (Wu et al., 1990). As a further measure of microbial activity, the microbial biomass C quotient (MBCQ) was calculated as [(MBC/TOC)100]. Alkaline phosphatase activity was determined on field-moist soils using *p*-nitrophenyl phosphate as a substrate after sample incubation for 1 h at 37°C (Tabatabai, 1994).

For AS, a subsample of field-moist soil was gently crumbled through a 6.3-mm sieve (Angers et al., 2008). Forty grams of <6.3-mm aggregates was then placed on a nest of two sieves with openings of 1.0 and 0.25 mm. Two energy levels were used to assess AS: pre-wet aggregates (i.e., low energy, air-dry aggregates slowly wetted in a humidifier before immersion in the wet-sieving apparatus) and non-wet (i.e., high energy, fast wetting of air-dry aggregates immersed directly). This allowed estimation of an AS ratio (high energy/low energy) (Carter et al., 2003). Wet sieving was performed under total immersion for 10 min. Aggregate fractions retained on the 1- and 0.25-mm sieves (macroaggregates) were oven dried, weighed, and expressed as a percentage of the total soil on an oven-dry basis. The percentage of total soil passing through the 0.25-mm (unstable microaggregates) sieve was estimated by difference. A correction was made for the presence of sand and coarse fragments in the stable aggregates. The AS ratio was calculated for the macroaggregate fractions only (0.25–1 and >1 mm) because the ratio is meaningless for the unstable microaggregate fraction (<0.25 mm).

Also in fall 2011, a larger set of soil samples was taken from all 104 plots to assess soil properties at the end of the study. This included soil bulk density for the 0- to 7.5-cm depth (composite of three 67-mm-diam. cores per plot), which was used along with C and N concentrations (whole soil, FOM, and POM) to express soil C and N fractions on a mass basis.

Statistical Analyses

All data were tested for outliers (PROC UNIVARIATE) before analysis with PROC MIXED (SAS Institute, 2010), with rotation as the main variable. Orthogonal contrasts compared overall management effects: CONV (average of 3- and 4-CONV) vs. CONS (average of 3-, 4-, 5-, and 6-CONS). Correlation analysis (PROC CORR) was conducted on C inputs and SOM properties with AS parameters. For this analysis, 1-CONT (n = 4) was not used, resulting in n = 24.

RESULTS AND DISCUSSION

Crop, Compost, and Total Carbon Inputs

Mean annual crop C returns (mean ± SD) to soil during the 12 yr were in the order: wheat (4.6 ± 1.4 Mg ha^{-1}, n = 125), timothy (4.5 ± 1.2 Mg ha^{-1}, n = 8), oat (3.0 ± 1.4 Mg ha^{-1}, n = 8), potato (2.3 ± 0.6 Mg ha^{-1}, n = 69), sugar beet (1.7 ± 0.4 Mg ha^{-1}, n = 40), and dry bean (1.1 ± 0.3 Mg ha^{-1}, n = 65). The mean C input from the fall rye cover crop was 0.4 ± 0.4 Mg ha^{-1} (n = 52). Because wheat and timothy gave the highest C returns, overall inputs were largely influenced by the proportion of these crops grown during the 12 yr. Hence, 1-CONT (100% wheat) returned significantly higher C (42.0 Mg ha^{-1}, Fig. 1), followed by 3-, 5-, and 6-CONS (34.5–36.7 Mg ha^{-1}), which comprised 33 to 42% wheat or timothy. Significantly lower C returns occurred with 4-CONV and 4-CONS (29.0–29.6 Mg ha^{-1}), where wheat comprised only 25% of the rotation (Fig. 1). Where CONS and CONV management had the exact same crop sequence (3- and 4-yr rotations), CONS management did not significantly increase crop C returns (Fig. 1).

Converting our 12-yr crop C returns to annual inputs allowed comparison with previously published data. Annual returns ranged from 2.4 Mg C ha^{-1} on 4-CONS to 3.5 Mg C ha^{-1} on 1-CONT. Angers et al. (1999) reported annual crop C inputs from 1.4 Mg C ha^{-1} for a 10-yr cropping sequence with a potato frequency of 90% to 3.6 Mg C ha^{-1} for a 10-yr sequence with frequencies of 30% potato, 30% red clover

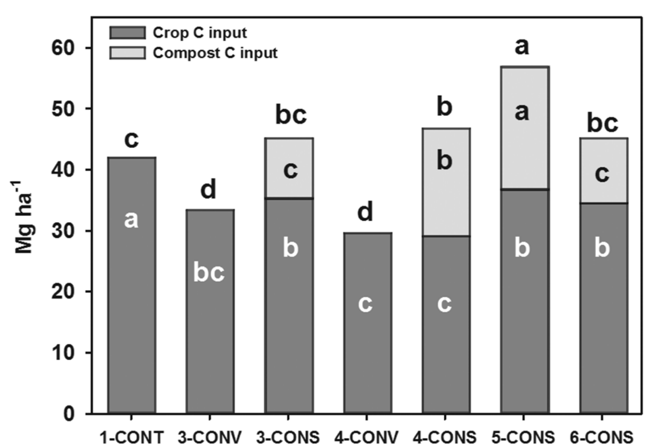

Fig. 1. Effect of rotation on crop C, compost C, and total (crop + compost) C inputs to soil (2000–2011). Means separation for crop C and compost C provided within respective bars. Means separation for total C provided above bars. Treatments included continuous wheat (1-CONT), 3- and 4-yr conventional rotations(3- and 4-CONV, respectively), and 3-, 4-, 5-, and 6-yr conservation rotations (3-, 4-, 5-, and 6-CONS, respectively).

(*Trifolium pratense* L.), 30% barley (*Hordeum vulgare* L.) underseeded with red clover, and 10% barley. Po et al. (2009) reported average annual C returns to soil ranging from 0.9 Mg ha^{-1} for 2-yr rotations of potato–snap bean (*Phaseolus vulgaris* L.) without cover crops to 3.3 Mg ha^{-1} for a 2-yr rotation of potato–sweet corn + fall rye/hairy vetch (*Vicia villosa* Roth.) cover crops in each year.

Compost C inputs (Fig. 1) were in the order 5-CONS (20.1 Mg ha^{-1}) > 4-CONS (17.7 Mg ha^{-1}) > 3- and 6-CONS (9.9–10.6 Mg ha^{-1}). The results are in agreement with additions of compost (Table 1) during the 12 yr. Overall, 5-CONS received the most compost (2 × 28 Mg ha^{-1} + 2 × 42 Mg ha^{-1} = 140 Mg ha^{-1} fresh weight), followed by 4-CONS (3 × 42 Mg ha^{-1} = 126 Mg ha^{-1}) and then 3- and 6-CONS, both of which received 84 Mg ha^{-1} (3-CONS as 3 × 28 Mg ha^{-1} and 6-CONS as 2 × 42 Mg ha^{-1}). On an annual basis, compost C inputs ranged from 0.8 to 1.7 Mg ha^{-1}, which was 17 to 37% of estimated C returns from a wheat crop (4.6 Mg ha^{-1}).

Total C inputs (Fig. 1) showed that only 5-CONS (56.9 Mg ha^{-1}) and 4-CONS (46.7 Mg ha^{-1}) were significantly higher than 1-CONT (42.0 Mg ha^{-1}). The addition of ~10 Mg ha^{-1} of compost C to 3- and 6-CONS was insufficient to make these rotations significantly higher than 1-CONT. For 4- and 5-CONS, compost C contributed ~33% of C inputs, with crop C at ~66%. For 3- and 6-CONS, ~25% of C inputs originated from compost, with 75% from crops. The 3- and 4-CONV rotations were dependent on crops only for C inputs and were therefore significantly lower (29.6–33.4 Mg ha^{-1}) than the CONS rotations (45.1–56.9 Mg ha^{-1}) and 1-CONT (Fig. 1).

Soil Organic Matter Fractions, Microbial Biomass, and Phosphatase Activity

Of 14 soil quality attributes (Table 2), rotation had significant effects on eight, the exceptions being TOC/N, FOM-C, FOM-N, FOM-C/N, POM C/N, and MBCQ. Total organic C was significantly higher for 5-CONS (18.1 Mg ha^{-1}) than all other rotations. The 3- and 4-CONV rotations had significantly lower TOC (9.8–10.5 Mg ha^{-1}) than all other rotations. Total N closely mirrored TOC. The POM-C and POM-N fractions were much more responsive to rotational and management practices than FOM-C and FOM-N. The 5-CONS rotation had significantly higher POM-C (7.9 Mg ha^{-1}) than all other rotations, being approximately four times higher than the lowest rotation (4-CONV, 2.0 Mg ha^{-1}). Similarly, POM-N for 5-CONS was significantly higher (0.67 Mg ha^{-1}) than all others and more than five times greater than 4-CONV (0.13 Mg ha^{-1}). The POM-N fraction was the best single predictor of soil N supply for canola (*Brassica napus* L.) following legumes and non-legumes on the Canadian prairies (St. Luce et al., 2013) and one of the best predictors of soil N supply for potato rotations in Maine (Sharifi et al., 2008).

The proportion of TOC present as POM-C (POM-C/TOC) was significantly higher for 5-CONS (44%) than all other rotations (20–38%, Table 2), as was the proportion of TN present as POM-N (POM-N/TN, 39 vs. 14–31%). This was in agreement with the higher compost inputs to 5-CONS discussed above. The range in POM-C/TOC from 20% for 4-CONV to 44% for 5-CONS meant that the reciprocal amounts of TOC resided in FOM-C because POM-C + FOM-C = 100%. Therefore, 80% of TOC resided in the FOM-C fraction for 4-CONV compared with 56% for 5-CONS.

Table 2. Effect of rotation and management on soil quality attributes (0–7.5-cm depth), fall 2011.

	Rotation‡								Management§		
Attribute†	**1-CONT**	**3-CONV**	**3-CONS**	**4-CONV**	**4-CONS**	**5-CONS**	**6-CONS**	***P* value**	**CONV**	**CONS**	***P* value**
TOC, Mg ha^{-1}	13.4 b¶	10.5 c	13.2 b	9.8 c	15.3 b	18.1 a	14.5 b	<0.001	10.2 b	15.3 a	<0.001
TN, Mg ha^{-1}	1.28 cd	1.13 de	1.43 bc	1.00 e	1.51 b	1.75 a	1.42 bc	<0.001	1.06 b	1.53 a	<0.001
TOC/N	10.5 a	9.4 a	9.2 a	9.9 a	10.1 a	10.4 a	10.2 a	0.23	9.6 a	10.0 a	0.35
FOM-C, Mg ha^{-1}	9.8 a	8.7 a	9.8 a	7.9 a	10.1 a	10.4 a	10.1 a	0.30	8.3 b	10.1 a	0.01
FOM-N, Mg ha^{-1}	0.98 a	0.87 a	1.04 a	0.87 a	1.04 a	1.07 a	0.99 a	0.26	0.87 b	1.04 a	0.01
FOM-C/N	10.0 a	10.0 a	9.4 a	8.7 a	9.7 a	9.8 a	10.3 a	0.18	9.3 a	9.8 a	0.19
POM-C, Mg ha^{-1}	4.0 d	2.4e	4.4 cd	2.0 e	5.7 b	7.9 a	5.1b c	<0.001	2.2 b	5.8 a	<0.001
POM-N, Mg ha^{-1}	0.30 cd	0.26 d	0.39 bc	0.13 e	0.47 b	0.67 a	0.44 b	<0.001	0.20 b	0.49 a	<0.001
POM-C/N	13.6 a	10.0 a	11.2 a	12.5 a	12.3 a	11.7 a	11.8 a	0.43	11.3 a	11.7 a	0.63
POM-C/TOC, %	30.4 c	23.1 d	33.1 bc	20.2 d	37.6 b	43.7 a	34.9 bc	<0.001	21.6 b	37.3 a	<0.001
POM-N/TN, %	23.6 c	22.8 c	27.5 bc	13.5 d	31.3 b	38.6 a	30.7 b	<0.001	18.2 b	32.0 a	<0.001
MBC, kg ha^{-1}	163 a	115 bc	140 ab	85 c	145 ab	165 a	143 ab	0.007	100 b	148 a	<0.001
MBCQ‡, %	1.23 a	1.14 a	1.05 a	0.87 a	0.95 a	0.92 a	0.99 a	0.35	1.01 a	0.98 a	0.78
Phosphatase, mg kg^{-1} h^{-1}#	170 c	113 c	263 b	134 c	345 a	344 a	299 ab	<0.001	124 b	313 a	<0.001

† TOC, total organic C; TN, total N; TOC/N, total organic C/N ratio; FOM-C, fine organic matter C; FOM-N, fine organic matter N; FOM-C/N, fine organic matter C/N ratio; POM-C, particulate organic matter C; POM-N, particulate organic matter N; POM-C/N, particulate organic matter C/N ratio; MBC, microbial biomass C; MBCQ, microbial biomass C quotient = [MBC (kg ha^{-1})/TOC (kg ha^{-1})]/100.

‡ 1-CONT, continuous wheat; 3- and 4-CONV, 3- and 4-yr conventional rotation, respectively; 3-, 4-, 5-, and 6-CONS, 3-, 4-, 5-, and 6-yr conservation rotations, respectively.

§ Management contrasts: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5-, and 6-CONS).

¶ Within rows, means followed by the same letter are not significantly different from each other ($P > 0.05$).

mg *p*-nitrophenol released kg^{-1} dry soil h^{-1}.

Microbial biomass C showed no significant difference across CONS rotations (140–165 kg ha^{-1}), and only 5-CONS was significantly higher (165 kg ha^{-1}) than 3-CONV (115 kg ha^{-1}), while all four CONS rotations were significantly higher than 4-CONV (85 kg ha^{-1}). Von Lützow et al. (2007) indicated that the active SOM pool with turnover rates of <10 yr was best represented by MBC, and our data indicate that turnover rates were similar on all CONS rotations. The 4- and 5-CONS rotations showed significantly higher alkaline phosphatase activity (344–345 mg kg^{-1} h^{-1}) than all other rotations (113–263 mg kg^{-1} h^{-1}) except 6-CONS (299 mg kg^{-1} h^{-1}). Lalande et al. (1998) reported a 30% increase in phosphatase activity in compost-amended soils compared with N-fertilized or control soils, while He et al. (2010) found an 80% increase in activity due to the addition of composted manure to potato rotations.

Using contrast analysis (Table 2), 10 of 14 attributes showed significant effects of overall management (CONV vs. CONS), the four exceptions being TOC/N, FOM-C/N, POM C/N, and MBCQ. Attributes with the largest increases (145–164%) included POM-C, POM-N, and phosphatase, making these the most sensitive to 12 yr of CONS management. Bolinder et al. (1999) found that macro-organic matter (similar to POM) was the soil quality attribute with the highest sensitivity index to conservation management in eastern Canadian agroecosystems. Gosling et al. (2013) used POM-C as a predictor of changes in total SOM that may not be measurable in short-term studies. In a meta-analysis they found only two management factors that consistently influenced soil POM levels, i.e., organic amendments (increased POM) and fallow (decreased POM). They also found that a number of management factors reported to increase SOM, e.g., tillage, fertilizer use, monocropping, or grazing, had inconsistent effects on POM. Our results agree those of Carter et al. (2009a), who compared CONV and CONS management for potato rotations on Prince Edward Island. They found that 7 yr of CONS management (inclusion of red clover in a 3-yr rotation and chisel rather than moldboard plowing) increased POM-C and POM-N. In the same study, Carter (2007) found that improved SOC conditions under CONS management benefitted the soil water-holding capacity. Phosphatase activity was also found to be more sensitive than TOC measurements to reductions in tillage intensity (Angers et al., 1999; Bergstrom et al., 1998).

Values for POM-C/TOC and POM-N/TN were about 75% higher with CONS management (Table 2), while TOC, TN, and MBC showed 44 to 50% increases. In potato cropping sequences on Prince Edward Island, Angers et al. (1999) found that changes in MBC and light-fraction C and N were greater than those in TOC and TN, suggesting that the former attributes better reveal management changes in soil quality. Griffin and Porter (2004) found that POM-C and -N were more responsive to management factors than TOC and TN in 2-yr rotations of corn (*Zea mays* L.) and potato. Although our study found that MBC, TOC, and TN were equally sensitive to CONS management, other researchers have shown MBC to be more sensitive than either TOC or TN (Bissonnette et al., 2001; Motta et al., 2007).

The FOM-C and -N fractions were less sensitive to CONS management, showing ~20% increases during the 12 yr. These fractions are often assumed to represent the oldest and most humified portion of SOM and represent relatively stable pools with a slower turnover rate than POM fractions (Baisden et al., 2002; Henderson et al., 2004). Because the FOM-C fraction contains little mineralizable C, it can act as a major sink for C storage (Jagadamma and Lal, 2010).

All three C/N ratios (TOC/N, FOM-C/N, and POM-C/N) were unaffected by management despite the addition of large doses of C in the form of compost under CONS management. Sequeira and Alley (2011) reported rotational effects on POM-C/N, which they attributed to the C/N ratios of the returned crop residues (e.g., cereal > legume).

The lack of responsiveness of the MBCQ to rotation or overall management (CONV vs. CONS) agreed with the findings of Carter et al. (2009b) for a potato rotation study on Prince Edward Island. However, Nelson et al. (2009) found that MBCQ responded positively to extended rotations for organic potato in Atlantic Canada. Gregorich et al. (1994) and Carter et al. (1998) reported that MBCQ generally ranged from 1 to 3%, with pasture soils consistently higher. Our MBCQ values ranged from 0.9 to 1.2% (Table 2), within or slightly below this reported range. Generally if a soil is being exploited, the MBCQ declines (Breland and Eltun, 1999). The lack of a significant effect on MCBQ in our study indicated that while the CONV rotations were significantly lower for most soil quality attributes, they may not be exploitative, at least during the timeline of our study.

Relationships between Carbon Inputs and Soil Organic Carbon Fractions

The mass (0–7.5-cm depth) of three SOC fractions (TOC, FOM-C, and POM-C) in fall 2011 were regressed on crop C, compost C, and total C (crop + compost C) additions during the study period (2000–2011) (Fig. 2). None of the three SOC fractions were responsive to crop C inputs (Fig. 2a), showing that C in the form of crop residue and shallow roots had no measureable effect on SOC. In contrast, Angers et al. (1999) found higher correlation coefficients between crop C inputs and TOC (r = 0.80), TN (r = 0.83), and MBC (r = 0.91) at the 0- to 15-cm depth. Po et al. (2007) showed that crop residue C inputs explained 31% of the variability in soil C (0–20-cm depth) for 2-yr potato rotations in Michigan. Our shallow sampling depth (0–7.5 cm) may have been responsible for the lack of significant effects because the contribution of crop roots to C inputs was probably not captured fully. Also, while the impact of a cropping system on soil C is dependent mainly on the quantities of C added, other factors including residue quality, tillage intensity, rate of C assimilation, and soil environment are also important (Po et al., 2009).

All three SOC fractions showed significant linear relationships with compost C inputs (Fig. 2b), showing that this form of C elicited measurable responses in surface SOC. Our compost application rates (normalized at 7–11.6 Mg ha^{-1} yr^{-1}, fresh weight) were higher than the 4 Mg ha^{-1} yr^{-1} of poultry manure used in a potato study in New Brunswick (Rees et al., 2014). While our rates elicited responses in SOC attributes, the lower rates of the New Brunswick study improved soil fertility (P, K, B, Cu, Na, S, and Zn) but not SOC. Our study was designed to add compost in large doses at less frequent intervals rather than small doses on an annual basis, which may explain the different responses in the SOC fractions.

The POM-C fraction was the most responsive to compost C inputs (R^2 = 0.76), with TOC intermediate (R^2 = 0.58) and FOM-C the least responsive (R^2 = 0.16). The slope of the relationship showed that TOC increased by 0.28 Mg ha^{-1} for each 1 Mg ha^{-1} of added compost C, which suggests that 28% of the compost C added during the study was retained and captured as soil TOC at the end of the study. The slopes of the relationships for the FOM- and POM-C fractions showed that 0.07 Mg ha^{-1} of FOM-C and 0.21 Mg ha^{-1} of POM-C were retained for each 1 Mg of compost C added. Because FOM- and POM-C relationships were additive to arrive at TOC (0.21 + 0.07 = 0.28 Mg ha^{-1}), the data show that compost was three times more effective at increasing POM-C than FOM-C.

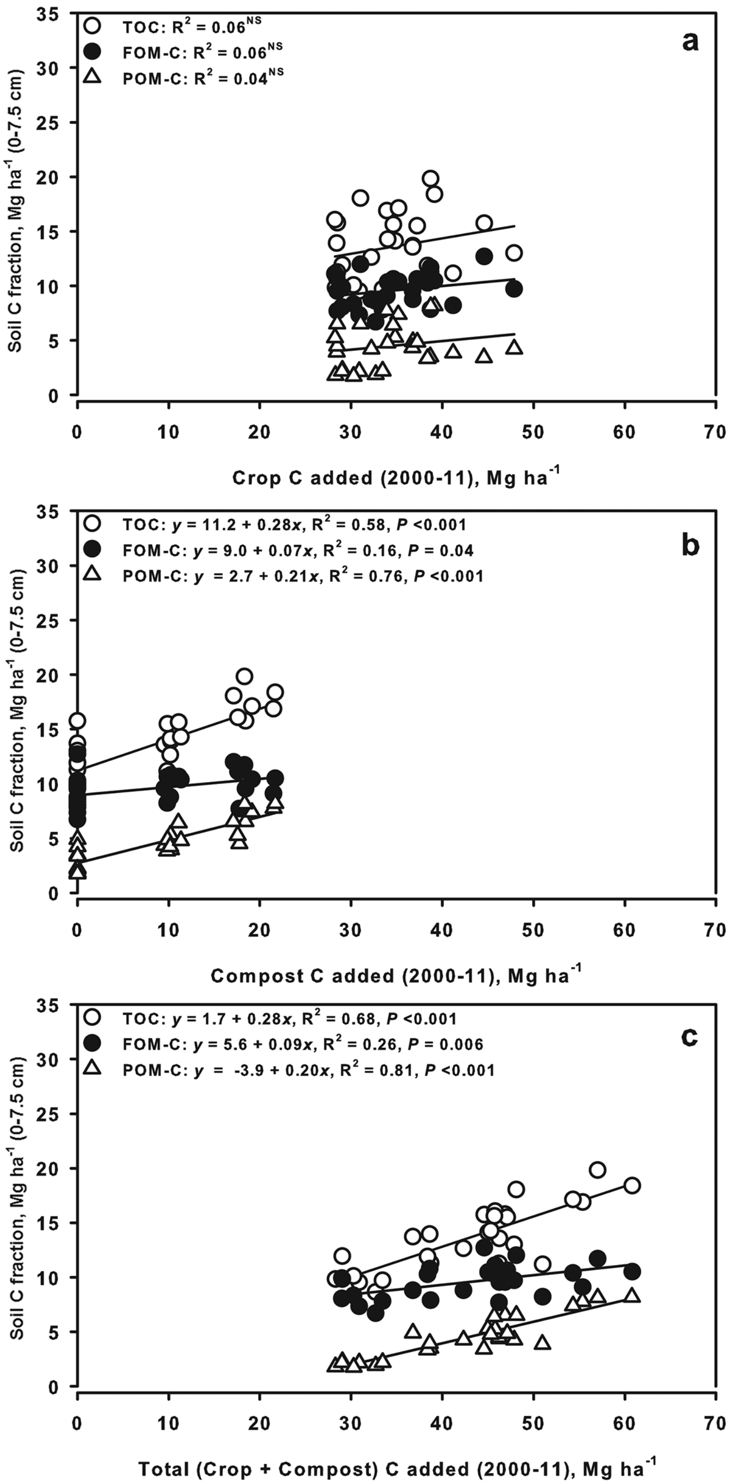

Fig. 2. Effect of (a) crop C, (b) compost C, and (c) total (crop + compost) C inputs (2000–2011) on soil organic matter fractions of total organic C (TOC), fine organic matter C (FOM-C), and particulate organic matter C (POM-C), fall 2011. Crop C includes C inputs from annual crops and fall-seeded cover crops.

The above C retention data are based on the 0- to 7.5-cm depth and as such may underestimate the full extent of C retention because C added at the >7.5-cm depth (e.g., root residue or exudate C and compost C incorporated by tillage) would not be accounted for. The above estimate does not distinguish rotation effects on C retention; however, this can be roughly calculated from the TOC (Table 2) and the total C (crop + compost) inputs (Fig. 1) using 4-CONV as a reference rotation because it had the lowest TOC at the 0- to 7.5-cm depth, the lowest proportion of wheat (25%) and the highest of row crops (75% potato, sugar beet, or dry bean), and was managed with more intensive tillage, no compost additions, no cover crops, and wide-row dry bean with interrow cultivation and undercutting at harvest. This exercise showed very little difference in C retained (range, 24–32%; mean, 29%) by the four CONS rotations. The mean value of 29% was very close to the slope of the relationship in Fig. 2b, showing that the two methods of estimating C retention agreed and that rotation effects on C retention were negligible, possibly due to the overriding influence of compost C addition, which decomposed at equal rates in all rotations.

Relationships between total C (crop + compost) inputs and SOC fractions were significantly linear (Fig. 2c), and the order of the response was POM-C > TOC > FOM-C. The influence of compost C rather than the crop C contributions in driving SOC fraction responses to total C inputs is especially evident from the similar slopes of the regression equations (Fig. 2b and 2c). Significant positive relationships between soil C storage and C inputs implied that the 0- to 7.5-cm depth of this soil had not reached an upper limit of C storage (i.e., not C saturated) and could therefore sequester further C inputs as soil C (Stewart et al., 2007).

Aggregate Stability

There were significant rotation effects on pre-wet and non-wet macroaggregates (>1 mm) only, with smaller fractions (<0.25 and 0.25–1 mm) at both energy levels being nonsignificant (Table 3). The 5- and 6-CONS rotations showed significantly greater stability (22–25%) for pre-wet aggregates >1 mm than 4-CONV (11%), while 6-CONS (25%) was significantly greater than 3-CONV (15%). The 1-CONT rotation (28%) was not significantly different than any of the CONS rotations (18–25%). For non-wet aggregates >1 mm, 1-CONT was significantly greater (16%) than all other rotations (4–6%) except 5- and 6-CONS (9%). Rotation had a nonsignificant effect on the AS ratio of the 0.25- to 1- and >1-mm fractions (Table 3).

Contrast analysis (Table 3) revealed that the aggregate size fraction most sensitive to CONS management depended on the energy level of AS determination. With pre-wetting (low energy, slow wetting), CONS (21%) had significantly greater AS than CONV (13%) for the largest (>1 mm) fraction only. However, with non-wet aggregates (high energy, fast wetting), only the 0.25- to 1-mm fraction responded to management, with CONS (26%) significantly greater than CONV (17%). The unstable microaggregate fraction (<0.25 mm) was significantly lower for CONS than CONV rotations (50 *vs.* 58% for pre-wet; 67 vs. 79% for non-wet). The stability ratio of the 0.25- to 1-mm fraction was significantly greater for CONS (0.88) than CONV (0.56) management (Table 3). A higher stability ratio shows that soils are less susceptible to slaking on wetting (Nimmo and Perkins, 2002). However, this ratio was nonsignificant for the largest (>1 mm) macroaggregate fraction (Table 3).

The trend in AS, i.e., greater stability for rotations with higher proportions of wheat (1-CONT) or wheat and timothy (6-CONS), closely mirrored crop C inputs (Fig. 1), showing that unlike SOC fractions, crop C inputs had an effect on AS. This is borne out by a significant correlation ($r = 0.46$, $P \leq 0.05$) between crop C inputs and >1-mm non-wet aggregates (Table 4). However, compost C inputs were also significantly correlated with pre-wet aggregates >1 mm, all three fractions of non-wet aggregates, and the stability ratio of the <0.25-mm fraction (Table 4). The highest r value (0.57, $P \leq 0.01$) occurred for total C inputs and the >1-mm non-wet aggregate fraction (Table 4). Moulin et al. (2011) also found that the addition of composted feedlot manure to a dry bean–potato rotation in Manitoba increased AS through the addition of organic C.

Aggregate stability parameters were also correlated with soil quality attributes (Table 4). For pre-wet aggregates, the 0.25- to 1-mm fraction was not significantly correlated with any of the 14 attributes. However, when this fraction was non-wet, significant positive correlations occurred with TOC, TN, FOM-C, FOM-N, POM-C, and phosphatase ($r = 0.40–54$). Significant negative correlations occurred between some attributes and the pre-wet and non-wet <0.25-mm aggregate fraction; however, this may be as a result of the calculation of this fraction via difference, i.e., positive correlations with the two measured fractions (0.25–1 and >1 mm) led to negative correlations with the fraction calculated by difference.

The highest r value was found between the >1-mm pre-wet fraction and FOM-C ($r = 0.68$, $P \leq 0.001$) (Table 4), followed by the same fraction and FOM-N ($r = 0.61$, $P \leq 0.01$), showing that the stable FOM fraction had a stronger influence on this size fraction than the more recently added POM fraction ($r = 0.45–0.49$, $P \leq 0.05$). Of the three aggregate fractions, the largest (>1 mm) fraction was the most responsive, with pre-wet aggregates showing significant correlations with 10 soil quality attributes and non-wet aggregates with eight. Pikul et al. (2007) suggested that the stability of larger aggregates may also be related to such factors as binding agents (hyphae and roots) and fungal exudates (polysaccharides and glomalin). Three SOC fractions (TOC, FOM-C, and POM-C) were significantly correlated to at least five AS parameters (Table

Table 3. Effect of rotation on aggregate stability, fall 2011.

Comparison	Pre-wet aggregates			Non-wet aggregates			Stability ratio†	
	<0.25 mm	0.25–1 mm	>1 mm	<0.25 mm	0.25–1 mm	>1 mm	0.25–1 mm	>1 mm
	%							
Rotation‡								
1-CONT	47 a§	25 a	28 a	64 a	20 a	16 a	0.82 a	0.53 a
3-CONV	57 a	29 a	15 bc	80 a	15 a	5 b	0.51 a	0.31 a
3-CONS	54 a	28 a	18 abc	71 a	23 a	6 b	0.81 a	0.36 a
4-CONV	59 a	31 a	11 c	78 a	18 a	4 b	0.60 a	0.39 a
4-CONS	54 a	28 a	18 abc	71 a	23 a	6 b	0.86 a	0.36 a
5-CONS	48 a	30 a	22 ab	65 a	26 a	9 ab	0.88 a	0.41 a
6-CONS	44 a	31 a	25 a	60 a	31 a	9 ab	1.00 a	0.37 a
P value	0.15	0.51	0.02	0.08	0.07	0.05	0.13	0.46
Management¶								
CONV	58 a	30 a	13 b	79 a	17 b	4 a	0.56b	0.35 a
CONS	50 b	29 a	21 a	67 b	26 a	8 a	0.88a	0.37 a
P value	0.04	0.77	0.01	0.009	0.005	0.14	0.006	0.69

† Stability ratio = Non-wet aggregates (high energy, fast wetting)/pre-wet aggregates (low energy, slow wetting).

‡ 1-CONT, continuous wheat; 3- and 4-CONV, 3- and 4-yr conventional rotation, respectively; 3-, 4-, 5-, and 6-CONS, 3-, 4-, 5-, and 6-yr conservation rotations, respectively.

§ Within columns, means followed by the same letter are not significantly different from each other ($P > 0.05$).

¶ Management contrasts: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5-, and 6-CONS).

Table 4. Pearson correlation coefficients (*r*) for C inputs and soil organic matter attributes with aggregate stability parameters (*n* = 24).

Parameter	Pre-wet aggregates			Non-wet aggregates			Stability ratio†	
	<0.25 mm	0.25–1 mm	>1 mm	<0.25 mm	0.25–1 mm	>1 mm	0.25–1 mm	>1 mm
C inputs								
Crop	−0.19 ns	−0.09 ns	0.28 ns	−0.20 ns	0.07 ns	0.46*	0.10 ns	0.24 ns
Compost	−0.32 ns	−0.08 ns	0.43*	−0.47*	0.44*	0.46*	0.49*	0.17 ns
Total	−0.34 ns	−0.10 ns	0.47*	−0.48*	0.40 ns	0.57**	0.45*	0.24 ns
Soil quality attributes‡								
TOC	−0.44*	0.10 ns	0.48**	−0.48*	0.45*	0.44*	0.43*	0.09 ns
TN	−0.51*	0.05 ns	0.59**	−0.52**	0.47*	0.52**	0.47*	0.02 ns
TOC/N	−0.21 ns	0.23 ns	0.12 ns	−0.22 ns	0.18 ns	0.27 ns	0.16 ns	0.34ns
FOM-C	−0.65***	0.20 ns	0.68***	−0.55**	0.50*	0.54**	0.47*	−0.03 ns
FOM-N	−0.56**	0.11 ns	0.61**	−0.58**	0.54**	0.55**	0.54**	0.08 ns
FOM-C/N	−0.33 ns	0.11 ns	0.34 ns	−0.16 ns	0.15 ns	0.16 ns	0.08 ns	−0.17 ns
POM-C	−0.38 ns	0.01 ns	0.45*	−0.46*	0.40*	0.52**	0.42*	0.21 ns
POM-N	−0.40*	0.01 ns	0.49*	−0.40 ns	0.35 ns	0.43*	0.36 ns	−0.02 ns
POM-C/N	0.15 ns	−0.26 ns	−0.06 ns	−0.12 ns	0.09 ns	0.19 ns	0.20 ns	0.51*
POM-C/TOC	−0.29 ns	−0.09 ns	0.40*	−0.42*	0.36 ns	0.46*	0.41*	0.21 ns
POM-N/TN	−0.31 ns	−0.09 ns	0.42*	−0.30 ns	0.26 ns	0.33 ns	0.28 ns	−0.11 ns
MBC	−0.37 ns	−0.04 ns	0.47*	−0.31 ns	0.28 ns	0.31 ns	0.29 ns	−0.17 ns
MBCQ	0.17 ns	−0.18 ns	−0.10 ns	0.26 ns	−0.23 ns	−0.27 ns	−0.22 ns	−0.38 ns
Phosphatase	−0.49*	0.15 ns	0.51*	−0.48*	0.46*	0.41*	0.43*	0.01 ns

* Significant at $P < 0.05$; ns, not significant.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

† Stability ratio = non-wet aggregates (high energy, fast wetting)/pre-wet aggregates (low energy, slow wetting).

‡ TOC, total organic C; TN, total N; TOC/N, total organic C/N ratio; FOM-C, fine organic matter C; FOM-N fine organic matter N; FOM-C/N, fine organic matter C/N ratio; POM-C, particulate organic matter C; POM-N, particulate organic matter N; POM-C/N, particulate organic matter C/N ratio; MBC, microbial biomass C; MBCQ, microbial biomass C quotient.

4). Correlation coefficients of AS with TOC ($r = 0.77$), TN ($r = 0.73$), and MBC ($r = 0.57$) were reported by Angers et al. (1999). In a tillage and stubble management study, loss of POM-C was significantly related to a decline in the stability of aggregates >2 mm (Chan et al., 2002). A fourth SOC fraction (MBC) was significantly correlated ($r = 0.47$, $P \leq 0.05$) with only one AS parameter (pre-wet >1-mm fraction). Six et al. (2004) found significant regressions between aggregation and MBC in a Mollisol, but aggregation was independent of MBC in an Oxisol.

The AS ratio of the 0.25- to 1-mm fraction was the most responsive to soil quality attributes, being significantly correlated with seven attributes, the highest being with FOM-N ($r = 0.54$, $P \leq 0.01$) and showing that increased C inputs led to improved ability to resist slaking on wetting. The AS ratio of the >1-mm fraction was significantly correlated ($r = 0.51$, $P \leq 0.05$) only with POM-C/N, showing that a wider C/N ratio reduced the slaking risk of this fraction on wetting.

Overall Implications of Conservation Management on Soil Quality

To rate the rotations for soil quality at the end of the study, they were ranked for 20 attributes (Table 5). Because there were seven rotations, the one with the highest value for a given attribute was assigned seven points, the rotation with the second highest value six points, and so on, until the rotation with the lowest value received one point. For C/N ratios of whole soil, FOM, and POM, it was assumed that higher values were indicative of greater C storage, and the rotations were ranked accordingly. To summarize the overall effects of rotation on soil quality, the rankings were summed, with the highest ranked rotation (5-CONS) set at 100% with the others expressed as a percentage of this (Fig. 3). Because the derived rankings weighted all variables equally and included variables that might be correlated with each other, they are not meant to provide a robust statistical analysis but merely a simple comparison of soil quality among rotations.

Overall soil quality rankings (Fig. 3) were in the order 5-CONS > 6-CONS > 4-CONS ≈ 1-CONT > 3-CONS > 3-CONV ≈ 4-CONV. The highest ranked rotation (5-CONS, 100%) had the largest input of compost C and a high proportion of wheat to row crops (40:60), with wheat interspersed between each row crop (sugar beet–wheat–dry bean–potato–wheat). The second highest ranked rotation (6-CONS, 90%) had the diversity of 2 yr of forage, three row crops, and a nurse crop of oat (timothy–timothy–sugar beet–dry bean–potato–oat), along with compost application, cover crops, and reduced tillage where possible, which helped maintain soil quality. Comparing 6-CONS with 3-CONS shows that compost C inputs were not significantly different (Fig. 1), corroborating that crop diversity and inclusion of a forage probably explained the gap in soil quality (90 vs. 59%).

Table 5. Ranking of rotations (1-CONT, continuous wheat; 3- and 4-CONV, 3- and 4-yr conventional rotation, respectively; 3-, 4-, 5-, and 6-CONS, 3-, 4-, 5-, and 6-yr conservation rotations, respectively) for 20 soil quality attributes (0–7.5-cm depth), fall 2011. For each attribute, the rotation with the numerically highest value was assigned seven points, the rotation with the second highest value was assigned six points, and so on until the rotation with the lowest value was assigned one point.

Attribute†	1-CONT	3-CONV	3-CONS	4-CONV	4-CONS	5-CONS	6-CONS
TOC	4	2	3	1	6	7	5
TN	3	2	5	1	6	7	4
TOC/N	7	2	1	3	4	6	5
FOM-C	4	2	3	1	5	7	6
FOM-N	3	2	5	1	6	7	4
FOM-C/N	6	5	2	1	3	4	7
POM-C	3	2	4	1	6	7	5
POM-N	3	2	4	1	6	7	5
POM-C/N	7	1	2	6	5	3	4
POM-C/TOC	3	2	4	1	6	7	5
POM-N/TN	3	2	4	1	6	7	5
MBC	6	2	3	1	5	7	4
MBCQ	7	6	5	1	3	2	4
Phosphatase	3	1	4	2	7	6	5
AS, pre-wet, 0.25–1 mm	1	4	3	6	2	5	7
AS, pre-wet, >1 mm	7	2	3	1	4	5	6
AS, non-wet, 0.25–1 mm	3	1	4	2	5	6	7
AS, non-wet, >1 mm	7	2	4	1	3	5	6
AS ratio, 0.25–1 mm	4	1	3	2	5	6	7
AS ratio, >1 mm	7	1	3	5	2	6	4

† TOC, total organic C; TN, total N; TOC/N, total organic C/N ratio; FOM-C, fine organic matter C; FOM-N fine organic matter N; FOM-C/N, fine organic matter C/N ratio; POM-C, particulate organic matter C; POM-N, particulate organic matter N; POM-C/N, particulate organic matter C/N ratio; MBC, microbial biomass C; MBCQ, microbial biomass C quotient; AS, aggregate stability.

The CONV rotations, with no compost inputs, more intensive tillage in fall and spring for seedbed preparation, no cover crops, and interrow cultivation and undercutting at harvest associated with wide-row dry bean production, led to much lower soil quality rankings (Fig. 3). The 4-CONV rotation performed poorest (33%), perhaps because wheat (and its associated higher return of C to the soil) was included once every 4 yr vs. once every 3 yr for 3-CONV (38%). There was a much wider gap in soil quality between 4-CONS and 4-CONV (81 vs. 33%) than between 3-CONS and 3-CONV (59 vs. 38%). This may be explained by the significantly higher compost C inputs to 4-CONS vs. 3-CONS (Fig. 1), although extending the rotation from 3 to 4 yr may also have contributed to improved soil quality by reducing the proportion of potato from 33 to 25%. The 1-CONT rotation was not a true rotation but indicated that continuous wheat without any conservation inputs (compost, cover crops, etc.) maintained better soil quality than 3-CONS (78 vs. 59%, Fig. 3) and was similar to 4-CONS (78 vs. 81%).

Because CONS management was administered as a package, it was not possible to quantify the relative contribution of each of the four CONS management practices to overall soil quality changes. However, compost addition probably had the greatest effect because large doses of organic C (up to 20.1 Mg ha^{-1} on 5-CONS) were added with this practice compared with smaller contributions from reduced tillage, cover crops, and narrow-row dry bean (reduced soil disturbance by the absence of interrow cultivation and undercutting at harvest, enhanced residue management). Bolinder et al. (1999) reported an average sensitivity index of 1.82 for organic amendment compared with 1.26 for tillage for a range of soil quality attributes. Pritchett et al. (2011) reported a greater overall influence of organic amendments on select soil quality properties (TOC, POM-C, and enzyme activities) than cover crops and tillage for organic vegetable production.

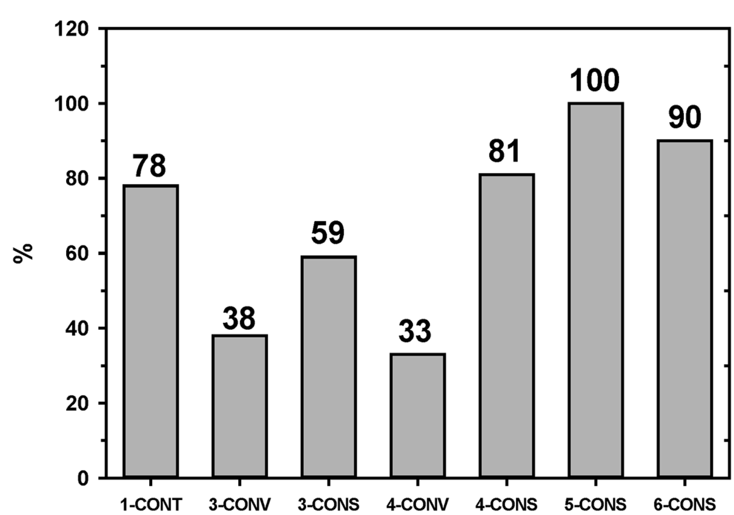

Fig. 3. Overall ranking of rotations for soil quality (based on the sum of rankings for 20 soil quality attributes, with the highest ranked rotation set at 100%). Treatments included continuous wheat (1-CONT), 3- and 4-yr conventional rotations(3- and 4-CONV, respectively), and 3-, 4-, 5-, and 6-yr conservation rotations (3-, 4-, 5-, and 6-CONS, respectively).

CONCLUSIONS

Surface soil quality attributes showing the largest increases under CONS management included POM-C, POM-N, and phosphatase activity, making them the most sensitive indicators of soil quality changes in this 12-yr study. Organic C via compost addition had significant effects on soil quality attributes and was probably the main contributor in the "building up" of soil quality compared with the other conservation management practices: reduced tillage, cover crops, and narrow-row dry bean production. While CONV management led to poorer soil quality than CONS management at the end of the study, further investigation, using baseline soil samples, is required to ascertain whether actual degradation occurred with CONV management or if soil quality on the CONV rotations remained relatively static while the CONS rotations improved during the 12 yr.

We hope to make soil management recommendations for irrigated cropping systems in southern Alberta based on the soil quality considerations outlined in this study.

ACKNOWLEDGMENTS

We thank Nicole Bissonnette and Gabriel Lévesque for laboratory analyses. Jim Sukeroff and staff at the Vauxhall Substation provided field assistance. Jennifer Nitschelm (2000–2006) and Peter Regitnig (2007–2011), Rogers Sugar Ltd./Lantic Inc. (Taber, AB), managed sugar beet husbandry. Funding contributions from the Alberta Agricultural Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster are gratefully acknowledged. The China Scholarship Council supported Dr. Lingling Li as a visiting scientist (2012–2013) at the Lethbridge Research Centre.

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ARTICLE

Soil changes over 12 yr of conventional vs. conservation management on irrigated rotations in southern Alberta

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Abstract: Increased irrigated production of potato (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), and sugar beet (*Beta vulgaris* L.) in southern Alberta in the 1990s prompted a 12 yr (2000–2011) study to evaluate conservation (CONS) management practices for these crops in 3–6 yr rotations. Conservation management included reduced tillage, cover crops, compost, and narrow-row dry bean. After 12 yr, soil organic carbon (SOC) at 0–30 cm depth increased by 0.48 Mg ha^{-1} yr^{-1} on a 5 yr CONS rotation, in line with average cumulative compost addition of 154 Mg ha^{-1}. In contrast, SOC stocks on a 3 yr conventional (CONV) rotation, which did not receive compost, declined by 0.25 Mg ha^{-1} yr^{-1}. Nitrate-N did not accumulate in the soil profile under CONS management, as it was largely influenced by previous crop. In contrast, available P increased with compost addition under CONS management, leading to surface buildup and downward movement in the soil profile. At 0–120 cm depth, the CONS rotations showed 26%–53% higher available P than CONV rotations between 2005 and 2011. Apart from a caveat regarding potential P accrual, the CONS management package in this study was validated as soil building for irrigated cropping systems in southern Alberta.

Key words: soil nutrients, soil quality, irrigation, rotations.

Résumé : La plus forte production de pommes de terre (*Solanum tuberosum* L.), de haricots (*Phaseolus vulgaris* L.) et de betteraves sucrières (*Beta vulgaris* L.) grâce à l'irrigation, dans le sud de l'Alberta, au cours des années 1990, a entraîné la tenue d'une étude de 12 ans (de 2000 à 2011) dont le but était d'évaluer les pratiques de conservation (CONS) pour ces plantes, cultivées en assolement de 3 à 6 ans. Les pratiques de conservation comprenaient le travail réduit du sol, l'usage de cultures-abris, l'application de compost et la culture du haricot en rangs serrés. Douze ans plus tard, la concentration de C organique (CO) à une profondeur de 0 à 30 cm avait augmenté annuellement de 0,48 Mg par hectare pour l'assolement de cinq ans CONS, ce qui est cohérent avec la quantité moyenne de compost ajoutée (154 Mg ha^{-1}). À l'inverse, la concentration de CO de l'assolement de 3 ans ordinaire, sans application de compost, avait diminué annuellement de 0,25 Mg ha^{-1}. Le N-nitrate ne s'est pas accumulé dans le profil des sols bénéficiant des pratiques de conservation, car ce paramètre est largement influencé par la culture antérieure. En revanche, l'addition de compost du traitement CONS a augmenté la concentration de P disponible, ce qui a entraîné l'accumulation en surface et le déplacement vers le bas de cet élément, dans le profil. À une profondeur de 0 à 120 cm, la concentration de P disponible dans les assolements CONS était de 26 à 53 % plus élevée que celle observée dans les assolements sans conservation, entre 2005 et 2011. Hormis la possibilité d'une accumulation de P, les pratiques de conservation examinées dans le cadre de cette étude contribuent à enrichir le sol des systèmes agricoles sous irrigation dans le sud de l'Alberta. [Traduit par la Rédaction]

Mots-clés : éléments nutritifs du sol, qualité du sol, irrigation, assolements.

Received 18 November 2016. Accepted 1 February 2017.

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Abbreviations: **AP**, available phosphorus; **CONS**, conservation management; **CONT**, continuous; **CONV**, conventional management; **EC**, electrical conductivity; **POM-C**, particulate organic matter carbon; **POM-N**, particulate organic matter nitrogen; **SOC**, soil organic carbon; **TC**, total carbon; **TN**, total nitrogen; **TP**, total phosphorus.

*Newton Z. Lupwayi currently serves as an Editor; peer review and editorial decisions regarding this manuscript were handled by Aime Messiga.

Introduction

Irrigated agriculture has been an integral part of the economic and social fabric of southern Alberta since the early 1900s. Although irrigation encourages crop diversification and value-added processing, it is also recognized as a large consumptive user of water, placing a high demand on the limited water resources available in southern Canadian prairie river basins. Although the irrigation sector has made significant gains in water use efficiency (Bennett et al. 2015), challenges persist as the sector continues to increase productivity from a finite resource. One specific challenge is maintenance of soil quality on irrigated land. Typical irrigated row crops (e.g., potato, sugar beet, and dry bean) produce less residue (compared with forages or cereals) for return to the soil, which may compromise soil organic carbon (SOC) if rotations include a higher frequency of row crops. A further issue is that potato and sugar beet rely on intensive seedbed preparation and being root crops, a large degree of soil disturbance at harvest. As such, wind erosion (Coen et al. 2004) and to a lesser extent water erosion, represent risks to soil quality on irrigated land.

These concerns prompted the establishment of a rotation study in 2000 with a focus on conservation (CONS) management and maintenance of soil quality on irrigated land. The rotations included potato, sugar beet, dry bean, and soft white spring wheat (*Triticum aestivum* L.), as well as timothy (*Phleum pratense* L.) and oat (*Avena sativa* L.) in the longest 6 yr rotation. Four CONS management practices were selected, and crop sequences within rotations decided in consultation with agricultural organizations representing potato, sugar beet, and dry bean growers in Alberta. The CONS rotations were built around four specific management practices applied as a package: (1) zero or reduced tillage where possible in the rotation; (2) fall-seeded cover crops; (3) partial replacement of fertilizer N and P with composted cattle manure; and (4) narrow-row dry bean. Rationales for selecting these practices follow.

By the late 1990s, zero or reduced tillage had been widely adopted in dryland rotations on the Canadian prairies, leading to increased SOC and reduced erosion risk (Larney et al. 1994). However, adoption on irrigated land was limited, as potato and sugar beet respond to intensively worked seedbeds, and being root crops, harvesting causes major soil disturbance. However, reduction in tillage was feasible for dry bean, wheat, or forages grown in CONS rotations with potato or sugar beet.

Cover crops are important components of conservation cropping systems (Delgado et al. 2007), providing surface cover during the vulnerable wind erosion period, which can extend from potato harvest (mid-September) to dry bean seeding (mid-May). They also act as a source of soil fertility, suppress weeds and pests (Moyer and Blackshaw 2009), and scavenge soil NO_3-N remaining after harvest, reducing the risk of leaching to groundwater (Weinert et al. 2002).

Composting had emerged in the 1990s as an alternative handling practice for the large volumes of manure produced by the beef cattle feedlot industry in southern Alberta (Larney et al. 2006). Growers were interested in compost's potential for replenishing SOC, partially substituting for N and P fertilizer inputs, and improving soil physical properties such as water retention, aggregate stability, and infiltration. There was also evidence that compost addition may suppress potato diseases (Conn and Lazarovits 1999).

Also by the late 1990s, solid-seeded narrow-row dry bean production was becoming an option on the Canadian prairies (Shirtliffe and Johnston 2002) as plant breeders selected for upright growth, early maturity, and improved pod clearance traits. Solid-seeded dry bean is planted with conventional grain drills in narrow rows (17.5–40 cm), thereby dispensing with interrow cultivation and hence reducing tillage intensity (Blackshaw et al. 2007). At harvest, they can be swathed or direct combined, which leaves standing stubble in narrow rows, and hence some protection against wind erosion, instead of undercut like conventional wide-row dry bean, which leaves loose unanchored stubble and increases wind erosion risk.

Lal and Stewart (1992) discussed the concepts of "soil-building" and "soil-degrading" practices in the context of sustainable soil management. Understanding the impact of management practices on soil quality changes, be they soil building or soil degrading, will help to assist growers in determining the best management practices. The specific objective of this paper was to look at changes in soil properties as the study evolved over 12 yr, starting with baseline samples (fall 1999), before treatments were imposed, through samples taken every 3 yr (fall 2002, 2005, and 2008) to the end of the study (fall 2011). Li et al. (2015) compared surface (0–7.5 cm) soil quality attributes on a subset of treatments (wheat or oat phases only, i.e., 28 plots) at the end of the study (fall 2011). After 12 yr, particulate organic matter carbon (POM-C) and particulate organic matter nitrogen (POM-N) showed >145% increases (POM-C, 2.2–5.8 Mg ha^{-1}; POM-N, 0.20–0.49 Mg ha^{-1}) with CONS management. Aggregate stability of the prewet >1 mm fraction increased significantly, from 13% under CONV to 21% under CONS management. Unlike Li et al. (2015), all phases of each rotation were sampled, and deeper depth increments were examined.

Materials and Methods

Treatments and experimental design

The study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada, in the Bow River Irrigation District of southern Alberta, on an Orthic Brown Chernozemic sandy loam. The site has a 30 yr (1971–2000) normal mean annual precipitation of

303 mm and mean annual air temperature of 5.7 °C. The entire plot area was planted to barley (*Hordeum vulgare* L.) in 1999. Seven rotations were established in spring 2000 (Table 1): continuous wheat (1-CONT), two 3 yr (3-CONV, 3-CONS) and two 4 yr (4-CONV, 4-CONS) rotations, one 5 yr (5-CONS), and one 6 yr (6-CONS) rotation. Similar crop sequences appeared in the 3-CONV and 3-CONS rotations (potato–dry bean–wheat). The 4-CONV and 4-CONS rotations added sugar beet, that is only contracted in ≥4 yr rotations to control sugar beet cyst nematode (*Heterodera schachtii* Schmidt), and also had similar sequences (wheat–sugar beet–dry bean–potato). The 5-CONS rotation was set up to include 2 yr of wheat interspersed with the three row crops (potato–wheat–sugar beet–wheat–dry bean). In the 6-CONS rotation, oat replaced wheat in the cereal phase to allow early harvesting as silage in July and timely planting of timothy in late August. Timothy was retained for 2 yr from planting to stand termination, and followed by the three row crops (oat–timothy–timothy–sugar beet–dry bean–potato). Wheat replaced first year timothy in 2000 and second year timothy in 2000–2001 because it was not feasible to plant timothy before the experiment started, to provide these timothy phases (Table 1).

Each phase of each rotation appeared in each year, resulting in 26 rotation phases (Table 1) in a randomized complete block design with four replicates. With each rotation phase present each year, the number of plots assigned to each rotation increased with rotation length: 4 plots for 1-CONT; 12 each for 3-CONV and 3-CONS; 16 each for 4-CONV and 4-CONS; 20 for 5-CONS; and 24 for 6-CONS for a total of 104 plots. Individual plot dimensions were 10.1 m × 18.3 m with a 2.1 m wide buffer between plots. At the end of the 2011 growing season (12 yr), the 3 yr rotations had completed four cycles; the 4 yr rotations, three cycles; the 5 yr rotation, 2.4 cycles; and the 6 yr rotation, two cycles (Table 1).

Conservation management practices

The four CONS management practices on the CONS rotations (reduced tillage, cover crops, compost addition, and narrow-row dry bean) were outlined by Li et al. (2015), and specifically as they related to dry bean (Larney et al. 2015), potato (Larney et al. 2016*b*), and sugar beet (Larney et al. 2016*a*). The CONV rotations received none of these four practices.

Tillage intensity was reduced under CONS vs. CONV management, particularly for dry bean and potato, and less so for wheat and sugar beet. For example, there was no spring tillage ahead of narrow-row dry bean on CONS rotations that were direct seeded into cover crop residue desiccated with glyphosate 7–10 d prior (3-CONS), shredded wheat stubble (5-CONS), or undisturbed soil (4-CONS, 6-CONS). In contrast, wide-row dry bean on 3- or 4-CONV received one to two passes of a spring-tine harrow. In the fall preceding potato (Table 1), the 3- and 4-CONV rotations were mouldboard ploughed to 25 cm depth. The 3-CONS rotation received one pass of a chisel plow + packers or disc harrow, whereas one pass of a Dammer Diker® (AG Engineering & Development Co. Inc., Kennewick, WA), a reservoir tillage implement, was used on 4-, 5-, and 6-CONS. Fall tillage prior to wheat was usually two passes of a disk harrow or heavy-duty cultivator on CONV vs. one pass on CONS rotations. On the 6-CONS rotation where timothy preceded sugar beet, fall moldboard plowing (to 25 cm depth) followed by one pass of a disk harrow was the only practical tillage option (commencing in fall 2002, Table 1), to prevent remnants of timothy sod from interfering with subsequent sugar beet planting in spring.

Fall-seeded cover crops were used at five entry points (Table 1) in CONS rotations: two entry points in 3-CONS (between potato and dry bean; between dry bean and wheat), and one each in 4- and 5-CONS (between potato and wheat), and 6-CONS (between potato and oat). From 2000 to 2002, two cover crops were used: oat at four entry points (3-CONS, between dry bean and wheat; and 4-, 5-, and 6-CONS) to provide fall cover which then winterkilled to avoid seeding problems in spring, and fall rye (*Secale cereale* L.) at one entry point (3-CONS, between potato and dry bean) which did not winterkill, and when successfully established in fall, regrew to provide surface cover and reduced wind erosion risk in the vulnerable March–April period. However, performance of the oat cover crop was suboptimal (low to nonexistent cover), and it was replaced by fall rye, which was used at all five entry points from fall 2003 onward. The 3-CONS rotation had the greatest proportion of fall-seeded cover crops (7–8 of 12 yr dependent on starting phase, Table 1) with lesser proportions in 4- and 5-CONS (2–3 of 12 yr), and 6-CONS (1–2 of 12 yr). Larney et al. (2017) provided details of fall rye planting dates and biomass yields. Fall rye was chemically desiccated in spring and either left on the soil surface (3-CONS, between potato and dry bean) or soil incorporated during spring tillage (remaining four entry points, Table 1).

Compost produced from straw-bedded beef cattle feedlot manure, as outlined by Larney et al. (2008*b*), was sourced from the same feedlot each year and fall applied (except in 2003, when it was postponed to 13 Apr. 2004 due to wet soil conditions) at five entry points on the CONS rotations only (Table 1). Fall application date ranged from 22 Sept. to 12 Nov. with an average (n = 10) date of 28 Oct. Compost was not applied annually, rather in larger doses at less frequent intervals to supply the bulk of crop P requirements for a 2–3 yr period. Four of the five compost entry points occurred prior to potato: 42 Mg ha^{-1} (fresh wt.) between dry bean and potato on the 4-, 5-, and 6-CONS rotations, and 28 Mg ha^{-1} (fresh wt., except 42 Mg ha^{-1} on starting phase 3 in 2000, Table 1) between wheat and potato on the shorter 3-CONS rotation. This lower rate was also applied at a second entry point in the 5-CONS rotation (between

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Table 1. Rotation histories (2000–2011) including cover crop and compost entry points in CONS rotations.

Rotation[a]	Crop sequence	Starting phase	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
			Rotation history[b]											
1-CONT	W	n/a	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}	{W}
3-CONV	P–DB–W	1	{P	DB	W}	{P	DB	W}	{P	DB	W}	{P	DB	W}
		2	{DB	W	P}	{DB	W	P}	{DB	W	P}	{DB	W	P}
		3	{W	P	DB}	{W	P	DB}	{W	P	DB}	{W	P	DB}
3-CONS	P–DB–W	1	{P[c]	DB[c]	W[d]}	{P[c]	DB[c]	W[d]}	{P[c]	DB[c]	W[d]}	{P[c]	DB[c]	W}
		2	{DB[c]	W[d]	P[c]}	{DB[c]	W[d]	P[c]}	{DB[c]	W[d]	P[c]}	{DB[c]	W[d]	P}
		3	{W[e]	P[c]	DB[c]}	{W[d,f]	P[c]	DB[c]}	{W[d]	P[c]	DB[c]}	{W[d]	P[c]	DB}
4-CONV	P–W–SB–DB	1	{P	W	SB	DB}	{P	W	SB	DB}	{P	W	SB	DB}
		2	{W	SB	DB	P}	{W	SB	DB	P}	{W	SB	DB	P}
		3	{SB	DB	P	W}	{SB	DB	P	W}	{SB	DB	P	W}
		4	{DB	P	W	SB}	{DB	P	W	SB}	{DB	P	W	SB}
4-CONS	P–W–SB–DB	1	{P[c]	W	SB	DB[e,f]}	{P[c]	W	SB	DB[e]}	{P[c]	W	SB	DB}
		2	{W	SB	DB[e]	P[c]}	{W	SB	DB[e]	P[c]}	{W	SB	DB[e]	P}
		3	{SB	DB[e]	P[c]	W}	{SB	DB[e]	P[c]	W}	{SB	DB[e]	P[c]	W}
		4	{DB[e]	P[c]	W	SB}	{DB[e]	P[c]	W	SB}	{DB[e]	P[c]	W	SB}
5-CONS	P–W–SB–W–DB	1	{P[c]	W	SB[d]	W	DB[e]}	{P[c]	W	SB[d]	W	DB[e]}	{P[c]	W
		2	{W	SB[d]	W	DB[e,f]	P[c]}	{W	SB[d]	W	DB[e]	P[c]}	{W	SB
		3	{SB[d]	W	DB[e]	P[c]	W}	{SB[d]	W	DB[e]	P[c]	W}	{SB[d]	W
		4	{W	DB[e]	P[c]	W	SB[d]}	{W	DB[e]	P[c]	W	SB[d]}	{W	DB
		5	{DB[e]	P[c]	W	SB[d,f]	W}	{DB[e]	P[c]	W	SB[d]	W}	{DB[e]	P
6-CONS	P–O–T1–T2–SB–DB	1	{P[c]	O	T1	T2	SB	DB[e]}	{P[c]	O	T1	T2	SB	DB}
		2	{O	T1	T2	SB	DB[e]	P[c]}	{O	T1	T2	SB	DB[e]	P}
		3	{W(T1)	W(T2)	SB	DB[e,f]	P[c]	O}	{T1	T2	SB	DB[e]	P[c]	O}
		4	{W(T2)	SB	DB[e]	P[c]	O	T1}	{T2	SB	DB[e]	P[c]	O	T1}
		5	{SB	DB[e]	P[c]	O	T1	T2}	{SB	DB[e]	P[c]	O	T1	T2}
		6	{DB[e]	P[c]	O	T1	T2	SB}	{DB[e]	P[c]	O	T1	T2	SB}

[a]Naming scheme for rotations is as follows: the integer refers to length of rotation (yr); CONT, continuous; CONV, conventional management; CONS, conservation management.

[b]W, wheat; P, potato; DB, dry bean; SB, sugar beet; O, oat (harvested as silage in July); T1, first year timothy (seeded in previous August); T2, second year timothy; W(T1), wheat replaced T1 as T1 not feasible in 2000 (startup year); W(T2), wheat replaced T2 as T2 not feasible in 2001. Rotation cycles are delineated within braces.

[c]Fall-seeded cover crop entry point: fall rye [except oat, 2000–2002, on 3-CONS (between dry bean and wheat), 4-, 5-, and 6-CONS].

[d]Compost entry point (fall): 28 Mg ha^{-1} fresh wt.

[e]Compost entry point (fall): 42 Mg ha^{-1} fresh wt.

[f]Compost entry point postponed to spring 2004 due to wet soil conditions in fall 2003.

sugar beet and wheat). Compost was broadcast using a manure spreader with horizontal beaters and incorporated by the final tillage operation of the season. Average cumulative compost inputs (fresh wt.) over 12 yr, which depended on the number of entry points (dictated by starting phase) and application rates (Table 1), ranked as follows: 5-CONS, 154 Mg ha^{-1}; 4-CONS, 116 Mg ha^{-1}; 3-CONS, 107 Mg ha^{-1}; and 6-CONS, 77 Mg ha^{-1}. On an annualized basis, this translated to 12.8 Mg ha^{-1} yr^{-1}, 5-CONS; 9.7 Mg ha^{-1} yr^{-1}, 4-CONS; 8.9 Mg ha^{-1} yr^{-1}, 3-CONS; and 6.4 Mg ha^{-1} yr^{-1}, 6-CONS.

Each fall, compost was sampled from the spreader on individual plots. Water content was determined on ~0.5 kg of compost oven-dried at 60 °C for 5 d. Oven-dried subsamples were coarse ground (<2 mm) and finely ground (<150 μm). Total carbon (TC) and total nitrogen (TN) were determined on finely ground material by flash combustion in an elemental analyzer (NA-1500, CE Instruments, Milan, Italy), and total phosphorus (TP) colorimetrically on coarse-ground material after wet digestion. Compost had average concentrations (dry wt. basis ± SE, $n = 11$) of 182 ± 14 g kg^{-1} TC, 15.4 ± 1.0 g kg^{-1} TN, and 5.4 ± 0.4 g kg^{-1} TP, and an average C:N ratio of 11.8 (±0.6) : 1. Using dry weights of compost applied and C, N, and P concentrations, the mass of TC, TN, and TP applied in the form of compost was calculated for each plot.

The fourth conservation management practice was specific to dry bean. The CONV rotations were seeded in wide rows (60 cm) with a custom small plot disc drill and CONS rotations in narrow rows (19–23 cm) with a no-till disc drill (2000–2010) or hoe drill (2011). Only wide-row dry bean on CONV rotations was interrow cultivated in June for weed control except in 2010–2011 when herbicides provided adequate control. Harvest of wide-row dry bean involved undercutting, causing soil disturbance, and pickup with a plot combine. Narrow-row dry bean were direct cut with a plot combine or hand harvested causing no soil disturbance.

Fertilizer inputs

Fertilizers used in the study included N (as ammonium nitrate, 34–0–0), P (as triple superphosphate, 0–45–0), and K (as muriate of potash, 0–0–60). Rates of P are expressed as P_2O_5, and K as K_2O. Although the sale of ammonium nitrate was restricted in 2008, as a public safety measure, enough was securely stored for use until the end of the study.

In the first 2 yr (2000–2001), potato was fertilized in spring. However, in keeping with commercial grower practice, fall fertilizing started in fall 2001. The CONV rotations received 134 kg ha^{-1} N and 67 kg ha^{-1} P_2O_5. Because four of the five compost entry points on the CONS rotations occurred in the fall prior to potato, credit was taken for N and P applied in compost. Fertilizer N was reduced to 62 kg ha^{-1} on 3-CONS that received 28 Mg ha^{-1} of compost, or to 37 kg ha^{-1} on 4-, 5-, 6-CONS that received 42 Mg ha^{-1} of compost. Fertilizer P was not applied to potato on 4-, 5-, and 6-CONS that received the higher compost rate (42 Mg ha^{-1}), whereas 28 kg ha^{-1} of P_2O_5 was applied to 3-CONS (except for the 2004 crop) that received the lower compost rate (28 Mg ha^{-1}). Potato was the only crop that received K fertilizer, at a rate of 67 kg ha^{-1} K_2O on all rotations.

Dry bean received N fertilizer broadcast prior to seeding (CONV) or banded below the seed (CONS). The 3-CONV, 3-CONS, and 5-CONS rotations received 90 kg ha^{-1} N, whereas 4-CONV, 4-CONS, and 6-CONS received 112 kg ha^{-1} N to account for higher N used by the preceding sugar beet crop compared with preceding potato or wheat. Only dry bean grown in 2000–2002 received P (50 kg ha^{-1} P_2O_5) as subsequent soil test P was considered adequate. Dry bean seed was not inoculated with *Rhizobia*.

For sugar beet, N was broadcast in spring 2000 and 2003–2011 or in fall 2000–2001 and soil incorporated by tillage. The application rate was 112 kg N ha^{-1} in the initial year (2000) and when sugar beet followed wheat on 4-CONV, 4-CONS and 5-CONS (2001–2005), and 6-CONS (2001–2002). The rate was increased to 134 kg N ha^{-1} on 4-CONV, and 4-CONS and 5-CONS for the second half of the study (2006–2011). On 6-CONS, sugar beet following timothy was first planted in 2003, and 224 kg N ha^{-1} was applied to counteract lower soil N following a deep-rooted forage. This rate was maintained in 2004 but lowered to 168 kg N ha^{-1}, which was considered adequate for the remainder of the study (2005–2011). Phosphorus fertilizer application coincided with N, as above, except in 2000 and 2003 when P was not applied. Application rates (P_2O_5) were reduced as the study progressed based on soil test P, from 67 kg ha^{-1} (2001–2002), to 56 kg ha^{-1} (2004–2005), to 28 kg ha^{-1} (2006–2011).

In spring 2000–2002, wheat received 112 kg ha^{-1} N, except 5-CONS in which the rate was reduced to 62 kg ha^{-1} to account for N in the 28 Mg ha^{-1} of compost applied the previous fall after sugar beet. From 2003 onwards, all wheat phases received the same rate of 90 kg ha^{-1} N in spring. Wheat did not receive P fertilizer. On 6-CONS, oat received 90 kg N ha^{-1} in spring, and first year, timothy received 112 kg N ha^{-1} in spring and 67 kg N ha^{-1} (2001–2002) or 112 kg N ha^{-1} (2003–2011) after the first cut in July. Second year timothy received 112 kg N ha^{-1} (2002) or 146 kg N ha^{-1} (2003–2011) in spring and 67 kg N ha^{-1} (2002) or 78 kg N ha^{-1} (2003–2011) after the first cut. First year timothy in 2001 and first and second year timothy in 2001–2002 received 32 kg ha^{-1} of P_2O_5, after which P addition to timothy was discontinued due to adequate soil test P.

Crop management

Herbicides, insecticides, and fungicides were used as required for adequate weed, insect, and disease control, with details provided by Larney et al. (2015, 2016*a*, 2016*b*). All crops were irrigated using a wheel-move system to maintain soil water content at ≥50% field capacity. Plots could be individually irrigated using four quarter-circle sprinklers. Mean annual irrigation amounts (n = 12) were 421 mm for potato, 333 mm for dry bean, 440 mm for sugar beet, 325 mm for wheat, 145 mm for oat, and 444 mm for timothy. Each fall, mature crops were harvested for yield and quality assessment as reported by Larney et al. (2015, 2016*a*, 2016*b*). Oat on 6-CONS was harvested as silage in July, and timothy on 6-CONS was harvested in first (late June to mid-July) and second (September to early October) cuts.

Soil sampling

Fall soil sampling was conducted five times over the duration of the study, at 3 yr intervals on all 104 plots. Sampling extended over 4–7 d with average dates of 20 Oct. 1999 (baseline), 4 Oct. 2002, 1 Nov. 2005, 14 Oct. 2008, and 29 Sept. 2011 (end of study). Samples were taken prior to compost applications which occurred in fall 2002, 2005, and 2008.

For baseline sampling in 1999, one narrow core (29 mm diam.) to 60 cm depth and one wide core (67 mm diam.) to 15 cm depth was taken from the centre of each plot. The narrow core was divided into 0–7.5, 7.5–15, 15–30, and 30–60 cm depth increments whereas the wide core was split into 0–7.5 and 7.5–15 cm depths increments. Narrow and wide cores were pooled by depth (0–7.5 and 7.5–15 cm) to provide one sample for each increment. All further sampling was done with wide (67 mm diam.) cores. In 2002, cores were taken to 30 cm depth at three locations (one-quarter-, half-, and three-quarter-way points) on a transect at the centre long axis of the plots. Cores were split into 0–7.5, 7.5–15, and 15–30 cm depth increments, and the three locations pooled to form one composite sample for each depth increment. At the half-way location, one 30–60 cm depth core was also taken. In 2005, cores were taken to 120 cm depth at three locations on a transect similar to 2002. Deeper increments were added to monitor NO_3-N leaching as the study progressed. Each core was split into 0–7.5, 7.5–15, 15–30, 30–60, 60–90, and 90–120 cm depth increments. Cores were pooled by depth to arrive at one sample per increment. The 2005 sampling protocol was retained for 2008 and 2011.

Soil analyses

Soil bulk density was estimated from dry weight in a known core volume calculated from an oven-dried (105 °C for 24 h) subsample for water content. Corrections for volume contributed by coarse rock fragments were made in 2005, 2008, and 2011 by removing and weighing fragments >5 mm diam. with an assumed density of 2.65 g cm^{-3}. Air-dried soils were coarse ground (<2 mm) and a subsample fine ground (<150 μm) on a roller mill for TC and TN determination in an elemental analyzer (CE Instruments, Milan, Italy). Inorganic C was measured by the method of Amundson et al. (1988) and SOC estimated as TC — inorganic C. Nitrate-N was extracted using 2 mol L^{-1} KCl and determined colorimetrically on an AutoAnalyzer II (Technicon Instruments Coro, Tarrytown, NY). Available phosphorus (AP) was determined colorimetrically on a modified Kelowna extract (Ashworth and Mrazek 1995). Using soil bulk density data and SOC, NO_3-N, and AP concentrations, nutrient stocks were estimated on an equivalent mass basis, similar to Ellert and Bettany (1995). pH and EC were determined (1999 excepted) on a 2:1 deionized water : soil extract (60 mL of water : 30 g of soil, shaken for 1 h) and read on a pH–conductivity meter calibrated with 0.1 mol L^{-1} KCl.

Statistical analyses

All data were tested for outliers (PROC UNIVARIATE) prior to analysis with PROC MIXED (SAS Institute Inc. 2010) with rotation as a variable. Orthogonal contrasts compared overall management effects: CONV (average of 3- and 4-CONV) vs. CONS (average of 3-, 4-, 5-, and 6-CONS). For the 1999 baseline soil samples, the analysis was conducted as if the rotation treatments were in place, to provide a measure of soil uniformity on the experimental site. The analysis (1999 excepted) was also conducted with previous crop (dry bean, potato, sugar beet, wheat, timothy, and oat) as a variable (i.e., across all rotations). The UNIVARIATE procedure indicated that soil EC did not conform to a normal distribution, and these data were therefore $\log_e(x)$-transformed before analysis.

Results and Discussion

Soil organic carbon

Baseline SOC stocks in 1999 were not affected by intended rotation treatments (Table 2), as would be expected, when treatments were not yet in place. This demonstrated the uniformity of the experimental site. As early as 3 yr into the study (fall 2002), significant rotation effects on SOC became apparent at 0–7.5 and 7.5–15 cm depths. The 5-CONS rotation was significantly higher than the 3-CONS (11.9 vs. 10.4 Mg ha^{-1}) and both CONV rotations (9.6–9.7 Mg ha^{-1}) at 0–7.5 cm depth, and significantly higher than 6-CONS (13.3 vs. 11.3 Mg ha^{-1}) and both CONV rotations (11.0–11.2 Mg ha^{-1}) at 7.5–15 cm depth.

In 2005, the 5-CONS rotation was significantly higher than 6-CONS (13.9 vs. 12.2 Mg ha^{-1}) and both CONV rotations (9.5–9.8 Mg ha^{-1}) at 0–7.5 cm, whereas all four CONS rotations and the 1-CONT rotation were significantly higher than both CONV rotations (12.1–13.2 vs. 10.2–10.7 Mg ha^{-1}) at 7.5–15 cm depth. These trends (CONS > CONV rotations) continued at both depths in 2008 and 2011 (Table 2). In 2011, there was no significant difference in organic C stocks among the four CONS rotations at 0–7.5 cm. However, at 7.5–15 cm, the

Table 2. Effect of rotation and soil management on organic C at 0–7.5, 7.5–15, and 15–30 cm depths, in 1999–2011.

	Organic C (Mg ha^{-1}) at:														
	0–7.5 cm depth					7.5–15 cm depth					15–30 cm depth				
	1999	2002	2005	2008	2011	1999	2002	2005	2008	2011	1999	2002	2005	2008	2011
Rotation[a]															
1-CONT	10.8	11.9ab	12.1abc	11.1bc	11.8a	12.4	12.1abc	12.1a	12.0bc	11.8bc	18.5	17.8	17.6	18.4	16.1
3-CONV	11.3	9.6c	9.5 d	9.5c	8.8b	11.7	11.2bc	10.7b	10.4c	10.3c	17.0	16.9	17.4	17.5	17.3
3-CONS	9.9	10.4bc	12.7ab	11.8b	12.0a	12.0	12.2abc	12.4a	12.8b	13.0b	18.0	15.7	16.3	16.7	17.1
4-CONV	9.9	9.7c	9.8 cd	9.6c	8.8b	11.8	11.0c	10.2b	10.2c	10.1c	14.9	14.8	16.2	16.6	15.5
4-CONS	9.7	11.4ab	12.8ab	12.0b	12.3a	10.8	12.3ab	12.7a	12.9b	12.7b	18.5	15.6	16.3	16.4	16.2
5-CONS	11.8	11.9a	13.9a	14.0a	13.3a	11.5	13.3a	13.2a	14.4a	14.7a	16.8	16.6	17.5	17.9	18.1
6-CONS	10.5	11.2ab	12.2b	11.8b	12.4a	11.2	11.3bc	12.7a	12.6b	12.7b	17.2	14.8	16.2	17.4	16.9
P value	0.29	<0.001	<0.001	<0.001	<0.001	0.78	<0.001	<0.001	<0.001	<0.001	0.20	0.16	0.52	0.70	0.24
Management[b]															
CONV	10.6	9.7b	9.7b	9.5b	8.8b	11.8	11.1b	10.5b	10.3b	10.2b	16.0	15.8	16.8	17.0	16.4
CONS	10.5	11.2a	12.9a	12.4a	12.5a	11.4	12.3a	12.8a	13.2a	13.3a	17.6	15.7	16.6	17.1	17.1
P value	0.87	<0.001	<0.001	<0.001	<0.001	0.47	0.002	<0.001	<0.001	<0.001	0.06	0.79	0.72	0.96	0.32

Note: Within columns, means followed by different letters are significantly different from each other (LSD, $P < 0.05$).

[a]Naming scheme for rotations is as follows: the integer refers to length of rotation (yr); CONT, continuous; CONV, conventional management; CONS, conservation management.

[b]Management contrast: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5-, and 6-CONS).

5-CONS rotation was significantly higher than the other CONS rotations (14.7 vs. 12.7–13.0 Mg ha^{-1}).

Differences in SOC stocks due to rotation were confined to the surface layers (0–7.5 and 7.5–15 cm), with no significant effects at the deeper 15–30 cm layer (Table 2). The 3- and 4-CONV rotations involved mouldboard ploughing that inverted the surface layer to 22–25 cm depth. This introduced crop residue to 15–30 cm, so that differences between CONV and CONS rotations were less likely to occur at this depth. Nonetheless, there was a significant linear trend in SOC stocks with time at 15–30 cm depth on the 5-CONS rotation, increasing from 16.8 to 18.1 Mg ha^{-1} between 1999 and 2011 (Table 2). The regression equation for the relationship was

$$y = 16.6 + 0.13x \qquad (R^2 = 0.87, P = 0.02) \tag{1}$$

which showed vertical SOC migration of 0.13 Mg ha^{-1} yr^{-1} to this depth. In contrast, Li and Evanylo (2013) found that C did not accumulate in the soil profile below the surface soil zone of incorporation (<15 cm) after long-term or large single-dose application of poultry litter – yard waste compost or biosolids.

In 2002, the management contrast effect on SOC stocks was significant (CONS > CONV) at 0–7.5 and 7.5–15 cm depths and increased in magnitude with time (Table 2). For example, SOC stocks were 15% higher under CONS vs. CONV management at 0–7.5 cm depth in 2002. This increased to 33% higher in 2005, 31% in 2008, and 42% in 2011 (12.5 vs. 8.8 Mg ha^{-1}). Although Li et al. (2015) reported a similar increase (50%) in SOC at 0–7.5 cm depth on a subset of plots in 2011, the increase in POM-C, the most labile C fraction, was >3 times higher at 164%. At 7.5–15 cm depth, C stocks were 11% higher under CONS management in 2002, increasing to 22% higher in 2005, 28% in 2008, and 30% in 2011. As animal manure contains organic matter, an increase in SOC stocks is generally expected following its land application (Grandy et al. 2002). However, there is great variability in the magnitude of SOC increases (Maillard and Angers 2014) with some studies showing an SOC decline after manure addition (Franzluebbers et al. 2001; Angers et al. 2010).

The behaviour of SOC stocks (0–30 cm depth) with time was highly dependent on rotation, with significant positive responses on the 4- and 5-CONS rotations, but a significant negative response on 3-CONV (Fig. 1*a*). The slopes of the relationships showed that SOC increased by 0.48 (5-CONS) and 0.30 Mg ha^{-1} yr^{-1} (4-CONS). These increases were in line with average cumulative amounts of compost added over 12 yr on 5-CONS (154 Mg ha^{-1}) and 4-CONS (116 Mg ha^{-1}). In contrast, SOC stocks on 3-CONV declined at a rate of 0.25 Mg ha^{-1} yr^{-1}. Expressing SOC changes in 2011 as a percent of initial C stocks (1999) resulted in 12% (5-CONS) and 9% (4-CONS) gains, or a 9% loss (3-CONV). Soil organic C did not significantly accrue on 6- and 3-CONS rotations (despite cumulative additions of 77–107 Mg ha^{-1} over 12 yr) nor decline on 1-CONT or 4-CONV rotations (Fig. 1*a*).

Whalen et al. (2008) reported that after 5 yr, compost-amended plots (up to 15 Mg ha^{-1}, dry wt., annually) in Quebec gained 1.35–2.02 Mg C ha^{-1} yr^{-1} in the SOC pool, higher than those from our study, perhaps due to their

Fig. 1. Effect of rotation on relationships between age of study and (*a*) soil organic carbon and (*b*) total nitrogen stocks (0–30 cm depth). NS, nonsignificant ($P > 0.05$).

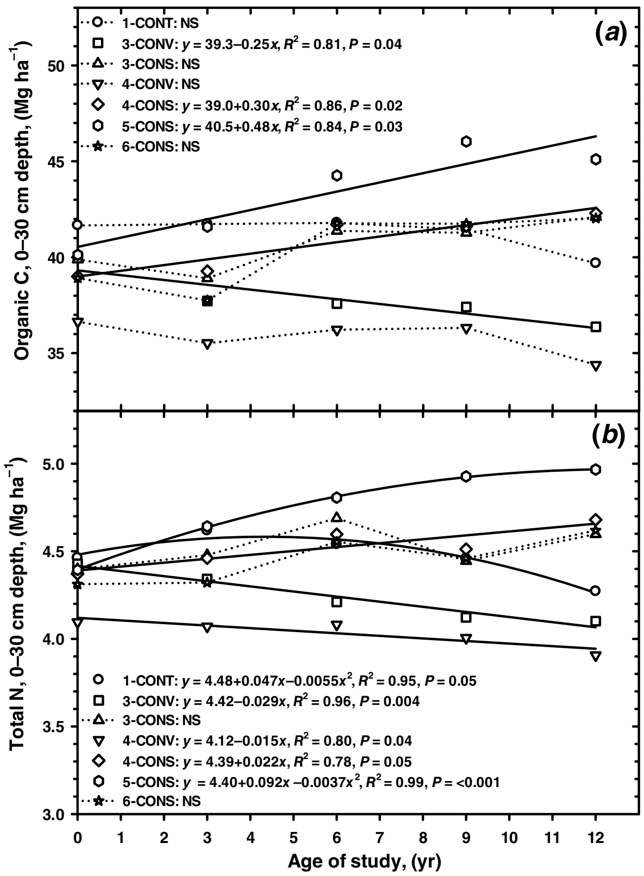
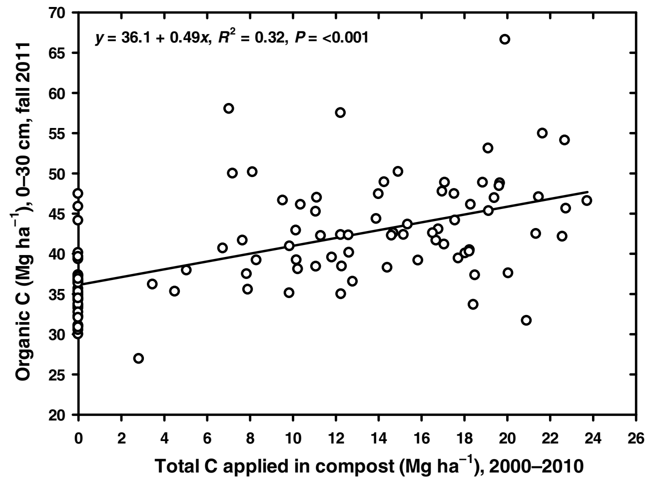


Fig. 2. Relationship between total carbon applied in compost (2000–2010) and soil organic carbon (0–30 cm depth) at the end of the study, in fall 2011.



shallower sampling depth (0–15 cm) as well as substantially higher compost C concentration (401 g C kg^{-1}) compared with our material (182 g C kg^{-1}). Carter et al. (2003) reported an SOC loss of 4% at 0–20 cm depth in 2 yr rotations of potato–Italian ryegrass (*Lolium multiflorum* Lam.) over 11 yr in Prince Edward Island. Losses increased to 16% in a potato–barley rotation. Parton et al. (1996) indicated that C inputs >2 Mg ha^{-1} yr^{-1} are required to maintain SOC on arable crop rotations, and Wang et al. (2016) recently confirmed this critical value for global wheat cropping systems. Li et al. (2015) reported cumulative C inputs from crops (above-ground residue, roots, and cover crops) and compost for the duration of this 12 yr study. Annualizing these data gave C inputs ranging from 2.5 (4-CONV) to 4.7 Mg ha^{-1} yr^{-1} (5-CONS). Carbon inputs for the other rotations were 2.8 (3-CONV), 3.5 (1-CONT), 3.8 (3- and 6-CONS), and 3.9 Mg ha^{-1} yr^{-1} (4-CONS). Our results showed that 2.5 Mg C ha^{-1} yr^{-1} was insufficient to maintain SOC stocks on the 4-CONV rotation, indicative of an intensive 4 yr (row crop:cereal ratio, 3:1) irrigated rotation in the region, with no effort to enhance soil conservation. However, slightly higher annual inputs of 2.8 Mg C ha^{-1} yr^{-1} on 3-CONV (row crop:cereal ratio, 2:1) averted a significant decline in SOC between 1999 and 2011 (Fig. 1*a*). The CONS rotations benefited from supplemental compost C (0.8–1.7 Mg ha^{-1} yr^{-1}), which led to annual C inputs ~2 times higher (3.8–4.7 Mg C ha^{-1} yr^{-1}) than the critical value of 2 Mg C ha^{-1} yr^{-1}.

Of the four CONS management practices, compost addition was likely the main driver of increased SOC stocks on the CONS rotations. Bolinder et al. (1999) reported an average sensitivity index of 1.82 for organic amendment compared with 1.26 for reduced tillage for a range of soil quality attributes in eastern Canada. Pritchett et al. (2011) showed a greater overall influence of organic amendments on selected soil quality properties (TC, POM-C, and enzyme activities) than cover crops or reduced tillage for organic vegetable production. However, the other CONS practices (reduced tillage, cover cropping, and narrow-row dry bean production), and the presence of 2 yr of timothy (specific to 6-CONS), also likely contributed to C accumulation on the CONS rotations. Using a global database of long-term experiments, West and Post (2002) reported C sequestration rates of 0.57 Mg ha^{-1} yr^{-1} (0–30 cm depth) following a change from conventional tillage to no-till. In the same study, enhanced rotation complexity (no monoculture or fallow, increased crop diversity) sequestered an average of 0.20 Mg C ha^{-1} yr^{-1}.

Cumulative (2000–2010) C applied in compost explained 32% of the variability (Fig. 2) in SOC (0–30 cm) at the end of the experiment (fall 2011). Many studies have estimated C retention coefficients from the slope of such relationships as outlined in a meta-analysis by Maillard and Angers (2014). In our study, SOC increased by 0.49 Mg ha^{-1} for each 1 Mg ha^{-1} of added compost C, which suggests that 49% of compost C was retained as SOC at the end of the study. Li et al. (2015) reported that

Table 3. Effect of rotation and soil management on total N at 0–7.5 and 7.5–15 cm depths, in 1999–2011.

	Total N (Mg ha^{-1}) at:									
	0–7.5 cm depth					7.5–15 cm depth				
	1999	2002	2005	2008	2011	1999	2002	2005	2008	2011
Rotation[a]										
1-CONT	1.11	1.20ab	1.22abc	1.13bc	1.19ab	1.31	1.31abc	1.29ab	1.29bc	1.26bc
3-CONV	1.15	1.06b	1.06c	1.04c	1.01bc	1.28	1.22c	1.16bc	1.13 cd	1.14c
3-CONS	1.03	1.19ab	1.35ab	1.24b	1.27a	1.29	1.34abc	1.32a	1.37ab	1.40b
4-CONV	1.05	1.09b	1.10c	1.06c	0.99c	1.26	1.23c	1.09c	1.11 d	1.12c
4-CONS	1.04	1.22a	1.35ab	1.30b	1.29a	1.22	1.33ab	1.35a	1.36b	1.37b
5-CONS	1.19	1.25a	1.42a	1.45a	1.38a	1.23	1.38a	1.38a	1.48a	1.53a
6-CONS	1.08	1.20a	1.29b	1.24b	1.31a	1.23	1.24ab	1.33a	1.31b	1.36b
P value	0.55	0.008	<0.001	<0.001	<0.001	0.89	0.007	<0.001	<0.001	<0.001
Management[b]										
CONV	1.10	1.08b	1.08b	1.05b	1.00b	1.27	1.23b	1.13b	1.12b	1.13b
CONS	1.09	1.21a	1.35a	1.31a	1.31a	1.24	1.32a	1.35a	1.38a	1.41a
P value	0.77	<0.001	<0.001	<0.001	<0.001	0.48	0.003	<0.001	<0.001	<0.001

Note: Within columns, means followed by different letters are significantly different from each other (LSD, $P < 0.05$).
[a]Naming scheme for rotations is as follows: the integer refers to length of rotation (yr); CONT, continuous; CONV, conventional management; CONS, conservation management.
[b]Management contrast: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5- and 6-CONS).

28% of added compost C was retained at 0–7.5 cm depth at the end of the study (for a subset 28 plots planted to wheat or oat in 2011). Our higher value shows that up to 21% of retained C (49%–28% = 21%) occurred at 7.5–30 cm depth. Maillard and Angers (2014) estimated a global manure-C retention coefficient of 12% (0–30 cm) for an average study duration of 18 yr. Our value is much higher possibly due to (1) a shorter timeline (12 vs. 18 yr); (2) use of compost (with more stable C and hence greater retention than fresh manure); and (3) employment of other CONS practices, as mentioned previously, which could also contribute to increased C stocks.

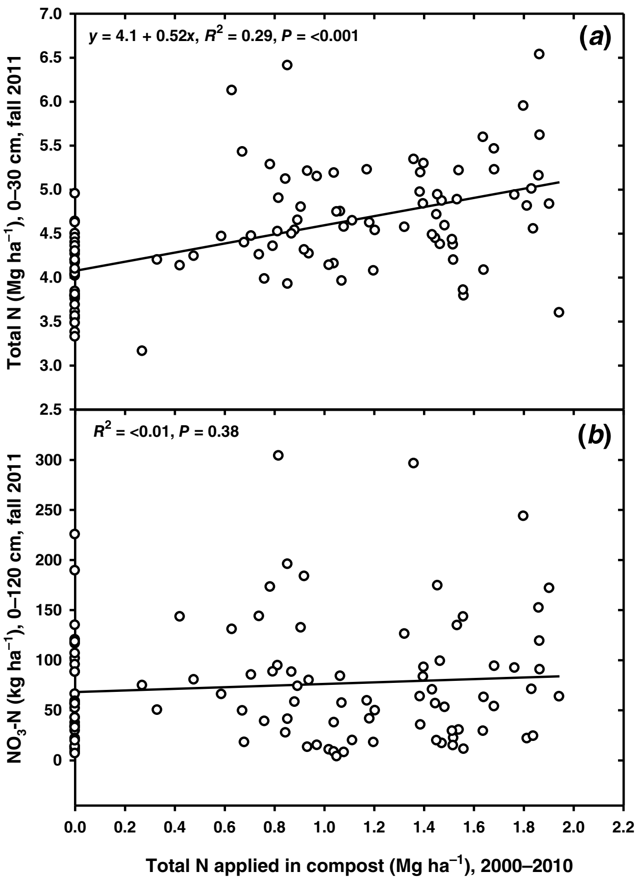
Total nitrogen

Rotation effects on TN closely mirrored those of SOC with accrued stocks at 0–7.5 and 7.5–15 cm on CONS rotations (Table 3) and no effect at 15–30 cm depth (data not shown). As with SOC, the management contrast became more pronounced with time, with TN stocks on CONS increasing from 12% higher than CONV in 2002 to 31% higher in 2011 at 0–7.5 cm depth, and from 7% higher in 2002 to 25% higher in 2011 at 7.5–15 cm depth.

The 1-CONT and 5-CONS rotations showed significant quadratic relationships between TN stocks and time (Fig. 1*b*). Total N stocks on 1-CONT started to decline after 4 yr, whereas those on 5-CONS were still increasing after 12 yr but at a slower rate than earlier in the study, e.g., 0.04 Mg ha^{-1} between 2008 and 2011, compared with 0.24 Mg ha^{-1} between 1999 and 2002. As with OC, there was a significant positive linear response with time for TN on 4-CONS (+0.022 Mg ha^{-1} yr^{-1}) and a negative response on 3-CONV (−0.029 Mg ha^{-1} yr^{-1}). In addition, there was a significant negative response on 4-CONV (−0.015 Mg ha^{-1} yr^{-1}), about half that of 3-CONV. Total N changes in 2011, as a percent of initial N stocks (1999) for the rotations with significant relationships over time, were 1-CONT, −4%; 4-CONV, −5%; 3-CONV, −7%; 4-CONS, +7%; and 5-CONS, +13%. As with OC, lower cumulative additions of compost on 6- and 3-CONS (77–107 Mg ha^{-1}) did not elicit significant TN changes over time. Whalen et al. (2008) reported that after 5 yr, compost-amended plots (up to 15 Mg ha^{-1}, dry wt., annually) in Quebec gained 0.18–0.24 Mg N ha^{-1} yr^{-1} in the TN pool, higher than values reported from our study, perhaps due to their shallower sampling depth (0–15 cm) as well as substantially higher compost N concentration (20.7 g N kg^{-1}) compared with our material (15.4 g N kg^{-1}).

Cumulative (2000–2010) N applied in compost explained 29% of the variability in soil TN (Fig. 3*a*) at 0–30 cm depth at the end of the experiment (fall 2011). Total N increased by 0.52 Mg ha^{-1} for each 1 Mg ha^{-1} of added compost N, which suggests that 52% of compost N was retained over the course of the study. However, as with OC, the other CONS practices (reduced tillage, cover crops, and narrow-row dry bean production), and the presence of 2 yr of timothy on the 6-CONS rotation, may also have contributed to N accumulation on the CONS rotations, rendering the 52% retention value an overestimate. However, Olson et al. (2010*b*) used a decay series of 13% (proportion of compost organic N subsequently made available) in the year of application, with residual decay of 7% in year 2 and 4% in year 3. This gave a cumulative decay of 24% over 3 yr, leaving a balance of 76% retained. The difference between the

Fig. 3. Relationships between total nitrogen applied in compost (2000–2010) and (*a*) soil total nitrogen (0–30 cm depth) and (*b*) soil NO_3-N (0–120 cm depth), at the end of the study, in fall 2011.



retained values in each study (76%–52% = 24%) may have been slowly released >3 yr after application.

NO_3-N

The effect of rotation was nonsignificant on shallow (0–60 cm depth) NO_3-N at all five sampling times (Table 4). At the deeper depth (60–120 cm), the rotation effect was significant only at the end of the study in fall 2011, when the 3-CONS rotation had significantly higher NO_3-N (44 kg ha^{-1}) than all other rotations (13–27 kg ha^{-1}), except 3-CONV (28 kg ha^{-1}). For overall profile (0–120 cm) NO_3-N, rotation was nonsignificant in fall 2005, 2008, and 2011. The rotation management contrast on NO_3-N (CONV vs. CONS) was nonsignificant at all 11 depth × sampling time combinations.

In contrast to rotation, the previous crop effect on NO_3-N was significant at all 10 depth × sampling time combinations measured (Table 4). At 0–60 cm depth, in fall 2002, NO_3-N after timothy and sugar beet was 4–14 kg ha^{-1} compared with 37–42 kg ha^{-1} after other crops. In fall 2005, NO_3-N after timothy and sugar beet was significantly lower (12–20 kg ha^{-1}) than wheat and dry bean (31–38 kg ha^{-1}) which were in turn significantly lower than potato (52 kg ha^{-1}). In fall 2008, NO_3-N after timothy (29 kg ha^{-1}) remained significantly lower than potato and dry bean (59–74 kg ha^{-1}) as well as sugar beet (58 kg ha^{-1}), which was not different to dry bean or potato, as in previous samplings. In 2011, sugar beet and timothy (13–22 kg ha^{-1}) again showed significantly lower NO_3-N than dry bean and potato (61–71 kg ha^{-1}).

At 60–120 cm depth, previous crop still exerted a significant effect on NO_3-N (Table 4). In 2005, NO_3-N after sugar beet (7 kg ha^{-1}) was significantly lower than wheat and potato (27 kg ha^{-1}) which were in turn lower than dry bean (39 kg ha^{-1}). In 2008, potato was significantly higher (53 kg ha^{-1}) than all other crops (16–29 kg ha^{-1}), while in 2011, potato (35 kg ha^{-1}) was higher than dry bean (24 kg ha^{-1}), which was higher than sugar beet (4 kg ha^{-1}). Looking at the soil profile to 120 cm depth, significantly lower NO_3-N generally occurred after sugar beet and timothy compared with potato and dry bean in 2005, 2008, and 2011 (Table 4).

Significantly lower NO_3-N following timothy and sugar beet was related to the deeper rooting patterns and hence NO_3-N extraction by these crops. In additional, sugar beet harvest occurred later than potato and dry bean, whereas timothy actively grew until late fall, allowing extended NO_3-N extraction. Nitrate-N in fall was generally significantly higher after potato or dry bean compared with other crops. This may be related to shallower rooting depth of these crops, although in the case of dry bean, it could be due to biological N fixation, even if dry bean is considered a poor N fixer (Bliss 1993; Farid and Navabi 2015). Oat generally showed high NO_3-N in fall, perhaps because plots were harvested early (July) and subsequently seeded to timothy (late August) which had a limited root system to draw down NO_3-N by soil sampling time in fall. Hao et al. (2001) also found that NO_3-N was significantly affected by previous crop in various sequences of sugar beet, legumes [dry bean or pea (*Pisum sativum* L.)], and soft wheat in southern Alberta.

There was a nonsignificant relationship between TN added in compost during the study and soil NO_3-N at the end of the study (Fig. 3*b*), showing that compost addition had no effect on NO_3-N. This corroborates the lack of a rotation effect on NO_3-N where CONS rotations (+ compost) were similar to CONV (− compost), and reiterates that profile NO_3-N was controlled by the previous crop. Our findings suggest that N mineralized from compost was utilized by crops because there was no rotation effect on NO_3-N at 0–120 cm depth at the end of the study. Given that, there was evidence of downward movement of NO_3-N in the 3-CONS rotation at 60–120 cm depth (Table 4), suggesting that some NO_3-N may have been lost to leaching below 120 cm depth.

Taking credit for N mineralized from compost additions, by reducing N fertilizer inputs to 33% on plots in which compost was applied prior to potato, helped to

Table 4. Effect of rotation, soil management, and previous crop on shallow (0–60 cm, 1999, 2002, 2005, 2008, 2011), deep (60–120 cm, 2005, 2008, 2011), and profile (0–120 cm, 2005, 2008, 2011) NO_3-N.

	NO_3-N (kg ha^{-1}) at:										
	0–60 cm depth					60–120 cm depth			0–120 cm depth		
	1999	2002	2005	2008	2011	2005	2008	2011	2005	2008	2011
Rotation[a]											
1-CONT	65	34	24	39	16	26	5	13b	51	44	29
3-CONV	46	39	38	51	44	34	45	28ab	72	96	72
3-CONS	53	36	40	63	63	32	35	44a	67	98	107
4-CONV	56	33	32	43	48	26	29	22b	58	72	69
4-CONS	41	33	37	66	46	25	22	22b	62	88	68
5-CONS	47	31	35	62	36	21	28	27b	50	90	63
6-CONS	52	25	29	59	49	25	25	18b	57	81	64
P value	0.32	0.50	0.54	0.45	0.54	0.64	0.13	**0.03**	0.59	0.48	0.28
Management[b]											
CONV	51	36	35	47	46	28	29	33	64	93	87
CONS	48	31	35	63	49	27	32	24	59	85	71
P value	0.59	0.28	0.93	0.06	0.78	0.72	0.60	0.06	0.51	0.46	0.20
Previous crop											
Dry bean	—[c]	41a	38b	59ab	71a	39a	29b	23b	78a	87b	94a
Potato	—	36a	52a	74a	61a	27b	53a	35a	80a	127a	96a
Sugar beet	—	14b	20c	58ab	13b	7c	18bc	4c	26c	76b	17c
Wheat	—	39a	31b	49bc	29b	27b	16c	29ab	58b	65b	59b
Timothy	—	4b	12c	29c	22b	20bc	23bc	23ab	32c	52b	45bc
Oat	—	42a	27bc	50abc	97a	25abc	27bc	36ab	52abc	77ab	133a
P value	—	**<0.001**	**<0.001**	**0.02**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

Note: Within columns means followed by different letters are significantly different from each other (LSD, $P < 0.05$). *P* values in bold are significant.

[a]Naming scheme for rotations is as follows: the integer refers to length of rotation (yr); CONT, continuous; CONV, conventional management; CONS, conservation management.

[b]Management contrast: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5-, and 6-CONS).

[c]Not applicable. Previous crop was barley on all treatments.

balance the N budget during the experiment. Larney et al. (2016*a*) concluded that compost application in this study did not interfere with N supply or uptake by sugar beet, which is very sensitive to late-season N flushes which can impair extractable sugar yield, as compost was applied 3–5 yr in advance of the sugar beet crop. Our findings agree with D'Hose et al. (2016) who demonstrated that compost (applied at 2 Mg C ha^{-1} yr^{-1}) and cattle and pig slurry (170 kg N ha^{-1} yr^{-1}) for at least 4 yr did not induce higher NO_3-N leaching.

Available phosphorus

At 0–60 cm depth, the effect of rotation on AP was nonsignificant in 1999 (as expected because treatments were not in place) and in 2002 (Table 5). However, by 2005, the 5-CONS rotation showed significantly higher AP (233 kg ha^{-1}) than all other rotations (132–194 kg ha^{-1}) except 3-CONS. By 2008, the 5-CONS rotation had significantly higher AP (316 kg ha^{-1}) than 4-CONS (234 kg ha^{-1}) which was significantly higher than 6-CONS (192 kg ha^{-1}), that was significantly higher than 4-CONV (146 kg ha^{-1}). This trend became even more pronounced in 2011. For the management contrast, CONS rotations showed 33%–57% higher AP than CONV rotations between 2005 and 2011 at 0–60 cm depth. Taking credit for compost P, by reducing P fertilizer to zero for the potato crop following compost addition, did not avert the buildup of P on CONS rotations. Although N is stabilized during composting, finished composts generally show a high P availability, with >70% of TP in the available form (Zvomuya et al. 2006; Larney et al. 2008*b*; Gagnon et al. 2012). Such high availability likely contributed to buildup of AP during the study, as P removal by crops lagged behind P inputs (compost P and fertilizer P).

Initial AP on the study site was relatively high with an average concentration of 70 mg kg^{-1} (0–15 cm) for baseline samples in 1999 (data not shown), slightly more than the agronomic threshold of 60 mg kg^{-1}, above which Alberta crops generally do not respond to added P (Howard et al. 2006). Over the course of the study, AP (0–15 cm) increased on the CONS rotations but remained relatively static on the CONV rotations (data not shown), e.g., by 2011, the management contrast was significantly

Table 5. Effect of rotation and soil management on shallow (0–60 cm, 1999, 2002, 2005, 2008, 2011), deep (60–120 cm, 2005, 2008, 2011), and profile (0–120 cm, 2005, 2008, 2011) available P.

	Available P (kg ha^{-1}) at:										
	0–60 cm depth					60–120 cm depth			0–120 cm depth		
	1999	2002	2005	2008	2011	2005	2008	2011	2005	2008	2011
Rotation[a]											
1-CONT	218	173	132cd	78f	92f	24	14b	20ab	156c	92e	112d
3-CONV	200	205	159bcd	163de	214de	26	22b	15b	185bc	184cd	236c
3-CONS	174	201	200ab	224bc	287bc	23	24ab	18b	222ab	248b	307b
4-CONV	192	193	148d	146ef	186e	27	15b	15b	176c	161de	201c
4-CONS	175	205	194b	234b	298b	22	20b	15b	213bc	250b	314b
5-CONS	174	230	233a	316a	365a	26	33a	31a	258a	349a	389a
6-CONS	189	183	183bc	192cd	239cd	28	17b	13b	211bc	209bc	250c
P value	0.41	0.15	**<0.001**	**<0.001**	**<0.001**	0.77	**0.01**	**0.001**	**<0.001**	**<0.001**	**<0.001**
Management[b]											
CONV	196	199	153b	154b	200b	27	19	15	180b	173b	218b
CONS	178	205	203a	242a	297a	25	23	19	226a	264a	315a
P value	0.09	0.64	**<0.001**	**<0.001**	**<0.001**	0.46	0.16	0.15	**<0.001**	**<0.001**	**<0.001**

Note: Within columns means followed by the same letter are not significantly different from each other (LSD, $P > 0.05$). *P* values in bold are significant.

[a]Naming scheme for rotations is as follows: the integer refers to length of rotation (yr); CONT, continuous; CONV, conventional management; CONS, conservation management.

[b]Management contrast: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5- and 6-CONS).

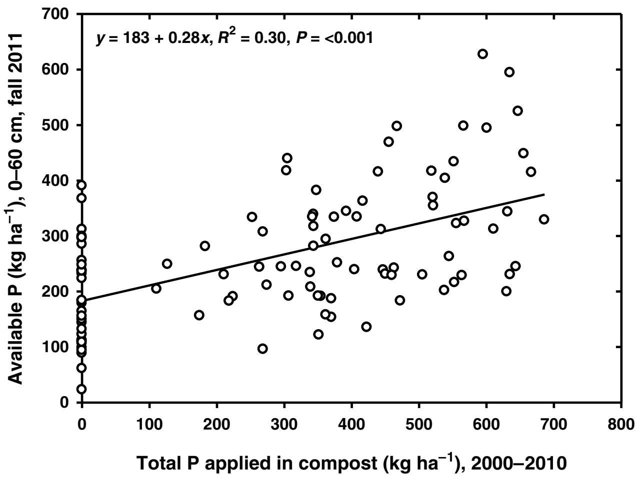
higher on CONS (113 mg kg^{-1}) than CONV rotations (64 mg kg^{-1}). Even the 6-CONS rotation, which received the lowest amount of cumulative compost (77 Mg ha^{-1} or 6.4 Mg ha^{-1} yr^{-1}), showed significantly increased P (85 mg kg^{-1}). This indicated that controlling soil P buildup on CONS rotations is challenging, despite relatively conservative compost application rates. Moreover, efforts were made to limit fertilizer P inputs, e.g., no fertilizer P on potato (after compost application) or wheat, discontinuance after 2002 on dry bean, and declining rates on sugar beet as the study progressed, as mentioned previously. Moulin et al. (2011) cautioned that compost inputs must be monitored to reduce potentially high water-soluble P at the soil surface even though they improved soil C and aggregate stability in dry bean–potato rotations in Manitoba. In New Brunswick, Rees et al. (2014) found that an application rate as low as 4 Mg ha^{-1} yr^{-1} of fresh poultry manure for 3 yr significantly increased soil P (but did not increase SOC). In the absence of organic amendments, Mohr et al. (2015) successfully maintained soil P below agronomic threshold for potato rotations which included wheat, canola (*Brassica napus* L.), and alfalfa (*Medicago sativa* L.) in Manitoba.

At 60–120 cm depth (Table 5), significant effects of rotation on AP were manifest only after 9 yr (fall 2008), when 5-CONS was significantly higher (33 kg ha^{-1}) than all other rotations (14–22 kg ha^{-1}), except 3-CONS (24 kg ha^{-1}). This trend continued in 2011. However, the management contrast (CONV vs. CONS) was nonsignificant at this depth. Deep leaching of P to groundwater is generally considered less of an issue in southern Alberta due to the considerable capacity of calcareous subsoils to adsorb P. However, under irrigation, downward P movement has been documented, at higher cumulative rates of manure, rather than compost. Whalen and Chang (2001) found elevated AP to a depth of 1.5 m, although appreciable increases were only evident to 60 cm. Olson et al. (2010*a*) also found movement of P to >60 cm depth (at manure rates up to 120 Mg ha^{-1} yr^{-1}) after 8 yr on a coarse-textured soil.

For the profile depth to 120 cm, rotation had a significant effect on AP in 2005, 2008, and 2011 (Table 5), with 5-CONS being significantly higher than all other rotations in 2008 (349 vs. 92–250 kg ha^{-1}) and 2011 (389 vs. 112–314 kg ha^{-1}). The 6-CONS rotation was the only CONS rotation not significantly different from the CONV rotations in 2008 and 2011, likely due to less cumulative compost inputs (77 vs. 107–154 Mg ha^{-1}) and the inclusion of deep-rooted timothy for 2 yr. For the management contrast, CONS rotations showed 26%–53% higher AP than CONV rotations between 2005 and 2011 at 0–120 cm depth. The effect of previous crop on AP was nonsignificant for 9 of 10 depth × sampling time combinations (data not shown).

Cumulative (2000–2010) TP applied in compost explained 30% of the variability in AP (Fig. 4) at 0–60 cm depth at the end of the study (fall 2011). Available P increased by 28 kg ha^{-1} for every 100 kg ha^{-1} of added compost TP. Olson et al. (2010*b*) used a decay series of 60% (proportion of compost TP subsequently made available) in the year of application, with residual carryover

Fig. 4. Relationship between total phosphorus applied in compost (2000–2010) and soil available phosphorus (0–60 cm depth) at the end of the study, in fall 2011.



of 15% in year 2 and 8% in year 3. They assumed that the residual effect was negligible after 3 yr. Over a long-term study such as this, decay series for added compost P overlap, and as such, the average value of the decay series, 28% [(60% + 15% + 8%) ⁄3], was similar to the slope of the relationship in Fig. 4.

Soil pH

At 0–7.5 cm depth, the effect of rotation on pH was nonsignificant in 2002 (Table 6). In 2005, both the 1-CONT (6.93) and 4-CONV (7.34) rotations had significantly lower pH than the 4-CONS rotation (7.58). This trend extended to 7.5–15 cm depth in which 1-CONT, 4-CONV, and 3-CONV (6.92–7.32) were significantly lower than 4-CONS (7.58). In 2008, the 4- and 5-CONS rotations had significantly higher pH (7.43–7.45) than 4-CONV (7.26) at 0–7.5 cm, which was in turn higher than 1-CONT (6.76). A similar trend occurred at 7.5–15 cm depth in 2008. By fall 2011, the 4-CONS rotation (7.77) was significantly higher than the 3- and 4-CONV rotations (7.49–7.53) that were in turn higher than 1-CONT (6.87), and again a similar trend was found at 7.5–15 cm.

The management contrast revealed that CONS management resulted in significantly higher pH in fall 2005 and 2011 at 0–7.5 cm and in fall 2005, 2008, and 2011 at 7.5–15 cm depth. The increase ranged from 0.15 to 0.28 pH units. The effect of rotation on pH was nonsignificant at 15–30 cm depth at all four sampling times (data not shown). However, the management contrast revealed that a significant increase in pH due to CONS management (7.86 vs. 7.71) extended to 15–30 cm depth at the final sampling (fall 2011). The ability of livestock manure or compost to increase soil pH has been attributed to buffering from bicarbonate and organic acids in manure (Whalen et al. 2000). Eghball (1999) reported that manure and compost contained significant amounts of $CaCO_3$ (added to diets of finishing cattle to meet Ca requirements) which caused a liming effect, especially when applied to low pH soils. Calcium carbonate was added to diets at the feedlot that supplied compost for this study.

The effect of previous crop on pH was nonsignificant for 10 of 12 depth × sampling time combinations (data not shown). The exceptions were both at 0–7.5 cm depth in which potato as the previous crop resulted in significantly higher pH than timothy, dry bean, and sugar beet (7.75 vs. 7.02–7.41) in 2002 and significantly higher pH than dry bean and wheat (7.74 vs. 7.50–7.57) in 2011. This is most likely related to four of five compost entry points occurring in the fall prior to potato, with residual effects influencing soil pH after potato 1 yr later.

Soil electrical conductivity

Only two of the 12 depth × sampling time combinations showed significant effects of rotation on EC (Table 6). At 0–7.5 cm, in 2002, the 4-CONV rotation had significantly higher EC than 3-CONV, 1-CONT, or 4-CONS (0.33 vs. 0.20–0.25 dS m^{-1}). At 7.5–15 cm in 2008, the 5- and 6-CONS rotations were significantly higher than 1-CONT and 3-CONV (0.33–0.35 vs. 0.25–0.27 dS m^{-1}). However, the management contrast revealed a more distinct trend whereby CONS management led to significantly higher EC at 0–7.5 cm in 2005, 2008, and 2011, and at 7.5–15 cm as the study evolved (2008 and 2011). The largest differences occurred at the end of the study (2011) in which CONS > CONV by 0.19 dS m^{-1} at 0–7.5 cm and 0.14 dS m^{-1} at 7.5–15 cm.

As with pH, increased EC under CONS management is attributed to compost application. Supplemental sources of several minerals are normally added to cattle diets, including soluble salts, Ca, Mg, K, and Na (Combs et al. 2001), and these are largely excreted. Furthermore, Larney et al. (2008*a*) reported that salts become more concentrated during composting due to significant dry matter losses. Previous locally conducted studies have shown increased EC with manure or compost application (Chang et al. 1991; Hao and Chang 2003; Miller et al. 2005). Chang et al. (1991) advised against application of >30 Mg ha^{-1} yr^{-1} (fresh wt.) for nonirrigated, or >60 Mg ha^{-1} yr^{-1} for irrigated land, due to increased EC concerns. They reported linear increases in EC over time, which were not reversed by irrigation, suggesting difficulty in leaching soluble salts from the soil profile. This agrees with our findings in which there were no significant effects of rotation, management (CONV vs. CONS), or previous crop on EC at 15–30 cm (data not shown).

The effect of previous crop on EC was significant at 0–7.5 cm in 2002, 2005, and 2008 (Table 6). On all three occasions, EC was significantly higher after sugar beet, compared with all crops (except potato), in 2002 (0.38 vs. 0.22–0.27 dS m^{-1}), dry bean and wheat in 2005 (0.56 vs. 0.29–0.31 dS m^{-1}), or all crops in 2008 (0.74 vs. 0.32–0.47 dS m^{-1}). In addition, potato showed significantly

Table 6. Effect of rotation and soil management on soil pH, and the effect of rotation, soil management, and previous crop on electrical conductivity at 0–7.5 and 7.5–15 cm depths, in 2002, 2005, 2008, and 2011.

	0–7.5 cm depth				7.5–15 cm depth			
	2002	2005	2008	2011	2002	2005	2008	2011
pH								
Rotation[a]								
1-CONT	6.86	6.93c[c]	6.76c	6.87d	6.89	6.92c	6.90c	7.27c
3-CONV	7.27	7.38ab	7.35ab	7.53bc	7.24	7.29bc	7.23ab	7.43bc
3-CONS	7.63	7.49ab	7.29ab	7.64abc	7.50	7.51ab	7.33ab	7.76a
4-CONV	7.46	7.34b	7.26b	7.49c	7.22	7.32b	7.17bc	7.49bc
4-CONS	7.72	7.58a	7.43a	7.77a	7.56	7.58a	7.43a	7.80a
5-CONS	7.43	7.48ab	7.45a	7.71ab	7.21	7.39ab	7.40a	7.77a
6-CONS	7.44	7.47ab	7.35ab	7.59abc	7.31	7.41ab	7.26ab	7.63ab
P value	0.10	**0.02**	**<0.001**	**<0.001**	0.36	**0.03**	**0.008**	**<0.001**
Management[b]								
CONV	7.36	7.36b	7.31	7.51b	7.23	7.31b	7.20b	7.46b
CONS	7.56	7.51a	7.38	7.68a	7.39	7.47a	7.35a	7.74a
P value	0.12	**0.04**	0.15	**0.01**	0.24	**0.04**	**0.02**	**<0.001**
Electrical conductivity (dS m^{-1})								
Rotation[a]								
1-CONT	0.21bc	0.23	0.34	0.47	0.19	0.16	0.25b	0.57
3-CONV	0.20c	0.33	0.33	0.44	0.20	0.26	0.27b	0.42
3-CONS	0.25abc	0.37	0.44	0.57	0.26	0.33	0.29ab	0.51
4-CONV	0.33a	0.26	0.42	0.49	0.29	0.28	0.30ab	0.34
4-CONS	0.25bc	0.36	0.49	0.85	0.26	0.33	0.32ab	0.51
5-CONS	0.29ab	0.41	0.49	0.68	0.27	0.29	0.33a	0.53
6-CONS	0.28ab	0.43	0.41	0.54	0.24	0.39	0.35a	0.53
P value	**0.03**	0.14	0.08	0.11	0.40	0.15	**0.02**	0.46
Management[b]								
CONV	0.26	0.29b	0.37b	0.46b	0.24	0.27	0.28b	0.38b
CONS	0.27	0.39a	0.46a	0.65a	0.26	0.33	0.32a	0.52a
P value	0.71	**0.03**	**0.03**	**0.02**	0.54	0.14	**0.02**	**0.04**
Previous crop								
Dry bean	0.25b	0.29b	0.34d	0.59	0.22	0.27	0.29	0.44
Potato	0.32a	0.39ab	0.47b	0.63	0.28	0.32	0.35	0.50
Sugar beet	0.38a	0.56a	0.74a	0.80	0.33	0.38	0.30	0.45
Wheat	0.22b	0.31b	0.40c	0.49	0.23	0.28	0.30	0.50
Timothy	0.22b	0.35ab	0.32cd	0.43	0.20	0.35	0.32	0.52
Oat	0.27ab	0.36ab	0.32cd	0.57	0.27	0.35	0.31	0.49
P value	**<0.001**	**0.01**	**<0.001**	0.17	0.09	0.52	0.13	0.97

Note: Within columns, means followed by the same letter are not significantly different from each other (LSD, $P > 0.05$). *P* values in bold are significant.

[a]Naming scheme for rotations is as follows: the integer refers to length of rotation (yr); CONT, continuous; CONV, conventional management; CONS, conservation management.

[b]Management contrast: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5-, and 6-CONS).

higher EC than dry bean, timothy, oat, or wheat (0.47 vs. 0.32–0.40 dS m^{-1}), and wheat showed higher EC than dry bean (0.40 vs. 0.34 dS m^{-1}) in 2008.

Soil salinity, and hence EC, is strongly linked to water table depth and water movement in the soil profile (Sommerfeldt et al. 1988). When subsoil moisture containing salts moves upward and evaporates, salts are precipitated at or near the soil surface. Irrigation maintains capillary continuity to the soil surface, and hence, EC is influenced by irrigation amounts and timing. In our study, the timing of the final irrigation of the growing season was dictated by crop and water demand. In 2002, 2005, and 2008, sugar beet, potato, and timothy received final irrigations (up to 102 mm) from 21 Aug. to 4 Sept., on average 15 d later than dry bean and wheat (9–14 Aug.). Kaffka and Hembree (2004) outlined transient salinity differences at the soil surface as a result of irrigation for sugar beet, showing that salinity levels changed with time after irrigation and as soil moisture varied. Later irrigations allowed more dynamic soil moisture conditions under sugar beet, and to a lesser extent potato, which increased EC for these crops.

Actively growing plants, especially those with deeper rooting systems, such as sugar beet, also impact surface soil salinity. As roots extract water from the soil, more water, carrying salts in solution, moves up to the root zone to replace that extracted (Sommerfeldt et al. 1988). As such the harvest date of the previous crop in relation to soil sampling can influence surface EC. In 2002, 2005, and 2008, 8–20 d elapsed between sugar beet harvest and soil sampling, compared with 14–54 d between wheat harvest and soil sampling. Sugar beet grew later into fall, allowing continued upward movement of salts, which deposited and crystallized on the soil surface and were captured by our shallow sampling (0–7.5 cm). A deeper sampling increment (e.g., 0–15 cm) may not have captured previous crop effects on soil EC as the salts close to the surface would be diluted with less saline underlying soil (7.5–15 cm, Table 6).

Summary and Conclusions

Our CONS management practices were soil building with regard to SOC and TN, while CONV management was soil degrading for these parameters. Total N was a more sensitive indicator of soil change than SOC, with five of seven rotations showing significant TN changes over time, compared with three of seven for SOC. The risk of NO_3-N buildup and potential leaching to groundwater was not an issue, with no obvious accumulation of NO_3-N in the soil profile due to rotation or CONS management. Nitrate-N was more heavily influenced by previous crop than rotation or management.

In contrast, AP in the root zone was unaffected by previous crop and controlled by rotation and management, with compost additions under CONS management leading to surface buildup, as well as downward movement to deeper profile depths (30–60 cm depth) as the study progressed. Phosphorus management entails balancing P inputs with crop removal, to minimize accumulation of soil P and decrease potential transfer to adjacent surface water bodies or groundwater. A better understanding of the forms and availability of compost P may have helped tailor more efficient and environmentally safe recommendations for application in this study. For AP, therefore, CONS management would be deemed soil degrading. Changes to soil pH and EC, although statistically significant, were likely of limited practical significance and could not be categorized as either soil building or soil degrading.

Monitoring of soil properties during long-term soil management experiments provides information on changes leading to the greatest crop yield coupled with the fewest environmental impacts. The CONS management practices conferred advantages to dry bean yield (Larney et al. 2015), potato yield, and disease incidence, notably a reduction in potato early dying (Larney et al. 2016*b*), sugar beet yield (Larney et al. 2016*a*), residue cover (Larney et al. 2017), and weed pressure (Blackshaw et al. 2015). Therefore, apart from a caveat regarding potential P loading, the CONS management package in this study could be validated as soil building with concomitant benefits to crop performance.

Acknowledgements

We thank Dale Reynolds, Andrew Olson, Frank Megella (deceased), Paul DeMaere, Dan Yagos, and Stan Cox for help with soil sampling. Jim Sukeroff and Vauxhall Sub-station staff assisted with crop husbandry. Jennifer Nitschelm (2000–2006) and Peter Regitnig (2007–2011), Rogers Sugar Ltd./Lantic Inc. (Taber, AB), managed sugar beet crops. Funding was provided by the Alberta Pulse Growers, the Potato Growers of Alberta, Lantic Inc., the Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster.

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Soil & Tillage Research 168 (2017) 1–10

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Phospholipid fatty acid biomarkers show positive soil microbial community responses to conservation soil management of irrigated crop rotations

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ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 15 November 2016
Accepted 6 December 2016
Available online 27 December 2016

Keywords:
Compost
Cover crops
Enzyme activity
Microbial biomass
PLFA
Tillage

ABSTRACT

The increasing acreages of crops like potato and sugar beet, which return little C to the soil, and whose harvesting methods cause soil disturbance, led to the establishment of a 12-yr study to evaluate soil conservation (CONS) management systems in southern Alberta. The CONS management systems, applied to 3- to 6-yr crop rotations, were compared with conventional (CONV) management systems that included wheat monoculture. The CONS management was a suite of practices that included addition of cattle manure compost, reduced tillage, diverse crop rotations and use of cover crops that CONV management did not have. In the last two years of the study (2010 and 2011), soil microbial biomass was measured in bulk soil and wheat rhizosphere using the substrate-induced respiration method and phospholipid fatty acid (PLFA) biomarkers. β-glucosidase enzyme activity was measured to evaluate soil functioning (C cycling). Total soil microbial biomass, and that of its components (fungi and bacteria), was significantly greater under CONS management than under CONV management. The total PLFA contents of 3- and 4-yr CONS rotations (15.24–34.69 nmol g^{-1} soil) were 84–193% greater than those in CONV management (33.45–63.66 nmol g^{-1} soil) when differences were significant, and fungal PLFA was up to 382% greater. β-glucosidase activity was 50% greater under CONS management than CONV management. Principal component analysis confirmed that the soil microbial community structures in the different rotations were shaped by management practices. These positive responses of soil microbial communities to conservation management will enhance biological processes including nutrient cycling and biological pest control.

1. Introduction

The area planted to potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.) and dry bean (*Phaseolus vulgaris* L.) in southern Alberta has increased 2- to 3-fold recently due to value-added food processing (Alberta Agriculture and Forestry, 2015). However, these crops produce less biomass than the cereal or forage crops that they replace in irrigated crop rotations (Li et al., 2015), and the reduced C returns to the soil may lead to reductions in soil organic C. In addition, potato is usually grown on raised beds (hills) which require extra tillage passes and the harvesting methods of both potato and sugar beet necessitate heavy soil disturbance, making the soil susceptible to wind and water erosion (Chow et al., 1990; Carter and Sanderson, 2001). Annual soil losses by water erosion from continuous potato plots on 8 and 11% slopes have been estimated at 17 and 24 Mg ha^{-1} yr^{-1}, respectively, in New Brunswick, Canada (Chow et al., 1990). Eroded soils lose some of their organic C and nutrients, and soil tillage further reduces organic C by accelerating its decomposition (Lupwayi et al., 2004). Therefore, growing these crops results in soil degradation.

To address the soil degradation issues of these soils, a study was conducted from 2000 to 2011 to determine if soil conservation practices could be applied to southern Alberta irrigated cropping systems. These practices included addition of cattle manure compost, reduced tillage, and use of cover crops and solid-seeded narrow-row dry bean, applied as a package. Yields of the crops in the study have been published, and they show increases of potato,

Abbreviations: ANOVA, Analysis of variance; CONS, Conservation management; CONV, Conventional management; GN, Gram negative; GP, Gram positive; PLFA, Phospholipid fatty acid; PCA, Principal component analysis.

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http://dx.doi.org/10.1016/j.still.2016.12.003
0167-1987/

sugar beet and dry bean yields under conservation management relative to conventional management (Larney et al., 2015, 2016a,b). Some of the soil properties that have been studied in the trial are organic C fractions and aggregate stability (Li et al., 2015). Results indicated that by the conclusion of the 12-yr study, particulate, fine and total organic C had increased by >145, 20 and 45%, respectively, under CONS management. The stability of soil aggregates also improved significantly under CONS management relative to CONV management that did not have soil conservation practices (Li et al., 2015). Here we report on the soil microbial responses to these soil conservation practices because the soil microbial community mediates many important biological processes for sustainable agriculture. These processes include biological nitrogen fixation (Jensen and Hauggaard-Nielsen, 2003; Gaby and Buckley, 2011), biomass decomposition and nutrient cycling (Schneider et al., 2012; Lupwayi and Soon, 2015), formation and maintenance of soil aggregates (Six et al., 2004; Blaud et al., 2012), biological disease and pest control (Janvier et al., 2007; Mendes et al., 2011), detoxification of agro-chemicals (Shelton and Doherty, 1997; Itoh, 2014) and regulation of climate through C and N cycles (Baldock et al., 2012; Gregorich et al., 2015). In addition to the importance of these biological processes for sustainable agriculture, soil microbial properties (e.g., biomass, diversity and activity) are sensitive indicators of soil quality (Doran et al., 1996; van Bruggen and Semenov, 2000) because they respond quickly to changes in soil management. Some new microbial indicators of soil quality or functionality include functional genes by molecular biological methods (Stone et al., 2016) and the 1-day CO_2 test (Muñoz-Rojas et al., 2016), but evaluation many indicators in field trials from diverse agro-ecosystems showed that the CO_2 test was one of the highly variable ones (Morrow et al., 2016).

The objectives of this study were to examine how CONS management affected soil microbial biomass, functioning and community structure in the last two years of the 12-yr study. The results will complement previously-published results on soil C and aggregate stability (Li et al., 2015), weed populations (Blackshaw et al., 2015), nematode populations (Forge et al., 2015) and dry bean (Larney et al., 2015), potato (Larney et al., 2016b) and sugar beet (Larney et al., 2016a) yields.

2. Materials and methods

2.1. Study location, experimental treatments and management

A 12-yr (2000–2011) irrigated field study was conducted at Vauxhall, Alberta (50° 03′ N, 112° 09′ W, elev. 781 m). The soil was a Dark Brown Chernozem (Typic Borroll in Soil Taxonomy; Haplic Kastanozem in World Reference Base) with 520 g kg^{-1} sand, 340 g kg^{-1} silt, 140 g kg^{-1} clay, and 12.9 g organic C kg^{-1} soil and pH 6.9 (0–15 cm depth). The 30 year (1981–2010) mean annual precipitation is 352 mm with a mean annual air temperature of 5.8 °C. The weather conditions during the 2010 and 2011 growing seasons, when soil samples were collected for the part of the study reported here, are presented in Fig. 1. These records were collected from an automated weather station located about 300 m from the plots.

The entire plot area was planted to barley (*Hordeum vulgare* L.) in 1999 and treatments were established in the spring of 2000. There were seven rotation treatments: continuous (monoculture) wheat (*Triticum aestivum* L.), two 3-yr rotations, two 4-yr rotations, one 5-yr rotation (but with two wheat phases that were each sampled for this study), and one 6-yr rotation (Table 1). These rotations were managed utilizing CONV or CONS management practices (described below). All crop phases of a rotation were grown each year to account for varying environmental conditions over years. This resulted in 26 rotation phases organized in a randomized complete block design (RCBD) with four replicates. The individual plot sizes were 10.1 by 18.3 m with 2.1 m buffer zones between plots.

For the CONS rotations (Table 1), a package of the following four practices was applied (for details, see Larney et al., 2015, 2016a,b):-

1. Direct seeding and/or reduced tillage where possible in the rotation: one pass of a chisel plough and packers or disc harrow.
2. Fall-seeded cover crops: oat (*Avena sativa* L.) and fall rye (*Secale cereale* L.) with entry points indicated in Table 1. However, fall establishment of oat was sub-optimal and was replaced with fall rye from fall 2003 onward.
3. Composted cattle manure: straw-bedded beef cattle feedlot manure compost (182, 15.4, and 5.4 g kg^{-1} dry wt. of total C, N,

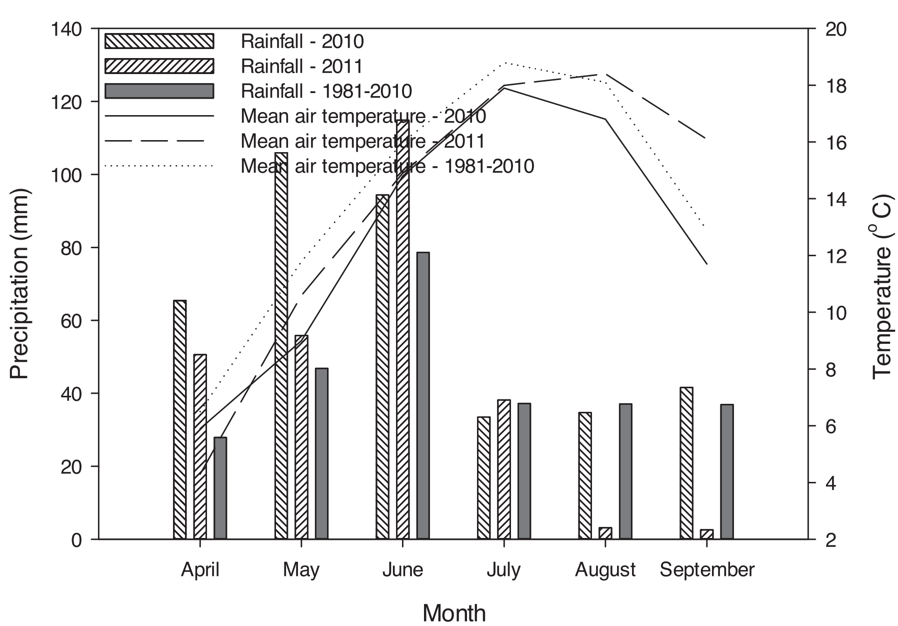

Fig 1. Total monthly precipitation and mean air temperatures during the study period, and 30-yr averages.

Table 1
List of treatments and management differences from 2000 to 2011.

Rotation[a]	Crop sequence[b]	No. of crop phases	Tillage	Nutrient source	Cover crop	Bean row spacing
1-CONV	W	1	Reduced	Fertilizer	None	No bean
3-CONV	P–B–W	3	Conventional	Fertilizer	None	Wide
3-CONS	P–B–W	3	Reduced	Fertilizer/Compost after W	After P & B	Narrow
4-CONV	P–W–SB–B	4	Conventional	Fertilizer	None	Wide
4-CONS	P–W–SB–B	4	Reduced	Fertilizer/Compost after B	After P	Narrow
5-CONS[c]	P–W–SB–W–B	5	Reduced	Fertilizer/Compost after SB & B	After P	Narrow
6-CONS	P–O/T[d]–T–T–SB–B	6	Reduced	Fertilizer/Compost after B	After P	Narrow
Total		26				

[a] Integers refer to the length (years) of each rotation; CONV = conventional management; CONS = conservation management.
[b] B = dry bean; O = oat; P = potato; SB = sugar beet; T = timothy; W = wheat. The underlined wheat phase of each rotation was sampled for soil microbiological analysis. Oat was sampled in 6-CONS because there was no wheat.
[c] The two underlined wheat phases of this rotation are described as 5-CONS1 (first wheat phase) and 5-CONS2 (second wheat phase) in the tables and figures below, and in the text.
[d] Oat harvested as silage in July, timothy (*Phleum pratense* L.) direct seeded in late August.

and P, respectively) was fall-applied as a substitute for inorganic fertilizer. A rate of 42 Mg ha^{-1} (fresh wt) was applied after dry bean and before potato in the 4-, 5- and 6-CONS rotations (Table 1). The shorter 3-CONS rotation received a lower rate (28 Mg ha^{-1}, fresh wt) after wheat and before potato. This lower rate was also applied at a second entry point in the 5-yr CONS rotation – after sugar beet and before wheat.

4. Solid-seeded, direct-cut narrow-row (19–23 cm) dry bean. There was no inter-row cultivation, and the crop was harvested by direct-cutting (no soil disturbance) with a plot combine.

Conventional management did not use any of the above practices, and hence the 3- and 4-yr CONV rotations (a) had more intensive tillage (see below), (b) no cover crops, (c) no compost amendments, and (d) dry bean had wide rows (60 cm), were inter-row cultivated for in-season weed control, and were harvested by undercutting (causing soil disturbance).

Tillage intensity was reduced as much as possible under CONS compared with CONV management. Fall tillage before dry bean was one pass of a disk harrow with harrows in all rotations except 5-CONS, which was left undisturbed. In spring, wide-row dry bean plots in 3- or 4-CONV received one or two passes of a Triple K spring-tine harrow (Kongskilde Industries). There was no spring tillage before direct-seeding narrow-row dry bean in the CONS rotations. In the fall preceding potato, the 3- and 4-CONV rotations were moldboard ploughed to 25-cm soil depth. The 3-CONS rotation received one pass of a chisel plow + packers or disk harrow, while one pass of a Dammer Diker (AG Engineering & Development Co.), a reservoir tillage implement, was used in the 4-, 5-, and 6-CONS treatments. In spring, both CONV and CONS potato plots received two passes of a Triple K spring-tine harrow. Fall tillage before wheat was one pass of a disk harrow (1-CONV), one pass of a heavy-duty cultivator or one to two passes of a disk harrow (CONV) or one pass of a disk harrow (CONS). Tillage before seeding for wheat in spring did not differ between CONS and CONV and was one pass of a disk harrow, a Triple K, or a heavy-duty cultivator, depending on the amount of residues. When following wheat, there was no difference in fall tillage between CONV and CONS rotations for sugar beet, with all plots receiving one to two passes of a disk harrow. In 6-CONS in 2008, timothy sod was moldboard ploughed to 25 cm in fall 2007. Spring tillage for sugar beet (all rotations) consisted of one pass of a Vibra Shank cultivator or Triple K. Tillage for oat followed that for wheat for the CONS rotations above, while timothy was direct seeded into oat stubble in August 2006 and remained for the 2007 and 2008 growing seasons.

Crops were fertilized according to soil test recommendations, with soil testing done every three years. Dry bean plots received spring applications of 90 kg N ha^{-1} in 3-CONV and 3- and 5-CONS, and 112 kg N ha^{-1} in 4-CONV and 4- and 6-CONS. Fertilizer P was not applied to dry bean because soil tests showed adequate available P. Dry bean was not inoculated with *Rhizobium* due to a lack of yield response in these soils (McKenzie et al., 2001). Potato plots in 3- and 4-CONV were fertilized (123 kg N, 29 kg P and 56 kg K ha^{-1}) in the previous fall except in 2000, when they were fertilized in spring. Potato plots in CONS rotations received a lower rate of N (37 kg ha^{-1}) and zero P to account for N and P in the compost. Wheat (and oat in 6-CONS) received 90–112 kg N ha^{-1}. Sugar beet received 112–134 kg N and 12–29 kg P ha^{-1} when following wheat. When sugar beet followed timothy in 6-CONS in 2008, the N rate was increased to 168 kg ha^{-1} to compensate for greater N uptake by the preceding two years of timothy. First-year timothy in 2006 received 112 kg N ha^{-1} in spring and 112 kg N ha^{-1} after the first cut in July. Second year timothy received 145 kg N ha^{-1} in spring 2007 and 78 kg N ha^{-1} after the first cut.

The crops were irrigated, using a wheel-move system, to maintain soil water (to 100 cm depth) at no lower than 50% field capacity. Irrigation scheduling was at the discretion of the farm manager. The plots could also be irrigated individually using four quarter-circle sprinklers. Irrigation water added to dry bean during the growing season ranged from 140 (in 2002) to 775 mm (in 2007) during the 12 years. For potato, the range was 126–846 mm irrigation water, and 140–724 mm for wheat (the lowest amount in 2002 and the highest in 2007 in both cases). Sugar beet was irrigated eight times a season, on average, applying 56 mm of water each time. A lot of irrigation water was applied in 2007 due to an extreme mid-season dry spell when only 21 mm of rainfall fell between 25 June and 19 August.

Pre-seeding, in-crop and post-harvest herbicides were used as required for weed control. Each fall, mature crops were harvested for yield and quality assessment. For the 6-CONS rotation, oat biomass was measured in July 2005 (milky dough stage) and timothy biomass (2006 and 2007) in July (first cut) and September (second cut). Fall rye cover crops were sampled for biomass yield before tillage or desiccation in spring.

2.2. Soil sampling

In the final two years of the 12-yr study (2010 and 2011), soil samples were collected in the wheat phase of 1- to 5-yr rotations, and the oat phase of the 6-yr rotation. The samples were taken at the flag leaf growth stage of wheat or oat, usually in midsummer (July). Plants were excavated from four random 0.5-m lengths of row. Loose soil was removed from the roots by shaking the plants vigorously by hand, and the remaining soil that had strongly adhered to the roots was carefully brushed off and recovered as rhizosphere soil. Bulk soil (0–7.5 cm depth) was sampled from the middle of two adjacent crop rows at four locations per plot. The four bulk or rhizosphere soil samples from each plot were combined, passed through a 2-mm sieve, stored at −20 °C and defrosted just before analysis.

2.3. Microbial biomass C (MBC) analysis

Soil MBC was measured using the substrate-induced respiration method (Horwath and Paul, 1994), in which 300 mg of glucose was dissolved in 4.5–6.0 mL water and added to 50 g soil to bring it to 50% water-holding capacity. The exact amount of water added depended on the pre-determined water content and water-holding capacity of the soil. After stir-mixing, the soil was incubated in a 1L jar for 3 h at 22 °C and the amount of CO_2 that accumulated in the head space was measured using gas chromatography.

2.4. β-Glucosidase enzyme activity analysis

The activity of β-glucosidase, a key enzyme in C cycling because it is involved in the hydrolysis and biodegradation of cellulose, was measured by colorimetrically determining *p*-nitrophenol released by the enzyme after incubating 1 g soil with buffered (pH 6.0) *p*-nitrophenyl-β-D-glucoside (Dick et al., 1996).

2.5. Phospholipid fatty acid analysis

The PLFA method used was a modification of that used by Petersen and Klug (1994) as described by Hamel et al. (2006). Total soil lipids were extracted with a mixture of dichloromethane (DCM):methanol (MeOH):citrate buffer (1:2:0.8 v/v) from approximately 4 g (dry weight equivalent) of soil. Phospholipids were isolated from the crude lipid extracts by solid phase extraction in silica gel columns, using 19:0 nonadecanoic acid as internal standard. Neutral lipid, glycolipid and phospholipid fractions were eluted by sequential leaching with DCM, acetone and methanol, respectively. The neutral lipid and glycolipid fractions were discarded and the phospholipid fraction was retained for methylation (conversion to fatty acid methyl esters, FAMEs) through mild acid methanolysis, i.e., addition of MeOH/H2SO4 (25:1 v/v) and hexane. The FAMES were analysed by gas chromatography on a GC fitted with a 30-m 5% phenyl and 95% methylpolysiloxane column. The GC running conditions were 80 °C for 1 min, increasing at 20 °C min^{-1} to 160 °C, and then increasing at 5 °C min^{-1} to the final temperature of 270 °C, which was held for 5 min (Frostegård et al., 1993). Peaks were identified by comparison of retention times to known standards. The abundance of individual PLFAs was expressed as nm g^{-1} dry soil as follows (Palojarvi, 2006):-

$$C_x\ (\mathrm{nmol\ g^{-1}\ soil}) = A_x * c_i[\mu g] * f * 1000/\{A_i * W[g] \times M[\mu g\ \mu mol^{-1}]\}$$

Where: C_x = concentration of the PLFA studied; A_x = peak area of the PLFA studied; A_i = peak area of the internal standard (19:0 nonadecanoic acid); c_i = absolute amount of internal standard in the vial (μg); f = response factors of different PLFAs (peak area to concentration ratio compared to internal standard; if not known, then 1); W = weight of soil (g); and M = molecular weight of the fatty acid (μg μmol^{-1}).

The PLFA biomarkers were assigned as follows (Helgason et al., 2010), and the fatty acid nomenclature is described by Hamel et al. (2006). The biomass of fungi was indicated by the biomarker 18:2ω6,9. The biomarkers i14:0, i15:0, a15:0, i16:0, i17:0 and a17:0 indicated gram+ (GP) bacteria. Gram- (GN) bacteria were indicated by the biomarkers 16:1ω7c, 16:1ω9c, 18:1ω7c, 18:1ω9c and cy17:0. Total bacterial biomass was the sum of GP and GN bacteria, and total microbial biomass was the sum of fungi and bacteria. Among the GP bacteria, actinomycetes were indicated by the biomarkers 10Me16:0, 10Me17:0 and 10Me18:0 10 (Stevenson et al., 2014). Ratios of specific PLFAs were not calculated because their interpretation is debatable (Frostegård et al., 2011).

2.6. Statistical analysis

Analysis of variance (ANOVA), with checks for data normality, variance homogeneity, and nonadditivity, was used to examine differences between rotations in soil microbial properties: MBC, β-glucosidase enzyme activity, total PLFAs, etc., using the randomized complete block design of the trial. These ANOVA analyses were conducted separately for each year and each soil location (bulk soil or rhizosphere). When ANOVA showed significant effects at 5% significance level, treatment means were separated by the least significant difference (LSD) method, also at 5% significance level. In addition to differences between all treatments, differences between 3-CONV and 3-CONS, or between 4-CONV and 4-CONS rotations, were noted because these pairs of treatments had the same crop sequences and differed only in management (CONV or CONS). Orthogonal contrast analysis was also run to test the effects of all CONV management treatments (Rotations 1-CONV, 3-CONV and 4-CONV) versus all CONS management treatments (Rotations 3-CONS, 4-CONS, 5-CONS1, 5-CONS2 and 6-CONS – Table 1). The soil microbial properties were related to C inputs (Li et al., 2015) by correlation analysis. Differences in soil microbial community structures (composition) between treatments were evaluated through ordination by principal component analysis (PCA) of all the 15 biomarkers using Multi-Variate Statistical Package (MVSP) software (Kovach, 1999). A covariance matrix of standardized PLFA profiles was used in PCA, and the PLFAs that accounted for differences between groups of treatments in microbial community structures were identified by correlating principal component scores with the standardized concentrations of individual PLFAs.

3. Results

3.1. Growing season precipitation and temperature

In 2010, the monthly growing season (May to September) precipitation was above normal (1981–2010 mean) in the first three months of the season, particularly in April and May when it was about 2.3× the normal precipitation (Fig. 1). The last three months of the season were about normal (90–113%). The 2010 mean air temperature was below normal (76%) in May, but about normal (91–95%) in the rest of the season. In 2011, monthly precipitation ranged from 119 to 181% of normal from April to June, 103% in July, but very low (<10%) in August and September (Fig. 1). While the mean air temperature was about normal (90–102%) in most of the 2011 season (May to August), it was 66% of normal in April, and 125% of normal in September. The excessive precipitation in 2010 flooded some plots, which were not sampled for soil microbial analyses, i.e., some treatments had only three of the four replicates sampled. In 2011, all plots were sampled.

3.2. Soil microbial biomass

Soil microbial biomass was assessed through microbial biomass C (Fig. 2) and total PLFAs (Table 2). In the wheat rhizosphere, there were no differences in MBC between treatments, both in 2010 and 2011 (data not presented). In 2010 bulk soil, the 5-CONS2 rotation had the highest MBC (683 mg C kg^{-1} soil), and 4-CONV the lowest (316 mg C kg^{-1} soil) (Fig. 2a). There were no differences in MBC between 3-CONV and 3-CONS, or between 4-CONV and 4-CONS

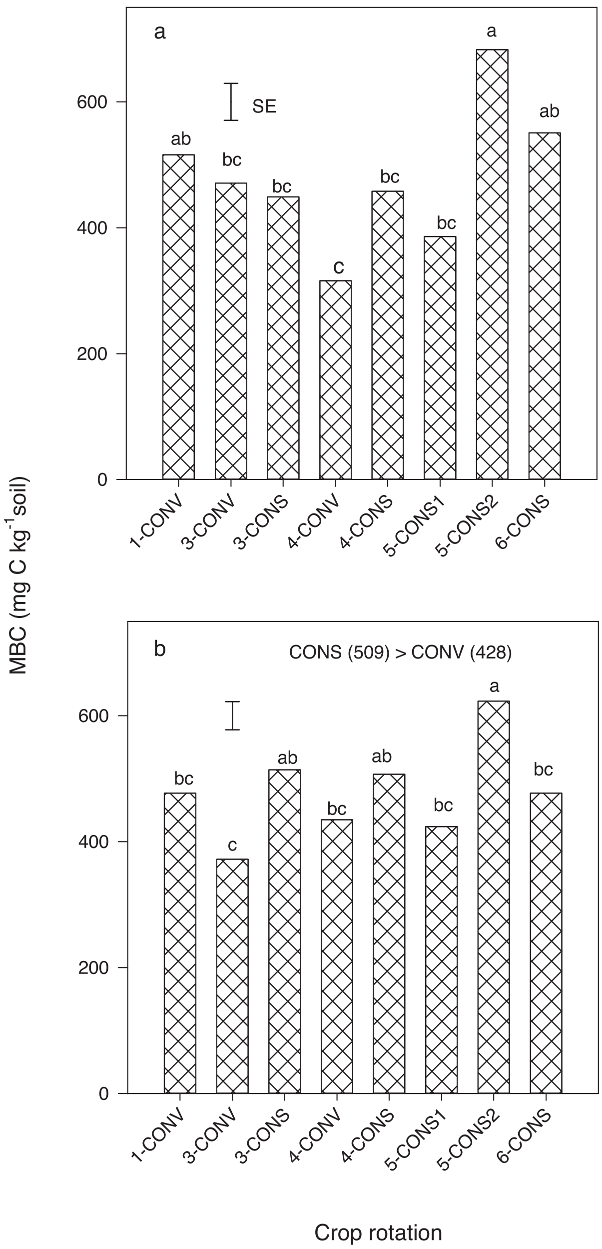

Fig. 2. Soil microbial biomass C (MBC) in bulk soil of different rotations and management practices in 2010 (a) and 2011 (b). In the abbreviated rotation names, the integer refers to the length (years) of the rotation; CONV = conventional management; CONS = conservation management. SE = standard error. See footnote c in Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations. Bars with the same letters are not significantly different at 5% significance level. Each bar is a mean of 4 replicates.

rotations. Contrast analysis also showed no differences between the two management systems (in all the treatments). One reason for the lack of difference was the relatively high MBC in the 1-CONV (wheat monoculture) treatment (516 mg C kg^{-1} soil). In 2011 in bulk soil, MBC ranged from 372 mg C kg^{-1} soil in 3-CONV rotation to 623 mg kg^{-1} soil in 5-CONS2 rotation (Fig. 2b). The 3-CONS rotation had 38% greater MBC than the 3-CONV rotation, and contrast analysis showed that MBC in all CONS management systems (509 mg C kg^{-1} soil) was 18% greater than that in CONV management systems (Fig. 2b).

Total PLFAs in bulk soil in both 2010 and 2011 were highest in 5-CONS2 rotation (62.61 and 52.58 nmol g^{-1} soil, respectively), and lowest in 4-CONV rotation (24.76 and 15.24 nmol g^{-1} soil, respectively) (Table 2). In both years, the 4-CONS rotation had about double the total PLFA contents than 4-CONV rotation (102% and 90% greater in 2010 and 2011, respectively). According to contrast analysis, CONS management systems had 46 and 61% greater total PLFA contents in 2010 (53.24 nmol g^{-1} soil) and 2011 (41.21 nmol g^{-1} soil), respectively, than CONV management systems. In the rhizosphere, treatment differences were observed only in 2010, when 3-CONS and 4-CONS rotations had 84% and 90% greater total PLFA contents, respectively, than their respective CONV rotations, and contrast analysis also revealed that CONS management systems had 71% greater total PLFAs (53.31 nmol g^{-1} soil) than CONV systems. Although ANOVA did not show treatment differences in total PLFAs in the rhizosphere in 2011, contrast analysis revealed 53% greater total PLFA contents in CONS management systems (46.19 nmol g^{-1} soil) than CONV management systems (Table 2).

Table 2
Soil microbial biomass, indicated by total phospholipid fatty acids (PLFAs), in different rotations and management practices.

Rotation[a]	2010		2011	
	Bulk soil	Rhizosphere	Bulk soil	Rhizosphere
Total PLFAs (nmol g^{-1} soil)				
1-CONV	39.43bc[e]	32.31bc	39.18ab	37.12a
3-CONV	45.09ab	34.69bc	22.19bc	26.90a
3-CONS	58.15ab	63.66a	33.45abc	45.27a
4-CONV	24.76c	26.57c	15.24c	26.33a
4-CONS	49.98ab	50.59ab	44.72a	46.99a
5-CONS1[b]	48.75ab	45.33abc	35.66abc	43.57a
5-CONS2[c]	62.61a	64.54a	52.58a	47.99a
6-CONS	46.70ab	42.43bc	39.61ab	47.11a
P value	0.027	0.016	0.032	0.051
Management contrasts[d]				
CONV	36.43b	31.19b	25.54b	30.12b
CONS	53.24a	53.31a	41.21a	46.19a
P value	0.004	<0.001	0.007	0.001

[a] Integers refer to the length (years) of each rotation; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote [c] in Table 1).
[c] Wheat preceded by sugar beet (see footnote [c] in Table 1).
[d] Management contrasts: CONV = mean of 1-CONV, 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1, 5-CONS2 and 6-CONS.
[e] Means followed by the same letter in a column within a treatment category are not significantly different at 5% significance level.

3.3. Total fungal and total bacterial PLFAs

Treatment effects on fungal PLFA were observed in the rhizosphere in 2010 and in bulk soil in 2011 (Table 3). In the rhizosphere in 2010, fungal PLFA content was highest in 3-CONS rotation (4.63 nmol g^{-1} soil) and lowest in 4-CONV rotation (1.54 nmol g^{-1} soil). The 3-CONS rotation had 89% greater fungal PLFA content than the 3-CONV rotation. Contrast analysis showed that fungal PLFA contents were 65% greater under CONS management (3.13 nmol g^{-1} soil) than under CONV management. In bulk soil in 2011, fungal PLFA was highest in 5-CONS2 rotation (2.74 nmol g^{-1} soil) and lowest in 4-CONV rotation (0.50 nmol g^{-1} soil). The 3-CONS and 4-CONS rotations had 40 and 382% greater fungal PLFA contents, respectively, than their CONV counterparts, and contrast analysis showed that fungal PLFAs were 62% greater under CONS management (2.28 nmol g^{-1} soil) than under CONV management. Even though ANOVA showed no differences between rotations in fungal PLFA contents in wheat rhizosphere in 2011, contrast analysis revealed 52% greater contents in CONS management systems (2.82 nmol g^{-1} soil) than in CONV systems.

For total bacterial PLFAs (Table 4), the trends in treatment effects were similar to those of fungal PLFAs. In bulk soil in both 2010 and 2011, bacterial PLFAs were highest in 5-CONS rotation

Table 3
Soil fungi, indicated by fungal phospholipid fatty acid (PLFA), in different rotations and management practices.

Rotation[a]	2010		2011	
	Bulk soil	Rhizosphere	Bulk soil	Rhizosphere
Fungal PLFA (nmol g^{-1} soil)				
1-CONV	2.34a[e]	1.72c	2.35ab	2.31a
3-CONV	3.91a	2.45bc	1.39bc	1.72a
3-CONS	4.24a	4.63a	1.95ab	3.20a
4-CONV	1.47a	1.54c	0.50c	1.54a
4-CONS	2.77a	2.96bc	2.41ab	2.73a
5-CONS1[b]	3.03a	2.44bc	1.86ab	2.30a
5-CONS2[c]	3.66a	3.82ab	2.74a	2.54a
6-CONS	3.17a	1.80c	2.43ab	3.35a
P value	0.116	0.008	0.029	0.057
Management contrasts[d]				
CONV	2.57a	1.90b	1.41b	1.86b
CONS	3.37a	3.13a	2.28a	2.82a
P value	0.115	0.006	0.011	0.004

[a] Integers refer to the length (years) of each rotation; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote [c] in Table 1).
[c] Wheat preceded by sugar beet (see footnote [c] in Table 1).
[d] Management contrasts: CONV = mean of 1-CONV, 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1, 5-CONS2 and 6-CONS.
[e] Means followed by the same letter in a column within a treatment category are not significantly different at 5% significance level.

(58.95 and 49.85 nmol g^{-1} soil, respectively) and lowest in 4-CONV rotation (23.29 and 14.74 nmol g^{-1} soil, respectively) (Table 4). The 4-CONS rotation had 103% and 187% greater bacterial PLFA contents than its CONV counterpart in 2010 and 2011, respectively, and contrast analysis revealed 47% and 61% greater bacterial PLFA contents under CONS management in 2010 and 2011, respectively, than CONV management. In the rhizosphere, ANOVA revealed differences only in 2010, when 3-CONS and 4-CONS rotations had 83 and 90% greater bacterial PLFA contents, respectively, than their CONV counterparts, and contrast analysis also showed 71% greater bacterial PLFA in CONS (50.19 nmol g^{-1} soil) than CONV management systems. Despite non-significant ANOVA results in the rhizosphere in 2011, contrast analysis still showed 53% greater bacterial PLFA contents under CONS (43.36 nmol g^{-1} soil) relative to CONV management.

Table 4
Soil bacteria, indicated by total bacterial phospholipid fatty acids (PLFAs), in different rotations and management practices.

Rotation[a]	2010		2011	
	Bulk soil	Rhizosphere	Bulk soil	Rhizosphere
Total bacterial PLFAs (nmol g^{-1} soil)				
1-CONV	37.09bc[e]	30.59cd	36.83ab	34.81a
3-CONV	41.17abc	32.24cd	20.79bc	25.18a
3-CONS	53.91ab	59.04ab	31.50abc	42.07a
4-CONV	23.29c	25.03d	14.74c	24.79a
4-CONS	47.20ab	47.63abc	42.32a	44.26a
5-CONS1[b]	45.71ab	42.90abcd	33.80abc	41.27a
5-CONS2[c]	58.95a	60.73a	49.85a	45.45a
6-CONS	43.54ab	40.63bcd	37.18ab	43.76a
P value	0.022	0.019	0.033	0.052
Management contrasts[d]				
CONV	33.85b	29.29b	24.12b	28.26b
CONS	49.86a	50.19a	38.93a	43.36a
P value	0.003	<0.001	0.007	0.001

[a] Integers refer to the length (years) of each rotation; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote [c] in Table 1).
[c] Wheat preceded by sugar beet (see footnote [c] in Table 1).
[d] Management contrasts: CONV = mean of 1-CONV, 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1, 5-CONS2 and 6-CONS.
[e] Means followed by the same letter in a column within a treatment category are not significantly different at 5% significance level.

3.4. Gram-negative bacteria, gram-positive bacteria and actinomycetes

Differences between treatments in the PLFA contents of GN bacteria, GP bacteria and actinomycetes were similar to those observed for total microbial biomass and its components (fungi and bacteria), i.e., they were greater under CONS management than under CONV management (data not presented).

3.5. Soil microbial community structures

Ordination by PCA of all 15 PLFA biomarker contents in soils of the different rotations revealed interpretable patterns in microbial community structures in 2010, but not 2011. In both bulk soil (Fig. 3a) and rhizosphere (Fig. 3b), Principal Component 1 (PC1) separated rotations under CONS management from those under CONV management (left to right). Remarkably, PC1 explained 78% of total variance in bulk soil, and 85% in the rhizosphere, even though the PLFA data were standardized before ordination. In agreement with the data presented in the preceding sections, the contents of almost all 15 PLFAs were greater under CONS management than under CONV management – the exceptions were 10Me16:0 (one of three actinomycete biomarkers) in bulk soil, and 10Me16:0 and 16:1ω9c (one of five GN bacterial biomarkers) in the rhizosphere.

3.6. β-Glucosidase activity

The activity of this enzyme was determined only in 2011. In bulk soil, β-glucosidase activity was lower in 4-CONV and 3-CONV rotations (86 and 103 mg nitrophenol kg^{-1} soil h^{-1}, respectively) than in the other rotations (184 to 228 mg nitrophenol kg^{-1} soil h^{-1}) (Fig. 4a). Therefore, these two CONV rotations had lower enzyme activities than their corresponding CONS rotations (3-CONS and 4-CONS had 83% and 121% higher activities, respectively, than their CONV counterparts). Even though the 1-CONV had relatively high enzyme activity at 200 mg nitrophenol kg^{-1} soil h^{-1}, contrast analysis showed 50% greater glucosidase activity under CONS management (195 mg nitrophenol kg^{-1} soil h^{-1}) than CONV management (Fig. 4a). In the rhizosphere, there were similar treatment effects on β-glucosidase activities as those observed in bulk soil: 3-CONS and 4-CONS had 56% and 117% higher activities, respectively, than 3-CONV and 4-CONV (Fig. 4b).

3.7. Correlations with C inputs

In bulk soil, correlations between C inputs (from compost and crop residues over 12 years, 2000–11) and all soil microbial properties (except actinomycete biomass) were positive and significant. The correlation with actinomycete biomass was not significant. The significant correlations ranged from 0.472 ($P = 0.006$) with MBC to 0.696 ($P < 0.001$) with β-glucosidase enzyme activity. However, regression analysis of the data revealed quadratic components of these relationships. Thus Fig. 5a shows that β-glucosidase enzyme activity increased with increasing C input up to 56 Mg C ha^{-1} before declining. In wheat rhizosphere, the results were similar. The regression with β-glucosidase activity showed increasing activity up to 55 Mg C ha^{-1} (Fig. 5b) before declining.

4. Discussion

In addition to integrated nutrient management by supplying some nutrients through cattle manure compost, the treatments of

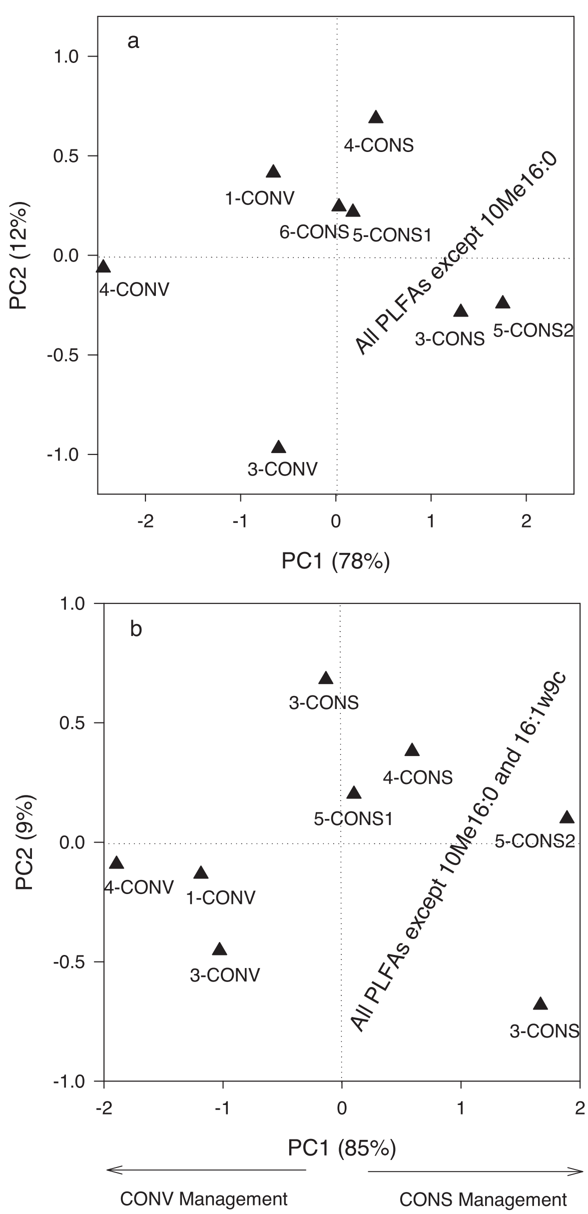

Fig. 3. Ordination by principal component analysis (PCA) of 15 phospholipid fatty acid (PLFA) biomarker contents in different crop rotations in bulk soil (a) and rhizosphere (b), both in 2010. The percentage of total variance explained by each axis is shown. In the abbreviated rotation names, the integer refers to the length (years) of each rotation; CONV = conventional management; CONS = conservation management. See footnote c in Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations. The main PLFAs that accounted for the separation of treatments are indicated in the graphs. Each data point is a mean of 3 or 4 replicates (there were some missing plots due to flooding).

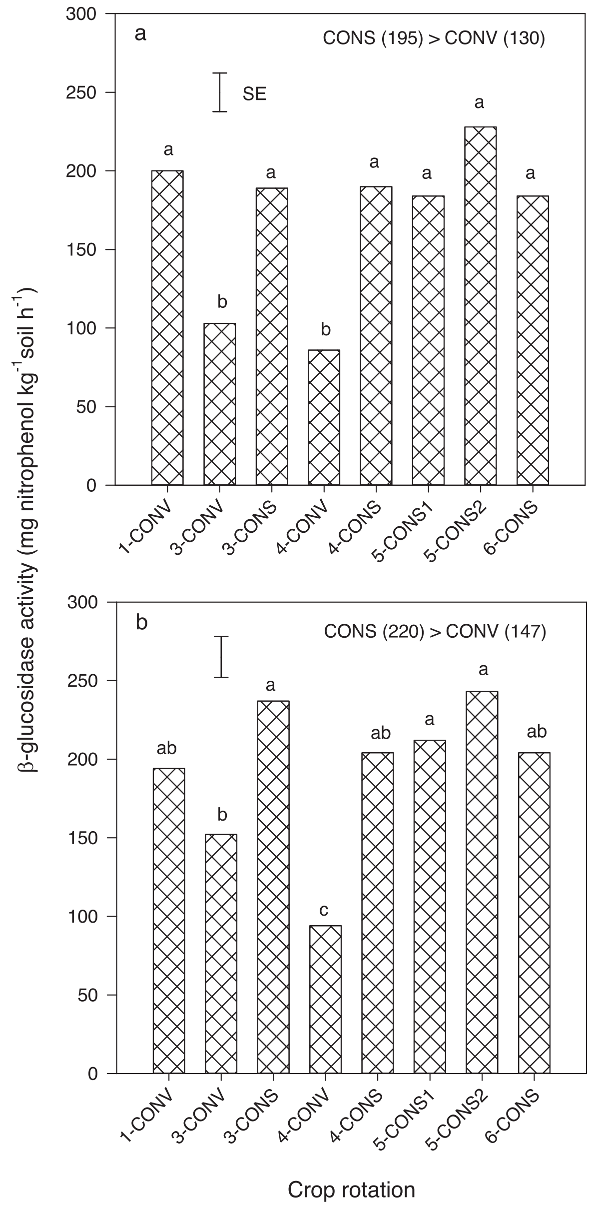

Fig. 4. β-glucosidase activities in different rotations and management systems in bulk soil (a) and wheat rhizosphere (b) in 2011. In the abbreviated rotation names, the integer refers to the length (years) of the rotation; CONV = conventional management; CONS = conservation management. SE = standard error. See footnote c in Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations. Bars with the same letters are not significantly different at 5% significance level. Each bar is a mean of 4 replicates.

this trial were based on the three tenets of conservation agriculture: (a) minimizing soil disturbance by tillage and cultural operations, (b) diversifying crop rotations, sequences and associations, and (c) maintaining a year-round organic matter cover by retaining residues from previous crops and introducing cover crops (Kassam et al., 2009). The growing of narrow-row (no inter-row cultivation) direct-cut (no soil disturbance at harvest) dry bean as another CONS management practice is also consistent with minimizing soil disturbance. The results show a positive response of soil microbial biomass to CONS management practices at all levels of resolution, i.e., from total microbial biomass (Fig. 2 and Table 2) down to actinomycetes within GP bacteria. Soil microbial biomass, including that of fungi, bacteria, GN bacteria, GP bacteria and actinomycetes, was usually greater under CONS management than under CONV management. These differences were confirmed by the observation that soil microbial community structures in the different rotations were mostly shaped by CONV or CONS management practices in 2010 (Fig. 3). For the standardized data that were used in ordination by PCA, it is remarkable that 78% and 85% of the variances in bulk soil and rhizosphere, respectively (PC1 in Fig. 3a and b), were explained by these management practices. Such high percentages usually occur when the data are not standardised and some variables have larger magnitudes than others. The other notable result from the ordination is that all but one or two PLFAs accounted for this difference between management systems (Fig. 3a and b), suggesting that these management practices affected almost all the soil microbial groups that we studied. Soil microbial functioning, indicated by β-glucosidase

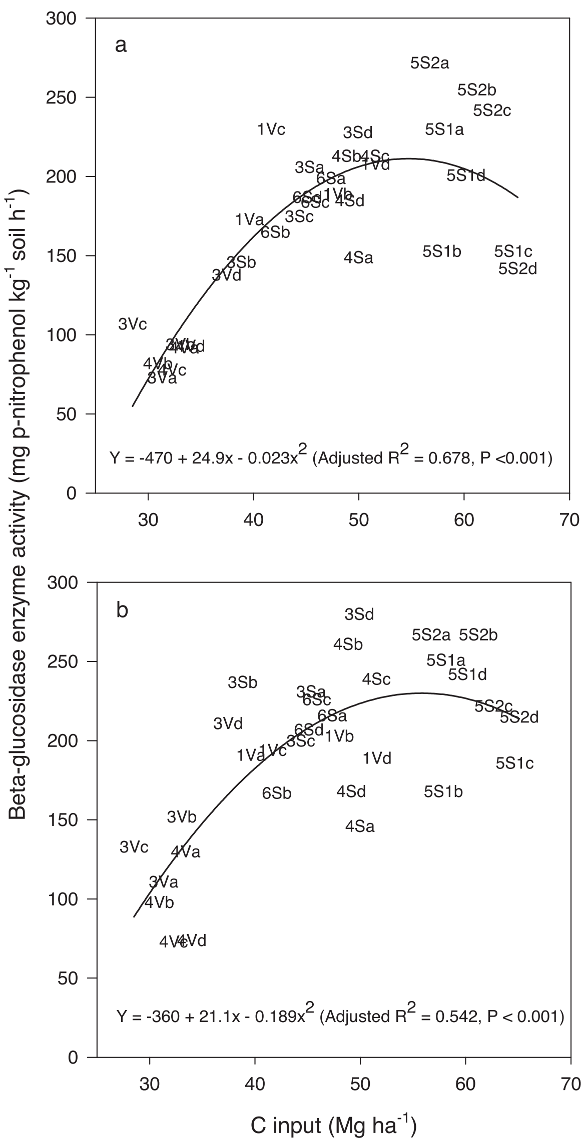

Fig. 5. Regressions between organic C inputs (from compost and crop residues over 12 years, 2000–11) and β-glucosidase activities in different rotations and management systems in bulk soil (a) and wheat rhizosphere (b) in 2011. In the abbreviated rotation names, the integer refers to the length (years) of the rotation; V = conventional management; S = conservation management; the last letter refers to the replicate: a = replicate 1, b = replicate 2, c = replicate 3, d = replicate 4. See Table 1 for the difference between 5S1 and 5S2 rotations.

enzyme activity, was also greater under CONS management than under CONV management (Fig. 4). These results are consistent with our observations on populations, community structures and functional attributes of endophytic bacteria isolated from roots of potato grown in these rotations (Pageni et al., 2013, 2014). By contrast, the populations of potato root-lesion nematodes (*Pratylenchus* spp.) in these rotations were affected by rotation length rather than management (Forge et al., 2015). Thus, there were more nematodes in 3-yr rotations than in longer rotations, but this result was ascribed to the fact that potato was preceded by wheat in this rotation, and wheat is a good host for *P. neglectus* (Forge et al., 2015).

The CONS management systems were bundled in this study, as they are usually done in agricultural systems, but similar results have been shown when the effects of compost, reduced tillage, crop rotation and cover crops on soil microbial communities are studied separately (McDaniel et al., 2014; Tian et al., 2015; Tiemann et al., 2015; Kibet et al., 2016). Compost affects soil microbial communities primarily through the organic C that it contains. In the current study, soil particulate organic C in 2011 and particulate organic N showed the largest increases under CONS management, and it is believed that organic C through compost addition was the major contributor to this effect (Li et al., 2015). Most saprophytic soil microorganisms depend on organic C for their growth and metabolism. Many studies have shown increases in soil microbial biomass, diversity and activity with compost application (Willekens et al., 2014; Hartmann et al., 2015; Tian et al., 2015), but heavy application of compost can reduce soil microbial diversity (Tian et al., 2015).

No-till or reduced tillage is usually associated with greater soil microbial biomass, but only in the top (about 10 cm) soil layers, i.e., paralleling soil organic C amounts (Van Capelle et al., 2012; Kibet et al., 2016). Crop residues are left on the soil surface under no-till systems, and soil organic C and microbial C accumulate just below the surface. In addition, microbial respiration, in relation to microbial biomass, is reduced under no-till, i.e., loss of C as CO_2 is reduced (Lupwayi et al., 1999; Mangalassery et al., 2015). With tillage, crop residues are mixed throughout the plough layer, and soil organic C and microbial C are evenly distributed throughout the plough layer. Tillage accelerates decomposition of organic C by increasing contact between crop residues and the soil, and also by allowing more oxygen into the soil during the tillage process. In the current study in 2011, CONS management systems had greater soil organic C in the 0–7.5 cm depth than the 3-CONV and 4-CONV rotations (Li et al., 2015).

Using crop rotation is one way of increasing plant biodiversity, which influences many ecosystem processes including primary productivity, pest suppression, availability of soil water and nutrients, and soil organic matter dynamics (McDaniel et al., 2014; Angus et al., 2015). Soil microorganisms are affected by the biochemical diversity of the C substrates that are added to the soil in crop rotations. These C additions are in the form of rhizodeposits from growing crops and from decomposing crop residues. A meta-analysis that covered 122 studies showed that crop rotations increased soil MBC and MBN by 21% and 26%, respectively, on average (McDaniel et al., 2014). As crop diversity in rotations increased from one to five species, Tiemann et al. (2015) observed distinct soil microbial communities related to soil aggregation, organic C, total N and microbial activity.

Cover crops are grown between cash crops, e.g., from fall to spring in northern temperate regions, to add biomass to the soil, reduce erosion risk, disrupt pest cycles and capture inorganic N to preclude leaching (McDaniel et al., 2014). The positive effect of cover crops on soil microorganisms is probably related to its positive effect on soil organic C (and N). In their meta-analysis of 122 studies, McDaniel et al. (2014) reported that cover crops accounted for most of the crop rotation effects on soil organic C (9% increase) and N (13% increase), presumably because cover crops tend to have greater root:shoot ratios than cash crops.

Although usually not significantly different from other rotations under CONS management, the 5-CONS2 rotation usually had numerically the highest total soil microbial biomass, fungal biomass, bacterial biomass and β-glucosidase enzyme activity. The probable reason for this result is soil organic C. The 5-CONS rotation had the highest total (crop + compost) C inputs of all rotations, and total soil organic C in the top 7.5 cm was also higher in this rotation than other rotations (Li et al., 2015). By the same token, the lowest total soil microbial biomass, fungal biomass, bacterial biomass and β-glucosidase enzyme activity were usually found in the 4-CONV rotation or 3-CONV rotation, not the 1-CONS (wheat monoculture) rotation. Wheat had the highest mean annual C return (4.6 Mg C ha^{-1}) of all crops, and although the 1-CONV rotation did not have compost C input, it had substantial wheat C input (42 Mg C ha^{-1} over the 12-yr period) (Li et al., 2015). The 4-CONV rotation had the lowest C input (29.0 Mg C ha^{-1}) because it had the lowest proportion of wheat in the crop sequences, and it did not receive compost C. Consequently, total soil organic C was lower in 4-CONV and 3-CONV rotations (9.8 and 10.5 Mg C ha^{-1}, respectively) than in all other rotations. This relationship between C inputs (Li et al., 2015) and soil microbial properties was confirmed by correlation analysis, which showed positive correlations between C inputs and all the measured soil microbial properties, except actinomycetes, in bulk soil and wheat rhizosphere. Actinomycetes belong to the bacterial phylum Actinobacteria, members of which have the most genes (among bacteria) involved in cellulose decomposition (Vetrovsky and Baldrian, 2015). Using next-generation sequencing, Vetrovsky and Baldrian (2015) confirmed earlier reports (Gremion et al., 2003; Berg et al., 2012) that some soil actinobacteria were less affected by heavy metal contamination than other bacteria. It is believed that their filamentous mycelial growth, their ability to form spores, and their powerful secondary metabolism enable them to survive under stress conditions (Vetrovsky and Baldrian, 2015). This capability probably explains the lack of correlation between C inputs and actinomycete biomass in our study. The quadratic nature of the relationships between soil organic C inputs and soil microbial properties indicates that C limited microbial growth and metabolism up to a point, beyond which other factors became limiting.

These differences in soil microbial characteristics between CONS and CONV management have implications not only for nutrient cycling, but also for biological crop protection, ultimately affecting crop yields. After 12 years of these rotations (in 2011), the weed seedbank was higher in 1-CONV (monoculture) wheat than all other rotations, confirming that monoculture cropping is a poor practice in terms of weed management (Blackshaw et al., 2015). Although some CONS rotations had higher weed seedbanks than CONV rotations in 2005, none of the CONS rotation treatments had higher weed seedbank densities compared with the CONV rotations in 2011, and all values were numerically lower than the background densities present when the study was initiated. This finding indicates that CONS practices can be implemented with no adverse long term effects on weed populations. Due to the improved soil quality in CONS management reported here and by Li et al. (2015), potato and sugar beet yields were also higher relative to those under CONV management (Larney et al., 2016a,b). Dry bean yields were also greater under CONS than CONV in 2010 and 2011, when harvest losses were reduced by using the undercutting method of harvesting the crop rather than the direct-combining method that had been used previously (Larney et al., 2015). These soil microbiological and crop yield responses to soil conservation management would be different under rain-fed conditions where rainfall is not supplemented with irrigation.

5. Conclusion

Soil microbial biomass, including that of fungi, bacteria, GN bacteria, GP bacteria and actinomycetes, was greater under CONS management than under CONV management in the final two years of the study. The soil microbial community structures in the different rotations were mostly shaped by CONV or CONS management practices in 2010. β-glucosidase activity was also greater under CONS management than under CONV management. These results are consistent with previously-published results which showed greater soil C and yields of dry bean, potato and sugar beet in CONS management practices than in CONV management practices. Therefore, CONS practices can improve soil microbiological properties and productivity in irrigated cropping systems of southern Alberta, where conservation soil management for these crops is new.

Acknowledgements

We are grateful to Mandy Collins and Andrea Eastman at Beaverlodge Research Farm for soil MBC and β-glucosidase enzyme activity analyses. Jim Sukeroff and staff at the Vauxhall Substation provided field assistance. Funding contributions from the Alberta Agricultural Research Institute, Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Pulse Science Cluster, and Agriculture and Agri-Food Canada's Matching Investment Initiative are gratefully acknowledged.

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Applied Soil Ecology 121 (2017) 65–73

Contents lists available at ScienceDirect

Applied Soil Ecology

journal homepage: www.elsevier.com/locate/apsoil

Pyrosequencing reveals profiles of soil bacterial communities after 12 years of conservation management on irrigated crop rotations

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ARTICLE INFO

Keywords:
Compost
Cover crops
Next-generation sequencing
Soil health
Tillage

ABSTRACT

Potato and sugar beet, which are widely grown in southern Alberta, may degrade soil quality because they return little C to the soil, and their harvesting methods cause soil disturbance that increases erosion risk. To reverse these effects, a 12-yr study was established to evaluate soil conservation (CONS) management systems for rotations that included potato, sugar beet, dry bean and wheat. These systems, comprising addition of feedlot manure compost, reduced tillage, diverse crop rotations and use of cover crops, were applied to 3- to 5-yr crop rotations. They were compared with conventional (CONV) management systems that did not have any of the CONS practices. In the final year of the study, pyrosequencing was used to determine differences in soil bacterial community profiles between the two systems (CONS vs. CONV) in wheat rhizosphere and bulk soil. Thirteen phyla were observed, and the most abundant were Proteobacteria (39.6%), Actinobacteria (19.1%) and Acidobacteria (14.9%). Soil bacterial α-diversity increased under CONS relative to CONV management. However, whereas the relative abundances of Bacteroidetes and Firmicutes were greater under CONS than CONV management, the reverse was observed for Acidobacteria and Gemmatimonadetes. Proteobacteria were also more abundant under CONS than CONV management, but only in bulk soil. The community structures of the bacterial communities were in agreement with the differences in relative abundances. These differences were consistent with the ecological classification of soil bacteria as copiotrophic or oligotrophic. Therefore, CONS management systems altered the soil bacterial community profiles and increased the productivity of these soils.

1. Introduction

Growing root crops like potato (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* L.) usually results in soil degradation, yet their acreage and that of dry bean (*Phaseolus vulgaris* L.) in southern Alberta has increased 2- to 3-fold recently (Alberta Agriculture and Forestry, 2015). Soil degradation occurs due to reductions in soil organic C because these crops produce less biomass and therefore return less C to the soil than the cereal or forage crops that they replace in irrigated crop rotations (Li et al., 2015). In addition, potato is usually grown on raised beds which require extra tillage passes, and the harvesting methods of both potato and sugar beet necessitate greater soil disturbance, making the soil susceptible to wind and water erosion (Chow et al., 1990; Carter and Sanderson, 2001). Annual soil losses by water erosion from continuous potato plots on 8 and 11% slopes have been estimated at 17 and 24 Mg ha^{-1} yr^{-1}, respectively, in New Brunswick, Canada (Chow et al., 1990). Eroded soils lose some of their organic C and nutrients, and soil tillage further reduces organic C by accelerating its decomposition (Lupwayi et al., 2004).

A field study was conducted from 2000 to 2011 to determine if soil conservation practices could be applied to southern Alberta irrigated cropping systems to address the soil degradation issues. These practices included addition of feedlot manure compost, reduced tillage, use of cover crops, and solid-seeded narrow-row dry bean, applied as a package. Yields of dry bean (Larney et al., 2015), potato (Larney et al., 2016b) and sugar beet (Larney et al., 2016a) increased under conservation management relative to conventional management. The increased crop yields were probably a result of the soil building nature of the soil conservation practices as indicated by increases in soil organic C and total N under CONS management during the study (Larney et al., 2017). The stability of soil aggregates also improved significantly under CONS management relative to CONV management (Li et al., 2015).

An examination of the soil microbial responses to these soil conservation practices is also important. Soil microbial properties are

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http://dx.doi.org/10.1016/j.apsoil.2017.09.031
Received 18 May 2017; Received in revised form 14 September 2017; Accepted 20 September 2017
0929-1393/

sensitive indicators of soil quality because they respond quickly to changes in soil management (Doran et al., 1996; Bruggen and Semenov, 2000; Stone et al., 2016), and in addition, the soil microbial community mediates many key biological processes for sustainable agriculture. These processes include biological nitrogen fixation (Jensen and Hauggaard-Nielsen, 2003; Gaby and Buckley, 2011), biomass decomposition and nutrient cycling (Schneider et al., 2012; Lupwayi and Soon, 2015), formation and maintenance of soil aggregates (Six et al., 2004; Blaud et al., 2012), biological disease and pest control (Janvier et al., 2007; Mendes et al., 2011), detoxification of agro-chemicals (Shelton and Doherty, 1997; Itoh, 2014) and regulation of climate through C and N cycles (Baldock et al., 2012; Gregorich et al., 2015). Using phospholipid fatty acid biomarkers in the final two years of the current field study, Lupwayi et al. (2017) reported greater soil microbial biomass (including that of fungi, Gram-negative bacteria, Gram-positive bacteria and actinomycetes) under CONS management than under CONV management. Soil β-glucosidase activity was also greater under CONS management than under CONV management. The objective of this study was to expand on those results by using next-generation sequencing to examine how CONS management affected soil bacterial diversity, composition and community structure by the final year of the 12-yr study.

2. Materials and methods

2.1. Study location, experimental treatments and management

A 12-yr (2000–2011) irrigated field study was conducted at Vauxhall, Alberta (50° 03′ N, 112° 09′ W, elev. 781 m). The soil was a Brown Chernozem (Soil Classification Working Group, 1998) (Haplic Kastanozem in World Reference Base) which had 520 g kg^{-1} sand, 340 g kg^{-1} silt, 140 g kg^{-1} clay, and 12.9 g organic C kg^{-1} soil and pH 6.9 (0–15 cm depth) at the start of the experiment. It is a typical soil type of southern Alberta. The 30 year (1971–2000) mean annual precipitation in the research area was 303 mm with a mean annual air temperature of 5.7 °C.

The entire plot area was planted to barley (*Hordeum vulgare* L.) in 1999 and treatments were established in the spring of 2000. There were six rotation treatments: continuous (monoculture) wheat (*Triticum aestivum* L.), two 3-yr rotations, two 4-yr rotations, and one 5-yr rotation (but with two wheat phases that were each sampled for this study) (Table 1). These rotations were managed utilizing CONV or CONS management practices (described below). All crop phases of each rotation were grown each year to account for varying environmental conditions over years. The treatments were arranged in a randomized complete block design (RCBD) with four replicates. The individual plot sizes were 10.1 by 18.3 m with 2.1 m buffer zones between plots.

For the CONS rotations (Table 1), a package of the following four practices was applied (for details, see Larney et al., 2015, 2016a,b):-

1. Direct seeding and/or reduced tillage where possible in the rotation.
2. Fall-seeded cover crops: oat (*Avena sativa* L.) and fall rye (*Secale cereale* L.) with entry points detailed in Table 1. However, due to sub-optimal fall establishment of oat, it was replaced with fall rye from fall 2003 onward. Oat cannot be used as a cover crop in the study area because it gets killed by frost before it produces enough dry matter to cover the soil.
3. Composted cattle manure: straw-bedded beef cattle feedlot manure compost (182, 15.4, and 5.4 g kg^{-1} dry wt. of total C, N, and P, respectively) was fall-applied to supply some of the N and P required (as determined by soil testing). The rest of the required N was supplied by inorganic fertilizer. A rate of 42 Mg ha^{-1} (fresh wt) was applied after dry bean and before potato in the 4- and 5- CONS rotations (Table 1). The shorter 3-CONS rotation received a lower rate (28 Mg ha^{-1}, fresh wt) after wheat and before potato. This lower rate was also applied at a second entry point in the 5-yr CONS rotation − after sugar beet and before wheat (Table 1).
4. Solid-seeded, direct-cut, narrow-row (19–23 cm) dry bean. There was no inter-row cultivation, and the crop was harvested by direct-cutting (no soil disturbance) with a plot combine.

Conventional management did not use any of the above practices, and hence the 3- and 4-yr CONV rotations (a) had more intensive tillage, (b) no cover crops, (c) no compost amendments (all nutrients were supplied by inorganic fertilizers), and (d) dry bean was grown in wide rows (60 cm), with inter-row cultivation for in-season weed control, and undercutting at harvest (causing soil disturbance and unanchored residue).

Tillage intensity was reduced as much as possible under CONS compared with CONV management. Crops were fertilized according to soil test recommendations, with soil testing done every three years. The crops were irrigated, using a wheel-move system, to maintain soil water (to 100 cm depth) at no lower than 50% field capacity, which was considered to be sufficient to eliminate moisture stress as a factor. Pre-seeding, in-crop and post-harvest herbicides were used as required for weed control. Each fall, mature crops were harvested for yield and quality assessment.

2.2. Microbiological soil sampling

In the final year (2011) of the 12-yr study, soil samples were collected in the wheat phase of 1- to 5-yr rotations. The samples were taken at the flag leaf growth stage of wheat on July 28. Plants were excavated from four random 0.5-m lengths of row. Loose soil was removed from the roots by shaking the plants vigorously by hand, and the remaining soil that had strongly adhered to the roots was carefully brushed off and recovered as rhizosphere soil. Bulk soil (0–7.5 cm depth) was sampled from the middle of two adjacent crop rows at four locations per plot. The four bulk or rhizosphere soil samples from each plot were combined, respectively, passed through a 2-mm sieve, stored

Table 1
Description of treatments indicating management differences from 2000 to 2011.

Rotation[a]	Crop sequence[b]	No. of crop phases	Tillage	Nutrient source	Cover crop	Bean row spacing[d]
1-CONT	<u>W</u>	1	Reduced	Fertilizer	None	No bean
3-CONV	P–B–<u>W</u>	3	Conventional	Fertilizer	None	Wide
3-CONS	P–B–<u>W</u>	3	Reduced	Fertilizer/Compost after W	After P & B	Narrow
4-CONV	P–<u>W</u>–SB–B	4	Conventional	Fertilizer	None	Wide
4-CONS	P–<u>W</u>–SB–B	4	Reduced	Fertilizer/Compost after B	After P	Narrow
5-CONS1[c]	P–<u>W</u>–SB–W–B	5	Reduced	Fertilizer/Compost after SB & B	After P	Narrow
5-CONS2[c]	P–W–SB–<u>W</u>–B	5	Reduced	Fertilizer/Compost after SB & B	After P	Narrow

[a] Integers refer to the length (years) of each rotation; CONT = Continuous wheat; CONV = conventional management; CONS = conservation management.
[b] B = dry bean; P = potato; SB = sugar beet; W = wheat. The <u>underlined</u> wheat phase of each rotation was sampled for soil microbiological analysis.
[c] In 5-CONS1 rotation, the first (<u>underlined</u>) wheat phase was sampled; in 5-CONS2 rotation, the second (<u>underlined</u>) wheat phase was sampled.
[d] Wide row spacing = 60 cm; narrow row spacing = 19 cm (2000–2003 and 2011) and 23 cm (2014-2010).

Table 2
Bacterial α-diversity in bulk soil in different crop rotations and management practices.

Rotation[a]	No. of sequences	Coverage	OTUs[h]	Chao1	Shannon	Inverse Simpson
1-CONT	2653a[g]	0.9841a	181a	221a	4.01a	22.44a
3-CONV	2294ab	0.9809a	176a	211a	3.98a	21.15a
3-CONS	2214b	0.9774a	178a	215a	4.01a	21.63a
4-CONV	2028b	0.9810a	169a	202a	3.95a	20.68a
4-CONS	1893b	0.9775a	185a	232a	4.05a	23.08a
5-CONS1[b]	2077b	0.9767a	184a	220a	4.04a	21.28a
5-CONS2[c]	2344ab	0.9770a	185a	243a	4.03a	19.63a
SE[d]	201.6	0.00454	7.3	11.9	0.045	1.669
CONV[e]	2161a	0.9810a	172b	207b	3.96a	20.92a
CONS[e]	2132a	0.9771b	183a	227a	4.03a	21.41a
Bean pre-crop[f]	2254a	0.9792a	177a	213a	4.00a	21.39a
Potato pre-crop[f]	2000a	0.9784a	179a	218a	4.01a	21.68a

[a] Integers refer to the length (years) of each rotation; CONT = Continuous wheat; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote in Table 1).
[c] Wheat preceded by sugar beet (see footnote in Table 1).
[d] SE = standard error of the mean.
[e] CONV = mean of 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1 and 5-CONS2.
[f] Bean pre-crop = mean of 3-CONV and 3-CONS; Potato pre-crop = mean of 4-CONV, 4-CONS and 5-CONS1.
[g] Means followed by the same letter in a column within a treatment group are not significantly different at 5% significance level.
[h] OTUs = operational taxonomic units.

at −20 °C until DNA was extracted using PowerSoil DNA Isolation Kit (MO BIO Laboratories Inc., Carlsbad, CA). One extraction was done per composite soil sample of each plot, but further extractions were done (and the DNA pooled) if inadequate high-quality DNA was obtained with the first extraction.

2.3. Pyrosequencing

The 16S rRNA gene universal Eubacterial primers 27F and 519R (Valverde et al., 2015) were used in a single-step 30-cycle polymerase chain reaction (PCR) using HotStarTaq Plus Master Mix Kit (Qiagen, Valencia, CA) under the following conditions: 94 °C for 3 min, followed by 28 cycles of 94 °C for 30 s; 53 °C for 40 s and 72 °C for 1 min; after which a final elongation step at 72 °C for 5 min was performed. Following PCR, all amplicon products from different samples were mixed in equal concentrations and purified using Agencourt Ampure beads (Agencourt Bioscience Corporation, Beverly, MA). Samples were pyrosequenced by MR DNA Lab (www.mrdnalab.com, Shallowater, Texas) utilizing Roche 454 FLX titanium instruments and reagents following manufacturer's guidelines.

2.4. Sequencing processing and data analysis

Sequence data derived from pyrosequencing were subjected to a stringent quality control screening processes using the open source pipeline Mothur and the recommended quality control procedures (Schloss et al., 2009). Briefly, sequences were depleted of barcodes and primers, and then short sequences < 200 bp, sequences with ambiguous base calls, and sequences with homopolymer runs exceeding 8 bp were removed. The remaining sequences were denoised and truncated to remove the poor quality base calls towards the end of each read. Sequences were then aligned against the SILVA alignment database for 16S rRNA genes to define operational taxonomic units (OTUs) at 97% pairwise identity threshold (Schloss et al., 2009). Sequences that did not span the longest alignment region were also removed from the dataset. Sequences were trimmed so that reads overlapped in the same alignment space. Pyrosequencing base call errors were minimized using the pre-cluster algorithm in Mothur software (Huse et al., 2010), whereby rare sequences that were highly similar to abundant sequences were re-classified as their abundant homologue. Chimeras were removed from the samples using the sequence collection (UCHIME) as its own reference database (Edgar et al., 2011). Mothur software was also used to calculate within community diversity (α-diversity): number of sequences, Good's coverage, OTUs, Chao 1 index, Shannon index and Simpson index. The diversity indices were calculated based on OTU data. Sequences and OTUs were classified using the Mothur software against the Silva reference v110 database (Pruesse et al., 2007) set to name uncultured clusters after the most recently deposited clone sequence. Calculation of the percentage of sequence within a taxonomic classification up to the genus level was performed using a custom summation script.

The PROC MIXED procedure of SAS (SAS Institute, 2009) was used to statistically analyse differences between rotations (fixed variable) in bacterial α-diversity (number of sequences, coverage, OTUs, Chao 1 index, Shannon index and Simpson index) and the relative abundances of bacterial communities at phylum and genus levels, using the randomized complete block design of the trial. Treatment differences were declared significant at 5% significance level, and means were separated by the least-significant difference (LSD) method. In addition to differences between all treatments, differences between 3-CONV and 3-CONS, or between 4-CONV and 4-CONS rotations, were noted because these pairs of treatments had the same crop sequences and differed only in management (CONV or CONS). Orthogonal contrast analysis also tested the effect of CONV management treatments (Rotations 3-CONV and 4-CONV) versus CONS management treatments (Rotations 3-CONS, 4-CONS, 5-CONS1, and 5-CONS2 − Table 1). The effect of preceding crop: dry bean (Rotations 3-CONV and 3-CONS) versus potato (Rotations 4-CONV, 4-CONS, and 5-CONS1) before wheat was also tested by orthogonal contrast analysis (Table 1). To compare the community structures (β-diversity) of the soil bacteria, principal component analysis (PCA) was used to classify CONS and CONV treatments according to their relative abundances using SigmaPlot 13 software (www.systat.com). A correlation matrix of standardized relative abundance data was used in the PCA analysis and, after classification of the treatments, the bacterial phyla that accounted for differences between classes of treatments in abundances were identified by correlating principal component scores with abundances of individual phyla. This analysis was also done at bacterial genus level.

3. Results

3.1. Bacterial α-diversity

In bulk soil, there were differences between crop rotations in the number of sequences, ranging from 2653 in 1-CONT rotation to 1893 in 4-CONS rotation (Table 2). However, there were no significant differences between CONV and CONS management systems, or between dry bean and potato as preceding crops. Although ANOVA did not reveal any differences between crop rotations in the other measures of α-diversity, contrast analysis indicated greater coverage under CONV than CONS management, but more OTUs and greater Chao1 index of diversity under CONS than CONV management. The preceding crop contrast was non-significant for all measures of diversity.

In the wheat rhizosphere, Chao1 and Shannon indices of diversity were affected by crop rotations (Table 3). Chao1 index was highest (247) in 5-CONS2 rotation and lowest (183) in 1-CONT rotation, but there were no differences between 3-CONV and 3-CONS rotations, or 4-CONV and 4-CONS rotations. Contrast analysis also did not show differences between management systems or pre-crops. Shannon index was highest (4.11) in 3-CONS rotation and lowest (3.88) in 1-CONT rotation (Table 3). This index was greater in 3-CONS rotation than in 3-CONV rotation, and contrast analysis revealed greater Shannon index

Table 3
Bacterial α-diversity in wheat rhizosphere in different crop rotations and management practices.

Rotation[a]	No. of sequences	Coverage	OTUs[h]	Chao1	Shannon	Inverse Simpson
1-CONT	2563a[g]	0.9845a	170a	183d	3.88c	19.77a
3-CONV	2385a	0.9810a	175a	221abc	3.92c	19.11a
3-CONS	2237a	0.9802a	174a	207bcd	4.11a	23.46a
4-CONV	2433a	0.9825a	163a	191 cd	3.95bc	20.32a
4-CONS	2119a	0.9759a	173a	206bcd	3.98bc	20.41a
5-CONS1[b]	1872a	0.9702a	180a	230ab	4.07ab	22.84a
5-CONS2[c]	2115a	0.9780a	191a	247a	4.06ab	21.01a
SE[d]	334.8	0.00474	8.9	12.7	0.045	1.614
CONV[e]	2409a	0.9806a	169a	206a	3.93b	19.71a
CONS[e]	2086a	0.9765a	179a	223a	4.05a	21.93a
Bean pre-crop[f]	2311a	0.9806a	174a	214a	4.01a	21.28a
Potato pre-crop[f]	2141a	0.9759a	172a	209a	4.00a	21.19a

[a] Integers refer to the length (years) of each rotation; CONT = Continuous wheat; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote in Table 1).
[c] Wheat preceded by sugar beet (see footnote in Table 1).
[d] SE = standard error of the mean, df = degrees of freedom for error.
[e] CONV = mean of 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1 and 5-CONS2.
[f] Bean pre-crop = mean of 3-CONV and 3-CONS; Potato pre-crop = mean of 4-CONV, 4-CONS and 5-CONS1.
[g] Means followed by the same letter in a column within a treatment group are not significantly different at 5% significance level.
[h] OTUs = operational taxonomic units.

under CONS management than under CONV management.

3.2. Bacterial community composition

Thirteen phyla were identified in the trial, but the most abundant across rotations (in the rhizosphere and bulk soil) followed the order: Proteobacteria (39.6% relative abundance), Actinobacteria (19.1%), Acidobacteria (14.9%), Bacteroidetes (8.2%), Firmicutes (4.1%), Gemmatimonadetes (4.0%), Chloroflexi (3.7%), Verrucomicrobia (2.2%) and Planctomycetes (1.3%). In bulk soil, differences between crop rotations were observed in the relative abundances of Proteobacteria, Acidobacteria, Firmicutes and Gemmatimonadetes (Table 4 & Fig. 1a). Although ANOVA did not indicate differences between rotations in the relative abundances of Bacteroidetes, contrast analysis indicated that they were more abundant under CONS (9.08%)

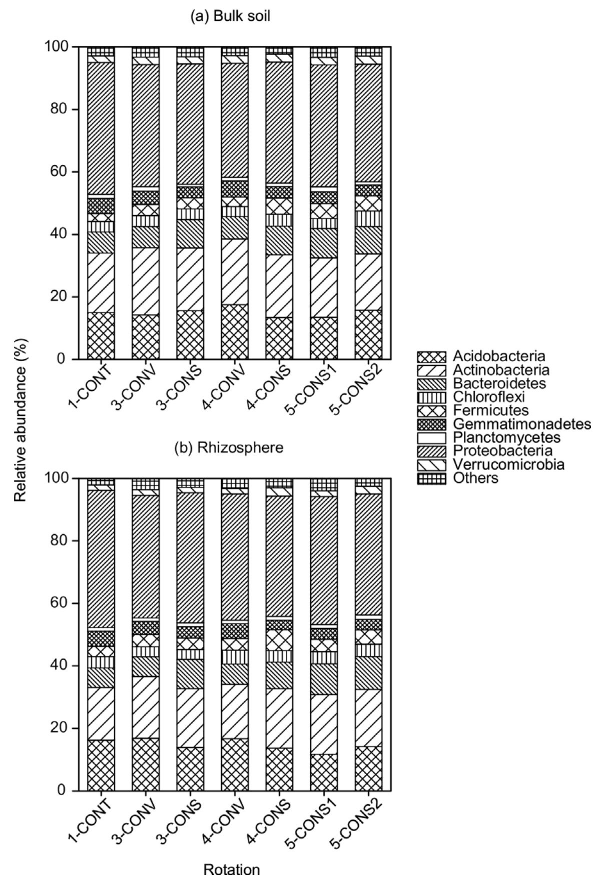

Fig. 1. Relative abundances of bacterial phyla in all treatments in bulk soil (a) and wheat rhizosphere (b). In the abbreviated rotation names, the integer refers to the length (years) of each rotation; CONT = Continuous wheat; CONV = conventional management; CONS = conservation management. See Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations.

Table 4
Relative abundances of the most abundant bacterial phyla in bulk soil in different crop rotations and management practices.

Rotation[a]	Proteobacteria	Actinobacteria	Acidobacteria	Bacteroidetes	Firmicutes	Gemmatimonadetes	Chlorflexi
	Relative abundance (%)						
1-CONT	42.09a[g]	19.01a	13.36c	6.76a	2.60c	4.75ab	2.65a
3-CONV	39.04b	21.56a	15.43b	6.73a	3.54bc	4.27abc	3.50a
3-CONS	38.48bc	20.14a	15.56b	9.01a	3.58bc	3.38c	3.47a
4-CONV	36.46c	20.98a	17.49a	7.23a	3.07c	5.17a	3.17a
4-CONS	38.74bc	20.13a	13.36c	9.17a	5.22a	3.61c	3.77a
5-CONS1[b]	39.03b	18.99a	13.51c	9.41a	4.73ab	3.78bc	3.22a
5-CONS2[c]	37.65bc	18.09a	16.68ab	8.72a	4.86a	3.42c	4.97a
SE[d]	0.836	1.559	0.645	0.844	0.470	0.392	0.466
CONV[e]	37.75b	21.27a	16.46a	6.98b	3.31b	4.72a	3.33a
CONS[e]	38.47a	19.34a	14.78b	9.08a	4.60a	2.55b	3.86a
Bean pre-crop[f]	38.76a	18.61a	15.50a	7.87a	3.56a	3.83a	3.48a
Potato pre-crop[f]	38.07a	18.80a	14.79a	8.60a	4.34a	4.19a	3.38a

[a] Integers refer to the length (years) of each rotation; CONT = Continuous wheat; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote in Table 1).
[c] Wheat preceded by sugar beet (see footnote in Table 1).
[d] SE = standard error of the mean, df = degrees of freedom for error.
[e] CONV = mean of 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1 and 5-CONS2.
[f] Bean pre-crop = mean of 3-CONV and 3-CONS; Potato pre-crop = mean of 4-CONV, 4-CONS and 5-CONS1.
[g] Means followed by the same letter in a column within a treatment group are not significantly different at 5% significance level.

Table 5
Relative abundances of the most abundant bacterial phyla in wheat rhizosphere in different crop rotations and management practices.

Rotation[a]	Proteobacteria	Actinobacteria	Acidobacteria	Bacteroidetes	Firmicutes	Gemmatimonadetes	Chlorflexi
	Relative abundance (%)						
1-CONT	43.81a[g]	16.70a	16.20ab	6.25b	3.25c	4.84a	3.66a
3-CONV	39.18b	19.84a	16.77a	6.31b	3.91bc	4.14a	3.25a
3-CONS	41.64ab	18.83a	13.94c	9.35a	3.67bc	3.53a	3.22a
4-CONV	40.41b	17.38a	16.71a	6.45b	3.77bc	4.74a	4.44a
4-CONS	38.47b	18.96a	15.56abc	8.49ab	6.72a	3.00a	3.68a
5-CONS1[b]	40.87ab	19.09a	11.71d	9.86a	5.10ab	3.46a	3.89a
5-CONS2[c]	38.68b	18.32a	14.16bc	10.46a	4.59bc	3.33a	3.97a
SE[d]	1.113	1.594	0.914	0.946	0.627	0.455	0.570
CONV[e]	39.79a	18.61a	16.74a	6.38b	3.84b	4.44a	3.84a
CONS[e]	39.91a	18.80a	13.84b	9.54a	5.02a	3.33b	3.69a
Bean pre-crop[f]	40.41a	19.34a	15.35a	7.83a	3.79b	3.84a	3.23a
Potato pre-crop[f]	39.91a	18.48a	14.66a	8.27a	5.20a	3.73a	4.00a

[a] Integers refer to the length (years) of each rotation; CONT = Continuous wheat; CONV = conventional management; CONS = conservation management.
[b] Wheat preceded by potato (see footnote in Table 1).
[c] Wheat preceded by sugar beet (see footnote in Table 1).
[d] SE = standard error of the mean, df = degrees of freedom for error.
[e] CONV = mean of 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1 and 5-CONS2.
[f] Bean pre-crop = mean of 3-CONV and 3-CONS; Potato pre-crop = mean of 4-CONV, 4-CONS and 5-CONS1.
[g] Means followed by the same letter in a column within a treatment group are not significantly different at 5% significance level.

than CONV (6.98%) management. Similar differences were observed for Proteobacteria (38.47% vs 37.75%) and Firmicutes (4.60% vs 3.31%). However, Acidobacteria and Gemmatimonadetes were more abundant under CONV than CONS management (16.46% vs 14.78%, and 4.72% vs 2.55%, respectively). There were no differences between dry bean or potato preceding crops in the relative abundances of any phyla.

In wheat rhizosphere soil, the relative abundances of Proteobacteria, Acidobacteria, Bacteroidetes, Gemmatimonadetes and Firmicutes were different between crop rotations (Table 5 & Fig. 1b). Contrast analysis indicated that Bacteroidetes and Firmicutes were more abundant under CONS than CONV management (9.54% vs 6.38%, and 5.02% vs 3.84, respectively), but Acidobacteria and Gemmatimonadetes were again more abundant under CONV than CONS management (16.74% vs 13.84%, and 4.44% vs 3.33%, respectively). Contrast analysis also showed that the relative abundance of Firmicutes in the rhizosphere of wheat preceded by potato (5.20%) was greater than that of wheat preceded by dry bean (3.79%).

At the genus level (data not presented), the most prevalent bacterial communities across treatments were *Gemmatimonas* spp. (Gemmatimonadetes) (3.96%), *Arthrobacter* spp. (Actinobacteria) (1.99%), *Sorangium* spp. (Proteobacteria) (1.48%), *Skermanella* spp. (Proteobacteria) (1.45%), *Afipia* spp. (Proteobacteria), (1.33%), *Sorilubacter* spp. (Actinobacteria) (1.32%) and *Opitutus* spp. (Verrucomicrobia) (1.30%). In bulk soil, the relative abundance of *Afipia* spp. was greater in 1-CONT rotation (wheat monoculture) than any other rotation. Whereas *Gemmatimonas* spp. and *Sorilubacter* spp. were more abundant under CONV than CONS management, the reverse was true for *Sorangium* spp. In the wheat rhizosphere, the same genera as in bulk soil were more abundant under CONV than CONS, but *Sorangium* spp., *Opitutus* spp. and *Skermanella* spp. were more abundant under CONS than CONV management.

3.3. Bacterial β-diversity (community structure)

In bulk soil, PCA revealed that the community structures of the bacteria in the different treatments were mainly shaped by management system. Thus, PC1, which explained 51% of the variance, mainly separated treatments under CONS management (except 3-CONS) from those under CONV management (Fig. 2a). Firmicutes, Bacteroides and Verrucomicrobia were among the phyla most associated with CONS management, while Armatomonadetes, Gemmatimonadetes and Actinobacteria were associated with CONV management (Fig. 2b).

In wheat rhizosphere, the bacterial community structures in the different treatments were also mainly shaped by management system. PC1 explained 38% of the variance and separated treatments under CONS management from those under CONV management (Fig. 3a). Verrucomicrobia, Firmicutes, and Bacteroides were again among the phyla most associated with CONS management, and Gemmatimonadetes and Acidobacteria with CONV management (Fig. 3b).

At the genus level in bulk soil, *Sorangium* spp. (Proteobacteria) and *Opitutus* spp. (Verrucomicrobia) were mostly associated with CONS management, and *Gemmatimonus* spp. (Gemmatimonadetes) and *Sorilubacter* spp. (Actinobacteria) mostly with CONV management (data not shown). In the wheat rhizosphere, *Skermanella* spp. (Proteobacteria), *Soranguim* spp. and *Opitutus* spp. (Verrucomicrobia) were mostly associated with CONS management, and as in bulk soil the same *Gemmatimonus* spp. and *Sorilubacter* spp. were mostly associated with CONV management (Fig. 4a, b).

4. Discussion

Although one metric of bacterial richness (coverage) was greater under CONV management than CONS management in bulk soil, two metrics (OTUs and Chao1) were greater under CONS than CONV management. In the wheat rhizosphere, Shannon index of diversity was greater under CONS than CONV management. In Manitoba, Canada, Li et al. (2012) reported greater coverage in conventional than in organic treatments, but vice-versa for abundance-based coverage estimator (ACE), which is another measure of bacterial richness. Francioli et al. (2016) also observed greater bacterial richness and Shannon index in soils fertilized with farmyard manure or manure + NPK fertilizer than in unfertilized or fertilizer-only soils. One reason for the increase in bacterial diversity under CONS management in our study is that it comprised practices that individually usually increase soil microbial diversity, including reduced tillage (Lupwayi et al., 1998; Sengupta and Dick, 2015; Wang et al., 2016), use of cover crops (Fernandez et al., 2016; Vukicevich et al., 2016) and compost application (Hartmann et al., 2015; Tian et al., 2015; Sorrenti et al., 2017). Reduced tillage, cover crops and compost application affect soil microbial communities by increasing soil organic C, which is the main substrate used for metabolism of heterotrophic soil microorganisms. In the current study,

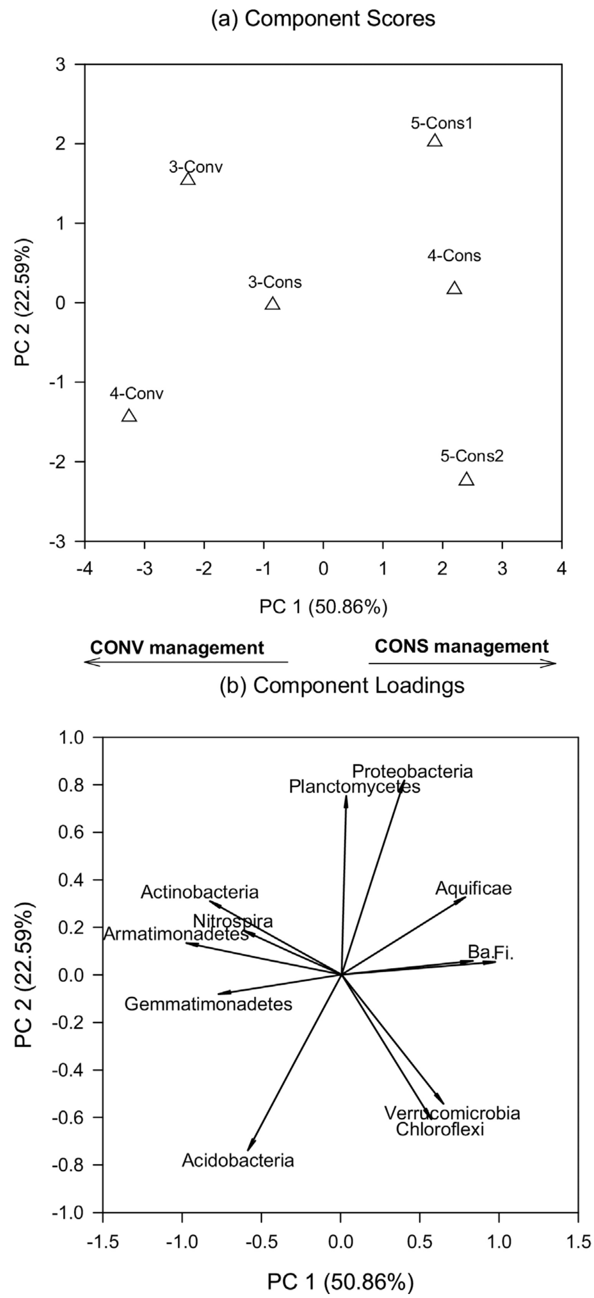

Fig. 2. Ordination, by principal component analysis (PCA) in bulk soil, of the relative abundances of bacterial phyla in different CONV and CONS treatments (a), and the main phyla that accounted for the separation of treatments (b). The percentage of total variance explained by each axis is shown. In the abbreviated rotation names, the integer refers to the length (years) of each rotation; CONV = conventional management; CONS = conservation management. See Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations. Ba. = Bacteroidetes; Fi. = Firmicutes. Each data point is a mean of 4 replicates.

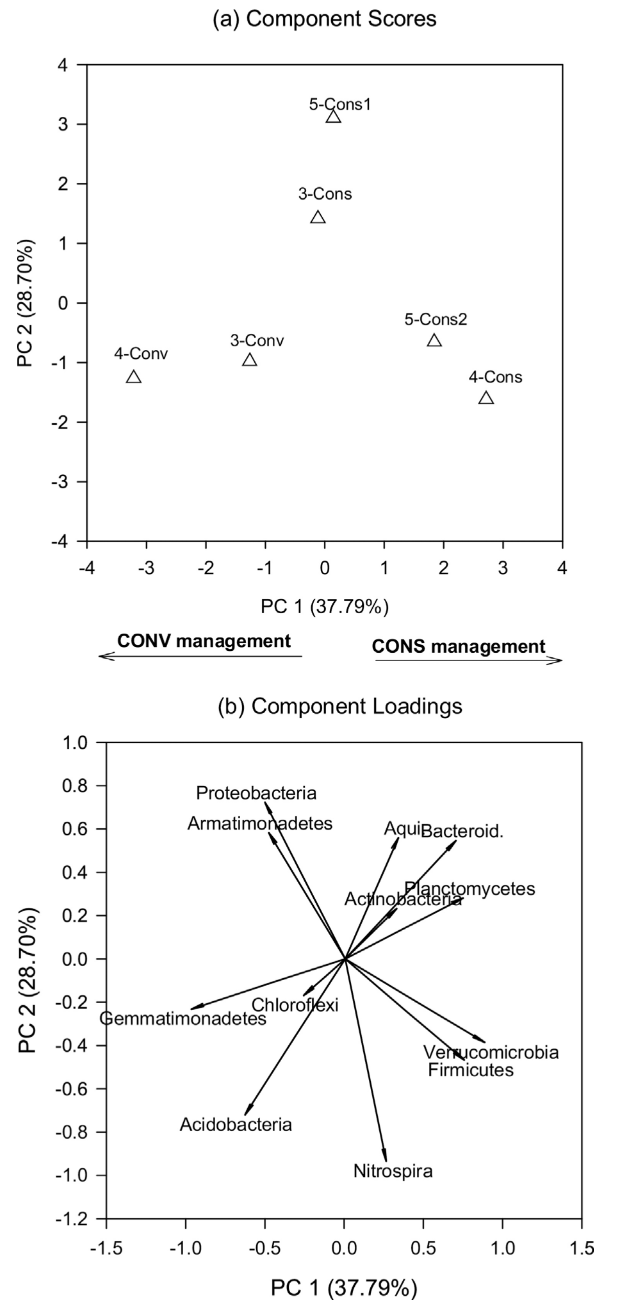

Fig. 3. Ordination, by principal component analysis (PCA) in wheat rhizosphere, of the relative abundances of bacterial phyla in different treatments CONV and CONS (a), and the main phyla that accounted for the separation of treatments (b). The percentage of total variance explained by each axis is shown. In the abbreviated rotation names, the integer refers to the length (years) of each rotation; CONV = conventional management; CONS = conservation management. See Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations. Aqui. = Aquificae; Bacteroid. = Bacteroidetes. Each data point is a mean of 4 replicates.

CONS management systems had greater soil organic C (Li et al., 2015; Larney et al., 2017) and total N (Larney et al., 2017) concentrations than CONV management systems.

Although soil bacterial diversity usually increased under CONS management, not all phyla responded similarly to management. The relative abundances of Bacteroidetes and Firmicutes were greater under CONS than CONV management both in bulk soil and wheat rhizosphere, but Acidobacteria and Gemmatomonadetes were more abundant under CONV than CONS management. Proteobacteria were also more abundant under CONS than CONV management in bulk soil, but there was no difference in wheat rhizosphere soil. Characterization of bacterial endophytes isolated from potatoes grown in these rotations revealed that, within 3-yr or 4-yr rotations, Proteobacteria were more abundant in CONS than CONV management, but Actinobacteria were more abundant in CONV than CONS management (Pageni et al., 2013). In rice compost treatments in rice field soils, Ahn et al. (2016) also reported increased abundances of Bacteroidetes, Firmicutes and Proteobacteria, but decreased abundances of Acidobacteria and Planctomycetes. Similar results have been reported in experiments comparing organic with conventional farming practices (Li et al., 2012; Hartmann et al., 2015; Ishaq et al., 2017). The ecological classification of soil

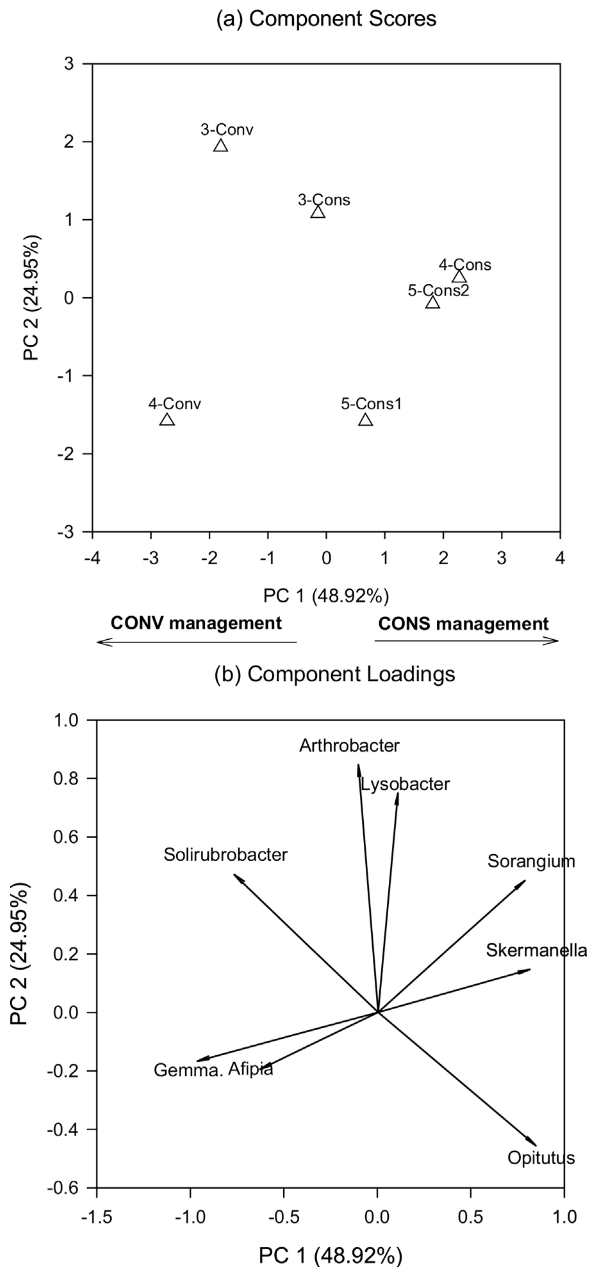

Fig. 4. Ordination, by principal component analysis (PCA) in wheat rhizosphere, of the relative abundances of bacterial genera in different CONV and CONS treatments (a), and the main genera that accounted for the separation of treatments (b). The percentage of total variance explained by each axis is shown. In the abbreviated rotation names, the integer refers to the length (years) of each rotation; CONV = conventional management; CONS = conservation management. See Table 1 for the difference between 5-CONS1 and 5-CONS2 rotations. Gemma = Gemmatimonas. Each data point is a mean of 4 replicates.

bacteria as copiotrophic or oligotrophic (Fierer et al., 2007, 2012) is helpful in understanding their different responses to soil management. Proteobacteria, Bacteroidetes and Firmicutes are generally classified as copiotrophic or *r*-strategists, i.e., fast-growing microorganisms that prefer C- and/or N-rich conditions (Fierer et al., 2007, 2012; Ahn et al., 2016). In our study, soils under CONS management contained more organic C and N than those under CONV management (Larney et al., 2017), and copiotrophs were expected to respond positively to such conditions. This was the case for Bacteroidetes and Firmicutes in bulk soil and wheat rhizosphere in our study, but only in bulk soil for Proteobacteria. In this experiment, PCR primer bias may have been a source of variation based on the specificity of the 27F-519R primer pair that covers the V1-V3 region (Engelbrektson et al., 2010; Kim et al., 2011). However, the V1 amplicon taxonomic assignments are more accurate than for primers in the V3-V5 region based on larger reference databases. Acidobacteria and Planctomycetes, by contrast, are generally described as oligotrophic or K-strategists, i.e., slow-growing microorganisms that compete and survive in resource-poor conditions (Fierer et al., 2007, 2012; Männistö et al., 2016; Ahn et al., 2016). Therefore, the relative abundances of oligotrophs are usually unaffected or negatively affected by the C- and N-rich soils under CONS management. While this was the case for Acidobacteria in our study, the relative abundances of Planctomycetes did not differ between CONS and CONV management systems. However, this classification is just a rough guide because, even though it may apply to the majority of members of each phylum, some members (e.g. at class, order, family, etc., level) can respond differently. In addition, the classification of some phyla into these two functional groups is different in different soils or environments (Fierer et al., 2007; Männistö et al., 2016). Also, sometimes the comparison of relative abundances of the microbial phyla is made between fertilized and unfertilized controls, and other times between organic and inorganic fertilizers. In our study, the comparison was between inorganic fertilizers (CONV) and organic + inorganic fertilizers (CONS), and treatment differences may not have been as large as in other two cases.

The community structures of the bacterial communities at phylum level (Figs. 2 and 3) were generally in agreement with the relative abundances of the different phyla (Fig. 1). At genus level, contrast analysis and PCA showed that *Gemmatimonas* spp. (phylum Gemmatimonadetes) and *Sorilubacter* spp. (phylum Actinobacteria) were more abundant under CONV than CONS management, but *Sorangium* spp. (phylum Proteobacteria) and *Opitutus* spp. (phylum Verrucomicrobia) were more abundant under CONS than CONV management, both in bulk soil and wheat rhizosphere (Fig. 4). The responses of these genera were in agreement with the responses at phylum level with respect to their classification as copiotrophs or heterotrophs. Although the relative abundances of Actinobacteria were not different between CONS and CONV management systems at phylum level, the response of *Sorilubacter* spp. at genus level indicated that they responded as heterotrophs. In a different study using PLFA biomarkers in this same trial, Lupwayi et al. (2017) reported positive correlations between C inputs and all the measured soil microbial properties except actinomycetes, which belong to the phylum Actinobacteria. It is believed that their filamentous mycelial growth, their ability to form spores, and their powerful secondary metabolism enable them to survive under stress conditions (Vetrovsky and Baldrian, 2015). In Manitoba, the relative abundances of Actinobacteria was negatively related to soil pH (Li et al., 2012). In a recent continent-wide Australian study, Actinomycetes were identified as the major microbial predictors of soil suppresiveness of the soil-borne model pathogen *Fusarium oxysporum* (Trivedi et al., 2017).

It is surprising that *Gemmatimona* spp. were less abundant under CONS management than CONV management because other studies have reported that they were more abundant in soil organic + inorganic amendments than in inorganic amendments only (Banerjee et al., 2016; Li et al., 2017) and positively correlated with organic matter decomposition (Banerjee et al., 2016). In a plant growth assay with apple rootstocks, the abundance of *Sorilubacter* spp., the other genus that was more abundant under CONV than CONS management in our study, was strongly correlated with apple growth (Franke-Whittle et al., 2015). *Sorangium* spp. and *Opitutus* spp. were more abundant under CONS than CONV management. *Sorangium* spp. in soil are known for their ability to degrade cellulose (Lampky, 1971; Yun, 2014) and for biocontrol of fungal plant diseases (Yun, 2014). *Opitutus* spp. have been reported to be abundant in rice paddy soils (van Passel et al., 2011) and the rhizospheres of maize (Correa-Galeote et al., 2016) and cucumber (Tian and Gao, 2014), but their agricultural or ecological significance is not clear.

There were no differences between dry bean and potato pre-crops in the soil microbial properties reported here, except in wheat rhizosphere where the relative abundance of Firmicutes was greater when the preceding crop was potato versus dry bean (Table 5). We expected differences between the N_2-fixing dry bean and potato, which does not fix atmospheric N_2. However, dry bean is known to be a poor fixer of N_2 (Hardarson et al., 1993).

Other soil microbial results from this field trial indicated that soil microbial biomass and enzyme activity increased under CONS management relative to CONV management (Lupwayi et al., 2017). However, Lupwayi et al. (2017) determined soil microbial biomass using the PLFA procedure, which is at a coarser scale (fungi, bacteria, Gram-positive bacteria, Gram-negative bacteria, actinomycetes, etc.) than the sequencing procedure used herein. The results presented here show that even if overall soil microbial biomass or diversity increases or decreases in response to soil management treatments, examining the microbial community at a finer scale may reveal that not all microbial taxa (phyla, classes, orders, families, genera, etc.) respond in the same way. These differences in soil microbial characteristics between CONS and CONV management have implications not only for nutrient cycling, but also for biological crop protection, ultimately affecting crop yields. Probably as a result of the improved soil health in CONS management, crop (potato and sugar beet) yields were also higher relative to those under CONV management (Larney et al., 2016a,b).

5. Conclusion

Soil bacterial α-diversity usually increased under CONS management relative to CONV management. However, the relative abundances of Bacteroidetes and Firmicutes were greater under CONS than CONV management both in bulk soil and wheat rhizosphere, but Acidobacteria and Gemmatimonadetes were more abundant under CONV than CONS management. Proteobacteria were also more abundant under CONS than CONV management, but only in bulk soil. The community structures (β-diversity) of the bacterial communities at phylum level were generally in agreement with the relative abundances of the different phyla. These differences were consistent with the ecological classification of soil bacteria as copiotrophic or oligotrophic, considering the previously published differences in soil organic C and total N concentrations between the management systems. Therefore, CONS management systems altered the soil bacterial community profiles and improved the productivity of these soils in southern Alberta.

Acknowledgements

We are grateful to Jim Sukeroff and staff at the Vauxhall Substation for field assistance. Funding contributions from the Alberta Agricultural Research Institute, Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Pulse Science Cluster, and Agriculture and Agri-Food Canada's Matching Investment Initiative are gratefully acknowledged.

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TECHNICAL ARTICLE

Soil Microbial Biomass and Its Relationship With Yields of Irrigated Wheat Under Long-term Conservation Management

Newton Z. Lupwayi,[1] Francis J. Larney,[1] Robert E. Blackshaw,[1] Drusilla C. Pearson,[1] and Andrea H. Eastman[2]

ABSTRACT:
Relating soil microbial properties to crop productivity is important to appreciate the value of soil microbial activities in sustainable agriculture. Over a 10-year period, we evaluated the effects of conservation (CONS) management practices on soil microbial biomass carbon (MBC). The CONS practices included addition of composted cattle manure; reduced tillage; diverse crop rotations that comprised wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), and sugar beet (*Beta vulgaris* L.); and use of cover crops. The CONS management was applied to 3- to 5-year irrigated crop rotations and compared with conventional (CONV) management systems that did not have any of the CONS practices. Continuous wheat was also included. We then related MBC to wheat yields. Averaged over the 10-year period, CONS management overall increased MBC in wheat rhizosphere and bulk soil by 18% and 34%, respectively. When rotations of the same length were compared, CONS management in 3-year rotations increased rhizosphere MBC by 18% and bulk soil MBC by 30%; the corresponding increases in 4-year rotations were 13% and 36%. Regressions between soil MBC and wheat yields were quadratic, with MBC in wheat rhizosphere associated with increasing wheat yields up to 720 mg C kg^{-1} soil. The corresponding value for MBC in bulk soil was 645 mg C kg^{-1} soil. These effects were related to the compost and crop C inputs to the soil, which impacted soil organic C contents. Therefore, CONS management resulted in a cycle of high MBC and high wheat yields.

Key Words: Compost, cover crops, crop rotation, soil quality, tillage

(Soil Sci 2018;183: 179–187)

Before the advent of modern molecular microbial methods, difficulties in measuring the unculturable microorganisms in soil led to the use of soil microbial biomass to quantify the total mass of microbial communities (Gonzalez-Quiñones et al., 2011). Microbial biomass can be defined as the living component of soil organic matter (SOM) that excludes plant roots and macrofauna (Jenkinson and Ladd, 1981). The activity of soil microbial biomass drives SOM transformations and nutrient cycling in the soil, thereby contributing to plant nutrition and other ecosystem functions. Therefore, several studies have related soil microbial biomass, usually measured as microbial biomass carbon (MBC), nitrogen, and sometimes phosphorous, to soil functioning and crop yields (Silva et al., 2010; Lopes et al., 2013; Lupwayi et al., 2014; Lupwayi et al., 2015). In Brazil, a study of four long-term field experiments with different soil and crop management systems showed that MBC and microbial biomass nitrogen were consistently higher under no-till than conventional tillage and were associated with higher corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) grain yields (Silva et al., 2010). Lopes et al. (2013) used regression analysis in a study of three long-term P fertilizer experiments in corn and soybean in the Cerrado region of Brazil to reveal critical levels (equivalent to 80% of the highest crop yields) for MBC, basal respiration, and the activities of cellulase, β-glucosidase, acid phosphatase, and arylsulfatase enzymes. In a canola (*Brassica napus* L.) seeding rate, N fertilizer and fungicide study conducted at seven sites on the Canadian prairies, soil MBC and β-glucosidase enzyme activity correlated positively with canola grain yields at the five sites where yields were less than 4 t ha^{-1}, but no or weak negative correlations were observed at the two sites with yields greater than 4 t ha^{-1}. (Lupwayi et al., 2015). Using next-generation sequencing methods for soil bacteria in China, Tao et al. (2017) observed that, at phylum level, the relative abundances of Acidobacteria and Verrucomicrobia were positively correlated with corn (*Z. mays* L.) yield, but there were negative correlations with Proteobacteria and Chloroflexi. These different correlations in China were explained by different effects of soil pH, available N, and available potassium (K) on the soil microbial communities and corn yield. Using similar methods in China, Ma et al. (2017) reported correlations between corn yield and the relative abundances of soil bacteria only at the bacterial species level.

Results of such studies relating soil microbial properties to crop yields will be different in different agroecological zones depending on factors that include soil management, soil type, and climate. An important soil management factor is how management impacts the balance between organic C inputs to the soil and C losses from the soil, that is, storage of soil organic C (SOC), because SOC affects both MBC and crop yields (Nunes et al., 2018). We used a long-term field experiment in semiarid southern Alberta to relate soil MBC to yields of irrigated crops. The 12-year (2000–2011) experiment was established to evaluate soil conservation (CONS) management systems for crop rotations that included irrigated potato, sugar beet, dry bean, and wheat. The CONS management practices, comprising addition of feedlot manure compost, reduced tillage, diverse crop rotations, and use of cover crops, were applied to 3- to 5-year crop rotations. They were compared with conventional (CONV) management systems that did not have any of the CONS practices. Yields of these crops have been published (Larney et al., 2015, 2016a, 2016b, 2018), and some soil microbial properties in the last 2 years of the study have also been published (Lupwayi et al., 2017a, 2017b). The objectives of this work were to examine how CONS management systems affected soil MBC in wheat rhizosphere and bulk soil over a 10-year (2002–2011) period and to relate MBC to wheat grain yields over the same period. We hypothesized that the soil management systems would affect MBC in wheat rhizosphere and bulk soil through SOC inputs, which would also affect wheat yields through biological nutrient cycling.

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Financial Disclosures/Conflicts of Interest: None reported.

Received November 9, 2018.

Accepted for publication December 21, 2018.

ISSN: 0038-075X

DOI: 10.1097/SS.0000000000000242

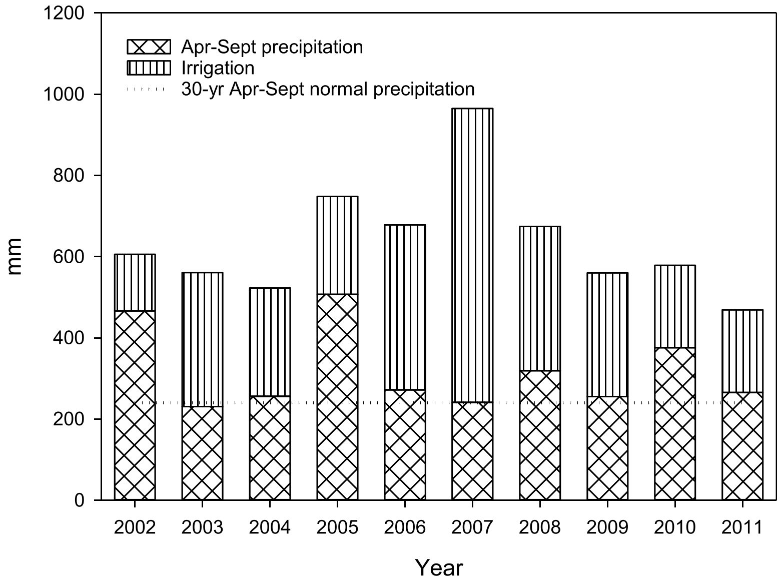

FIGURE 1. Precipitation (April to September) and irrigation amounts for wheat during the study period (2002–2011) and 30-year (1971–2000) average precipitation.

MATERIALS AND METHODS

Study Location, Experimental Treatments, and Management

The study was conducted in a 12-year (2000–2011) irrigated field trial at Vauxhall, Alberta (50° 03′ N, 112° 09′ W, elev. 781 m). The soil at the site is a Typic Boroll (Soil Survey Staff, 2010) or Haplic Kastanozem (IUSS Working Group WRB, 2007) typical of southern Alberta, which at the start of the experiment had (0- to 15-cm depth) 520 g kg^{-1} sand, 340 g kg^{-1} silt, 140 g kg^{-1} clay, and 12.9 g organic C kg^{-1} soil, and pH 6.9. Changes in some of these soil properties during the trial have been reported by Larney et al. (2017). Weather data were collected at a weather station about 300 m from the site. Growing season (April to September) annual rainfall is presented in Fig. 1. The 30-year (1971–2000) mean annual air temperature was 5.7°C.

The entire plot area was planted to barley (*Hordeum vulgare* L.) in 1999, and treatments were established in the spring of 2000. There were six rotation treatments: continuous (monoculture) wheat, two 3-year rotations, two 4-year rotations, and one 5-year rotation (but with two wheat phases that were each sampled for this study) (Table 1). These rotations were managed utilizing CONV or CONS management practices (described below). All crop phases of each rotation were grown each year to account for varying environmental conditions over years. The treatments were arranged in a randomized complete block design with four replicates. The individual plot sizes were 10.1 × 18.3 m with 2.1-m buffer zones between plots.

For the rotations under CONS management (Table 1), a package of the following four practices was applied together (for details, see Larney et al., 2015, 2016a, 2016b and 2018): (1) direct seeding and/or reduced tillage where possible in the rotation; (2) fall-seeded cover crops: oat (*Avena sativa* L.) and fall rye (*Secale cereale* L.)

TABLE 1. List of Treatments From 2000 to 2011

Rotation[a]	Crop Sequence	No. of Crop Phases	No. Rotation Cycles[b]
1-CONT	Wheat	1	12
3-CONV	Potato–dry bean–wheat	3	4
3-CONS	Potato[c]–dry bean[c]–wheat[d]	3	4
4-CONV	Potato–wheat–sugar beet–dry bean	4	3
4-CONS	Potato[c]–wheat–sugar beet–dry bean[d]	4	3
5-CONS1	Potato[c]–wheat[e]–sugar beet[d]–wheat–dry bean[d]	5	2.4
5-CONS2	Potato[c]–wheat–sugar beet[d]–wheat[e]–dry bean[d]	5	2.4

The underlined wheat phases of each rotation (treatment) were sampled.

[a]Integers refer to the length (years) of each rotation.

[b]Number of rotation cycles by 2011 = 12 (y)/no. of crop phases.

[c]Fall-seeded cover crop entry point: fall rye [except oat, 2000–2002, on 3-CONS (between dry bean and wheat), 4- and 5-CONS].

[d]Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-CONS; 5-CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-CONS; 5-CONS after dry bean) applied after harvest, except 2003 (postponed to spring 2004 due to wet soil conditions).

[e]The underlined wheat phase was sampled for soil microbiological analysis, that is, wheat preceded by potato in 5-CONS1 and wheat preceded by sugar beet in 5-CONS2.

CONT = continuous; CONV = conventional management; CONS = conservation management.

with entry points detailed in Table 1 (footnotes). However, because of suboptimal fall establishment of oat, it was replaced with fall rye from fall 2003 onward; (3) composted cattle manure: straw-bedded beef cattle feedlot manure compost (182, 15.4, and 5.4 g kg^{-1} dry weight of total C, N, and P, respectively) was fall-applied to supply some of the N and P required (as determined by soil testing). The rest of the required N was supplied by inorganic fertilizer. A compost rate of 42 Mg ha^{-1} (fresh weigh) was applied after dry bean and before potato in the 4- and 5- CONS rotations (Table 1). The shorter 3-CONS rotation received a lower rate of 28 Mg ha^{-1} after wheat and before potato. This lower rate was also applied at a second entry point in the 5-year CONS rotation—after sugar beet and before wheat (Table 1); and (4) solid-seeded, direct-cut, narrow-row (19–23 cm) dry bean. There was no interrow cultivation, and the crop was harvested by direct cutting (no soil disturbance) with a plot combine.

Conventional management did not use any of the above practices, and hence the 3- and 4-year CONV rotations had (*a*) more intensive tillage, (*b*) no cover crops, (*c*) no compost amendments (all nutrients were supplied by inorganic fertilizers), and (*d*) dry bean grown in wide rows (60 cm), with interrow cultivation for in-season weed control, and undercutting at harvest (causing soil disturbance and unanchored residue).

Tillage intensity was reduced as much as possible under CONS compared with CONV management. Crops were fertilized according to soil test recommendations, with soil testing done every 3 years. The crops were irrigated, using a wheel-move system, to maintain soil water (to 100-cm depth) at field capacity of 50% or greater, which was considered to be sufficient to eliminate moisture stress as a factor. The amounts of irrigation water applied each year are presented in Fig. 1. Preseeding, in-crop, and postharvest herbicides were used as required for weed control. Each fall, mature crops were harvested for yield and quality assessment.

Soil Sampling

From 2002 to 2011, the final year of the study, soil samples were collected in the wheat phases of 1- to 5-year rotations. The samples were taken at the flag leaf growth stage of wheat in July. Plants were excavated from four random 0.5-m lengths of row. Loose soil was removed from the roots by shaking the plants vigorously by hand, and the remaining soil that had strongly adhered to the roots was carefully brushed off and recovered as rhizosphere soil. Bulk soil (0- to 7.5-cm depth) was sampled from the middle of two adjacent crop rows at four locations per plot. The four bulk or rhizosphere soil samples from each plot were combined, respectively, passed through a 2-mm sieve, and air dried.

MBC Analysis

Each year, soil MBC was measured using the substrate-induced respiration method (Horwath and Paul, 1994), in which 300 mg of glucose was dissolved in 4.5 to 6.0 mL water and added to 50 g air-dry soil to bring it to 50% water-holding capacity, that is, the difference in water contents between field capacity and permanent wilting point. The exact amount of water added depended on the predetermined water content and water-holding capacity (28% vol/vol) of the soil. After stir mixing, the soil was incubated in a 1-L jar for 3 h at 22°C, and the amount of CO_2 that accumulated in the head space was measured using gas chromatography.

Wheat Grain Yields

Yields of wheat were determined as described by Larney et al. (2018). They were estimated from 2 × 1.25-m subplots, and the grain was air dried for about 3 weeks before weighing.

Statistical Analysis

Analysis of variance was used to examine differences between rotations in soil MBC, using the randomized complete block design of the trial in Statistix 9 (Analytical Software, Tallahassee, FL). These analyses of variance were conducted separately for each year and each soil location (rhizosphere or bulk soil). Statistical analysis combining all the years was also conducted, separately for each soil location, as a repeated-measures design where year was the repeated measure. In all statistical analyses, treatment differences were declared significant at 5% significance level, and means were separated by the least significant difference method. In describing the MBC results, in addition to differences between all treatments, differences between 3-CONV and 3-CONS, or between 4-CONV and 4-CONS rotations, were noted because these pairs of treatments had the same crop sequences and differed only in management (CONV or CONS). In addition, orthogonal contrast analysis tested the effect of CONV management treatments (rotations 3-CONV and 4-CONV) versus CONS management treatments (rotations 3-CONS, 4-CONS, 5-CONS1, and 5-CONS2; Table 1).

Soil MBC, either in wheat rhizosphere or bulk soil, was related to wheat grain yields by plotting relative wheat grain yields (percentages of the maximum yield recorded in a plot over the 10-year period) against MBC in individual replicates over the 10-year period (2002–2011). The maximum wheat grain yield used to calculate the relative yields was 9.543 t ha^{-1}, obtained in Replicate 2 of the 3-year conventional rotation (3-CONV) in 2008, which was marginally greater than the 9.538 t ha^{-1} yield obtained in Replicate 2 of the second wheat crop of the 5-year conservation rotation (5-CONS2) in the same year. Linear and quadratic regression models were then performed, and the appropriate function was chosen on the basis of goodness of fit according to the proportion of variance explained by the model (adjusted R^2, i.e., adjusted for the number of independent variables in the model). To explain the soil MBC results, we used regression analysis to relate our MBC results (from 2002 to 2011) to SOC inputs from compost and crop residues (Li et al., 2015) over the duration of the field trial (from 2000 to 2011). SigmaPlot 13.0 (Systat Software Inc., San Jose, CA) was used for regression analyses.

RESULTS

Weather Conditions

The annual growing season precipitation from 2002 to 2011 ranged from 96% of normal (1971–2000 average of 240 mm) precipitation in 2003 to 211% in 2005 (Fig. 1). Besides 2005, the other wetter-than-normal growing seasons were 2002 (194% of normal), 2008 (133% of normal), and 2010 (157% of normal). The normal average growing season air temperature was 13.8°C. The warmest growing season was 2006 (15.2°C), and the coolest was 2002 (12.6°C) (air temperature data not shown). Annual irrigation amounts for wheat ranged from 140 (2002) to 724 mm (2007), depending on precipitation (Fig. 1). A large input was required in 2007 due to an extreme midseason dry spell.

Soil MBC

Averaged over all 10 years (2002–2011), crop rotation significantly affected MBC (Table 2, last column). The top two rotations for MBC contents were 5-CONS2 and 3-CONS (564 and 531 mg C mg kg^{-1} soil, respectively), and the bottom two were 4-CONV and 3-CONV (436 and 450 mg C mg kg^{-1} soil, respectively). Year-by-year, rotation effects were significant in 2002, 2007, and 2009. In 2002, the 5-CONS2 rotation had higher MBC content than all other treatments. In 2007, 5-CONS2 and 3-CONS rotations had the greatest MBC, whereas 4-CONV and 3-CONV rotations had the lowest. In 2009, the 4-CONV rotation had lower MBC content than any other rotation.

Orthogonal contrast analysis showed that, averaged over all years, MBC under CONS management (521 mg C kg^{-1} soil) was 18% greater than that under CONV management (443 mg C kg^{-1} soil, Table 2). Direct comparison of 3-CONV versus 3-CONS

TABLE 2. Soil MBC in Wheat Rhizosphere From 2002 to 2011

Treatment[a]	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean[b]
	MBC (mg kg^{-1} Soil)										
Rotation											
1-CONT	248b[c]	485a	501a	413a	587a	590bcd	644a	704a	407a	484a	506b
3-CONV	274b	413a	424a	373a	419a	545cd	559a	669a	396a	430a	450cd
3-CONS	260b	489a	492a	395a	634a	714ab	621a	676a	455a	573a	531ab
4-CONV	226b	493a	514a	363a	476a	482d	515a	461b	410a	420a	436d
4-CONS	305b	372a	501a	471a	564a	555cd	583a	698a	430a	462a	494bc
5-CONS1[d]	264b	453a	537a	520a	557a	626bc	545a	611a	308a	507a	493bc
5-CONS2[e]	406a	407a	583a	470a	615a	816a	628a	647a	497a	576a	564a
P	0.001	0.711	0.327	0.567	0.081	0.001	0.506	0.039	0.414	0.318	<0.001
Management[f]											
CONV	250b	453a	469a	368a	448b	514b	537a	565b	403a	425b	443b
CONS	309a	430a	528a	464a	593a	678a	594a	658a	423a	530a	521a
P	0.033	0.665	0.111	0.105	0.004	<0.001	0.138	0.049	0.760	0.044	<0.01

[a]Integers refer to the length (years) of each rotation.
[b]Treatment means for all years (2002–2011).
[c]Means followed by the same letter in a column within a treatment category are not significantly different at 5% significance level.
[d]Wheat preceded by potato (see footnote [e] in Table 1).
[e]Wheat preceded by sugar beet (see footnote [e] in Table 1).
[f]Management contrasts: CONV = mean of 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1, and 5-CONS2.
CONT = continuous; CONV = conventional management; CONS = conservation management.

rotations also revealed an 18% increase of MBC in 3-CONS rotation (at 531 mg C kg^{-1}) relative to the 3-CONV rotation (450 mg C kg^{-1} soil), and the increase under 4-CONS (494 mg C kg^{-1} soil) over 4-CONV (436 mg C kg^{-1} soil) was 13%. Year-by-year, CONS management had greater MBC than CONV management in 2002, 2006, 2007, 2009, and 2011 by margins ranging from 16% (in 2009) to 32% (in 2006 and 2007).

There were differences between years in MBC, but there was no interaction between year and crop rotation; that is, the differences between crop rotations in MBC contents were similar each year. The

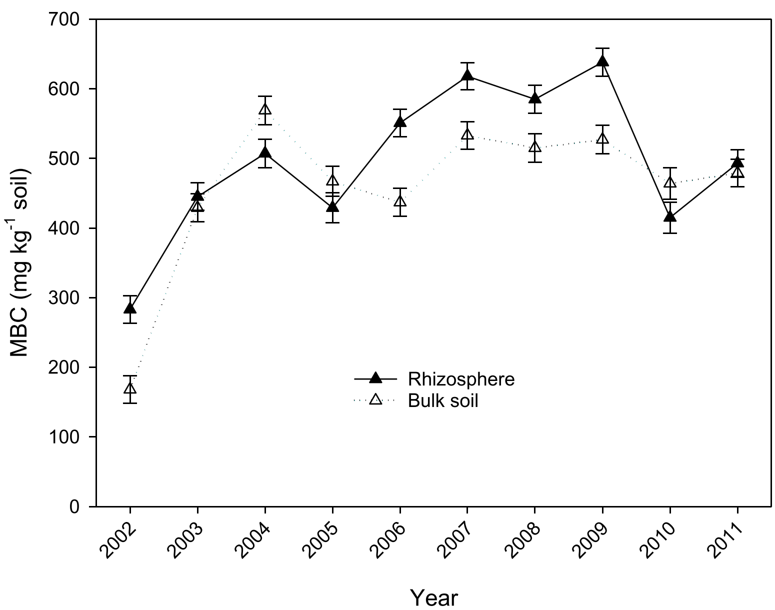

FIGURE 2. Microbial biomass C in wheat rhizosphere and bulk soil from 2002 to 2011. There was no interaction between crop rotation and year in the rhizosphere or bulk soil.

trend was increasing MBC over the years, but with decreases in 2005, 2008, and 2010 (Fig. 2, rhizosphere graph). The order was as follows: 2002 (283 mg C kg^{-1}) < 2010 (415 mg C kg^{-1}) = 2005 (429 mg C kg^{-1}) ≤ 2003 (445 mg C kg^{-1}) ≤ 2011 (493 mg C kg^{-1}) ≤ 2004 (507 mg C kg^{-1}) ≤ 2006 (551 mg C kg^{-1}) ≤ 2008 (585 mg C kg^{-1}) ≤ 2007 (618 mg C kg^{-1}) = 2009 (638 mg C kg^{-1}).

Averaged over all years, MBC was significantly affected by crop rotation (Table 3, last column). The rotation with the most MBC was 5-CONS2 (552 mg C kg^{-1} soil), and the least MBC was in rotation 4-CONV (354 mg C mg kg^{-1} soil). In yearly comparisons, rotation effects were significant in all years except 2003, 2004, and 2010. In all cases, a CONS rotation had the highest MBC content, and a CONV rotation the lowest.

Contrast analysis showed that, averaged over all years, MBC under CONS management (497 mg C kg^{-1} soil) was 34% greater than that under CONV management (371 mg C kg^{-1} soil, Table 2). In head-to-head comparisons of rotations with the same lengths, 3-CONS rotation (504 mg C kg^{-1} soil) had 30% more MBC than 3-CONV rotation (388 mg C kg^{-1} soil), and the increase under 4-CONS (at 483 mg C kg^{-1} soil) over 4-CONV (354 mg C kg^{-1} soil) was 36%. Year-by-year, CONS management had greater MBC than CONV management in all years except 2003, 2004, and 2010, and the increases ranged from 25% (in 2011) to 57% (in 2005).

Yearly trend results in bulk soil were similar to those in wheat rhizosphere described above. Thus, there were yearly differences in MBC, but there was no interaction between year and crop rotation. The trajectory was increasing MBC every year, but with reductions in 2005, 2006, 2008, and 2010 (Fig. 2, bulk soil graph). The order was as follows: 2002 (167 mg C kg^{-1}) < 2003 (429 mg C kg^{-1}) = 2006 (437 mg C kg^{-1}) ≤ 2010 (464 mg C kg^{-1}) = 2005 (467 mg C kg^{-1}) ≤ 2011 (479 mg C kg^{-1}) ≤ 2008 (515 mg C kg^{-1}) ≤ 2009 (527 mg C kg^{-1}) = 2007 (533 mg C kg^{-1}) ≤ 2004 (569 mg C kg^{-1}).

Wheat Yields

Wheat grain yields over all the 12 years of the study have been published by Larney et al. (2018). Briefly, wheat grain yields were affected by crop rotation in 10 of 12 years, where wheat grown in rotation yielded 23% to 82% higher than continuous wheat (1-CONT). Significant differences in wheat yields among the different rotations (excluding continuous wheat) occurred in 5 of the 10 years. However, comparisons of CONV versus CONS management of the same 3- or 4-year rotations revealed no differences in wheat yields in all the 5 years that had significant rotation effects.

Relating MBC to Wheat Yields

Wheat yield increased in a quadratic manner with MBC, both in wheat rhizosphere (Fig. 3A) and bulk soil (Fig. 3B). Thus, wheat grain yield increased with increasing rhizosphere MBC up to 720 mg C kg^{-1} soil (for 69% of maximum yield; Fig. 3A), and the same pattern was observed with bulk soil MBC up to 645 mg C kg^{-1} soil (to reach 66% of maximum yield; Fig. 3B). When regressions for wheat in rotation with other crops (3- to 5-year rotations) and continuous wheat (1-CONT) were ran separately, the quadratic response of yield to MBC was observed only for wheat grown in rotations (Figs. 4A, B). Thus, rhizosphere MBC up to 750 mg C kg^{-1} soil were associated with increasing wheat yields (to reach 72% of maximum yield; Fig. 4A), and bulk-soil MBC reached 655 mg C kg^{-1} soil (for 69% of maximum wheat yield; Fig. 4B). Continuous wheat increased linearly with increasing rhizosphere MBC (Fig. 5A) and bulk-soil MBC (Fig. 5B).

Relating MBC to Soil Organic C Inputs

There were linear regressions between MBC in wheat rhizosphere, or bulk soil, and organic C inputs to the soil from compost and crop

TABLE 3. Soil MBC in Wheat Bulk Soil From 2002 to 2011

Treatment[a]	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean[b]
	MBC (mg kg^{-1} Soil)										
Rotation											
1-CONT	152b[c]	386a	703a	482ab	478ab	479bcd	553b	584a	532a	477bc	483bc
3-CONV	134b	425a	505a	316c	360bc	439 cd	364c	505a	458a	372c	388d
3-CONS	159b	526a	559a	503a	592a	628a	544b	570a	443a	514ab	504b
4-CONV	121b	369a	485a	355bc	313c	392d	382c	377b	316a	435bc	354d
4-CONS	156b	429a	650a	464abc	475ab	587ab	520b	579a	458a	507abc	483bc
5-CONS1[d]	155b	402a	485a	582a	379bc	565abc	577ab	537a	369a	424bc	447c
5-CONS2[e]	297a	464a	598a	553a	463ab	645a	666a	538a	672a	623a	552a
P	0.040	0.459	0.119	0.014	0.006	0.006	<0.001	0.028	0.121	0.037	<0.001
Management[f]											
CONV	128b	397a	495a	336b	337b	416b	373b	441b	387a	404b	371b
CONS	192a	455a	573a	526a	477a	606a	577a	556a	486a	507a	497a
P	0.048	0.222	0.209	0.001	0.002	<0.001	<0.001	0.007	0.232	0.013	<0.001

[a]Integers refer to the length (years) of each rotation.
[b]Treatment means for all years (2002–2011).
[c]Means followed by the same letter in a column within a treatment category are not significantly different at 5% significance level.
[d]Wheat preceded by potato (see footnote [e] in Table 1).
[e]Wheat preceded by sugar beet (see footnote [e] in Table 1).
[f]Management contrasts: CONV = mean of 3-CONV and 4-CONV; CONS = mean of 3-CONS, 4-CONS, 5-CONS1 and 5-CONS2.
CONT = continuous; CONV = conventional management; CONS = conservation management.

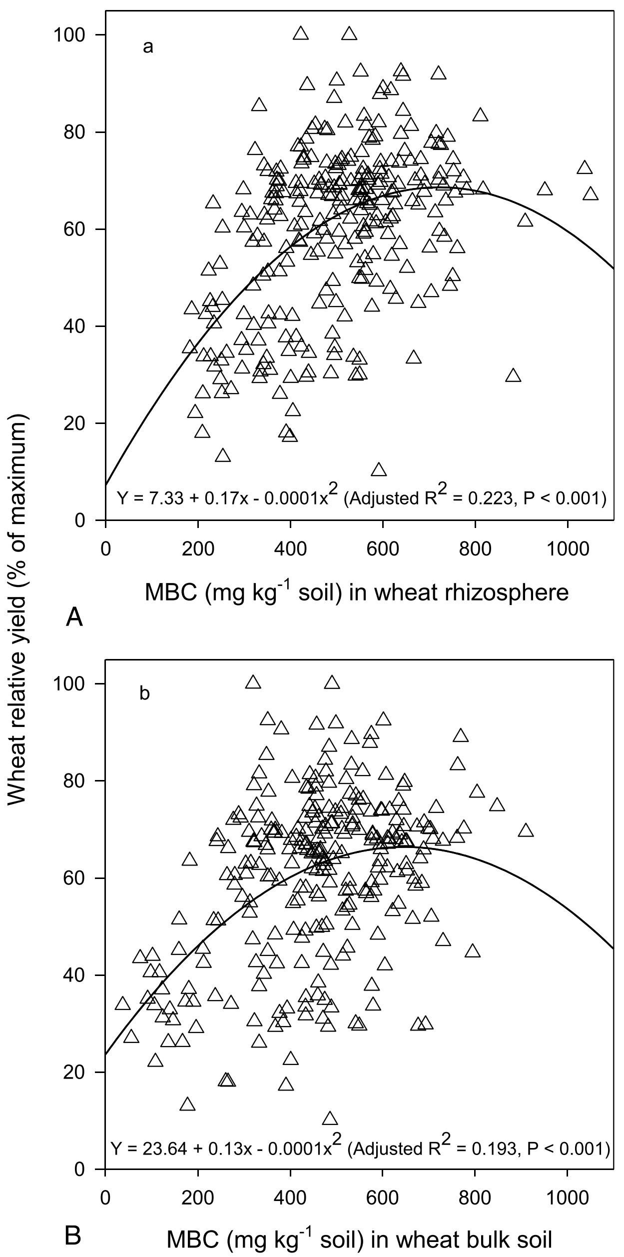

FIGURE 3. Relationship between wheat grain yield and MBC in wheat rhizosphere (A) and bulk soil (B) (n = 269). Relative yields are percentages of the maximum yield of 9.543 t ha^{-1}, obtained in Replicate 2 of the 3-year conventional rotation (3-CONV) in 2008, which was marginally greater than the 9.538 t ha^{-1} yield obtained in Replicate 2 of the second wheat crop of the 5-year conservation rotation (5-CONS2) in the same year.

residues in the various crop rotations (Figs. 6A, B). The regression slope in bulk soil (4.47) was steeper than that in wheat rhizosphere (2.90).

DISCUSSION

The upward trajectories of soil MBC by year, in wheat rhizosphere and bulk soil, were reduced in 2005, 2008, and 2010. The initial MBC contents in 2002 were also low. All these 4 years (seasons) had greater than normal precipitation (Fig. 1). Excessive rainfall in 2002, 2005, and 2010 resulted in waterlogging in low-lying areas of the trial. These soil conditions likely reduced soil MBC, as reported in other studies (Yang et al., 2005; Sánchez-Rodríguez et al., 2018). The lack of interactions between crop rotation and year suggests that the adverse effects of excessive soil water in the years cited above did not affect the differences between rotations in soil MBC. Because the crops in this trial were irrigated to maintain soil moisture content of at least 50% water-holding capacity, there were no soil moisture deficits that could have reduced soil MBC contents.

Soil MBC in wheat rhizosphere and, especially, in bulk soil was often lowest in 3-CONV or 4-CONV rotations, and highest in 5-CONS1 or 5-CONS2 rotations. It is possible that rotation length

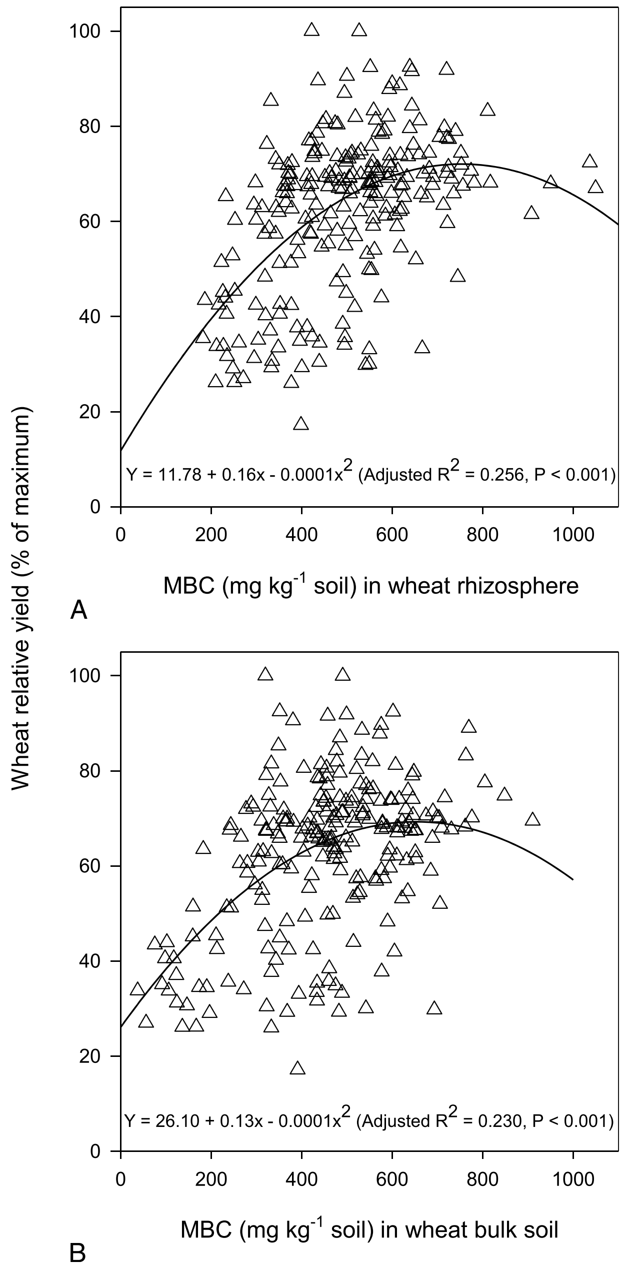

FIGURE 4. Relationship between wheat grain yield in rotations (without continuous wheat) and MBC in wheat rhizosphere (A) and bulk soil (B) (n = 232). Relative yields are percentages of the maximum yield of 9.543 t ha^{-1}, obtained in Replicate 2 of the 3-year conventional rotation (3-CONV) in 2008, which was marginally greater than the 9.538 t ha^{-1} yield obtained in Replicate 2 of the second wheat crop of the 5-year conservation rotation (5-CONS2) in the same year.

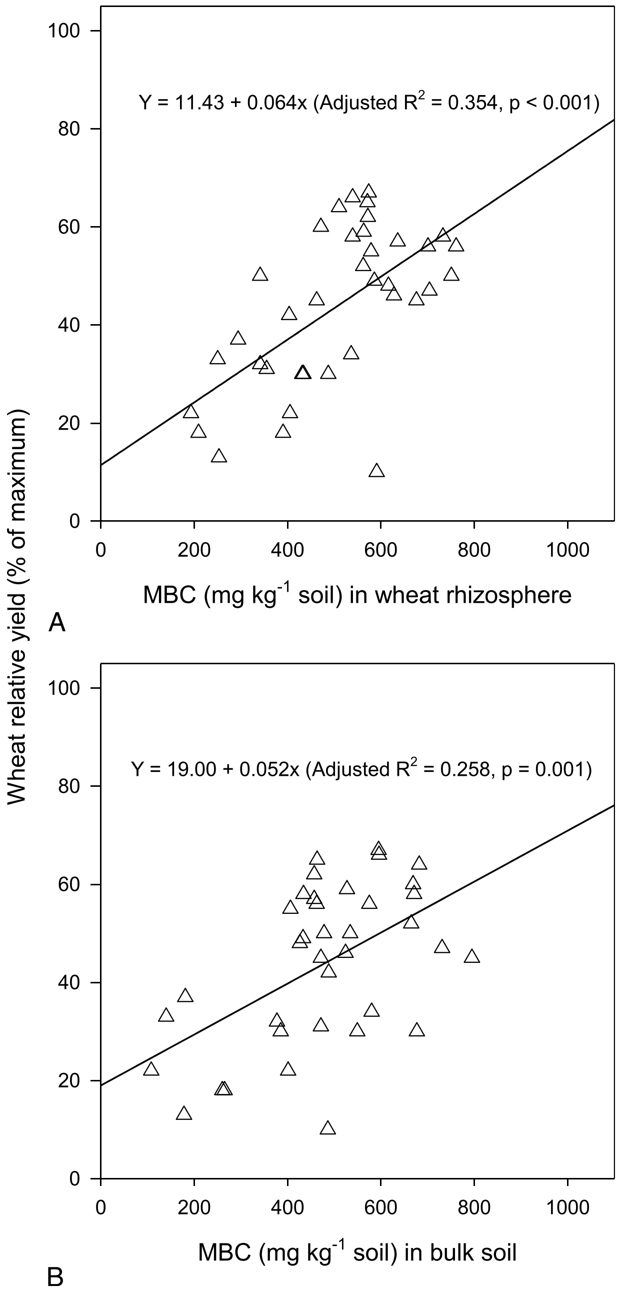

FIGURE 5. Relationship between continuous wheat (1-CONT) grain yield and MBC in wheat rhizosphere (A) and bulk soil (B) (n = 37). Relative yields are percentages of the maximum yield of 9.543 t ha^{-1}, obtained in Replicate 2 of the 3-year conventional rotation (3-CONV) in 2008, which was marginally greater than the 9.538 t ha^{-1} yield obtained in Replicate 2 of the second wheat crop of the 5-year conservation rotation (5-CONS2) in the same year.

was a factor in these differences, but CONS versus CONV management was probably the main reason as evidenced by (*a*) comparison of these systems within rotations of the same length, that is, 3- or 4-year rotations, and (*b*) contrast analysis of the management systems. Similar differences were observed when soil microbial biomass was determined by the phospholipid fatty acid procedure in the final 2 years of this 12-year trial (Lupwayi et al., 2017a). With respect to crop rotations, these differences can be explained by differences in organic C inputs, derived from compost in CONS management and from crop residues in all treatments. Wheat had the highest mean annual C return (4.6 Mg C ha^{-1} y^{-1}) of all crops (Li et al., 2015). Over the duration of the study (2000–2011), the 5-CONS rotation had the highest total (crop + compost) C inputs (56.9 Mg C ha^{-1}) of all rotations, and SOC in the top 7.5 cm was also higher in this rotation than other rotations at the end of the study (Li et al., 2015). At the other extreme, the 4-CONV rotation had the lowest cumulative C input (about 29 Mg C ha^{-1}) because it had the lowest proportion of wheat in the crop sequences, and it did not receive compost C. This positive relationship between C inputs and MBC was clearly demonstrated by the linear regressions both in wheat rhizosphere (Fig. 6A) and bulk soil (Fig. 6B). In the final 2 years of this trial, positive correlations between C inputs and the contents of soil phospholipid biomarkers (except that for actinomycetes) were also observed (Lupwayi et al., 2017a). The observation that wheat had the highest mean annual C return of all

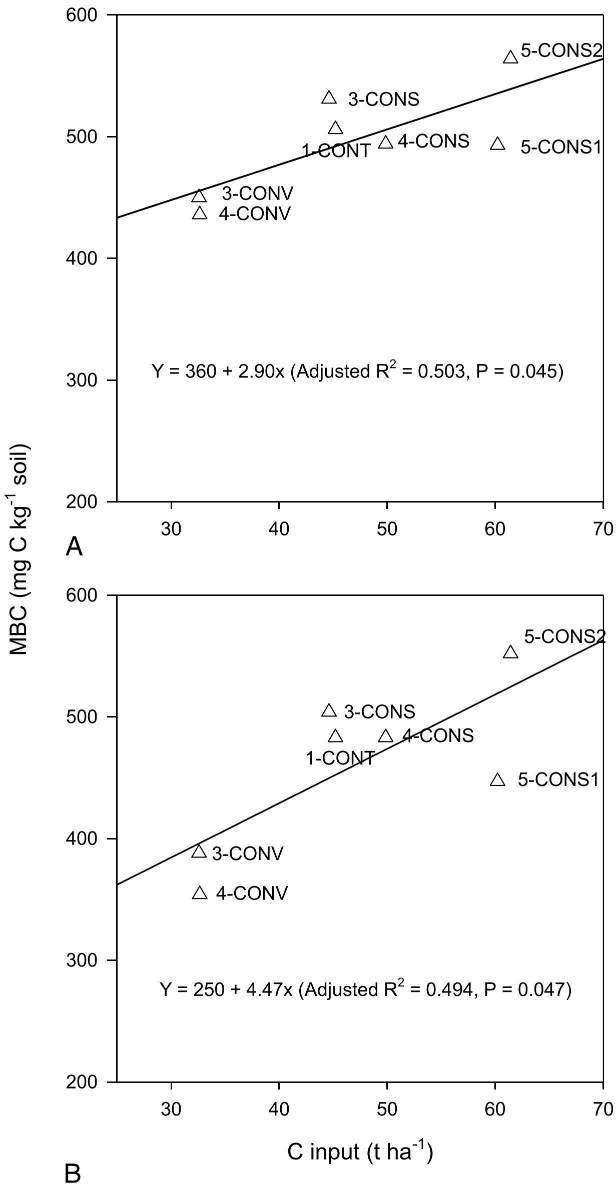

FIGURE 6. Regressions between organic C inputs to soil (from compost and crop residues from 2000 to 2011) and MBC (from 2002 to 2011) in wheat rhizosphere (A) and bulk soil (B). The data points (10-y means) are rotation names in which integers refer to the length (years) of each rotation. CONT = continuous; CONV = conventional management; CONS = conservation management.

crops explains why the 1-CONT (continuous wheat) treatment never had the lowest soil MBC, either in wheat rhizosphere or bulk soil, even though it did not have compost C input; it had substantial wheat C input (42 Mg C ha^{-1} over the 12-year period) (Li et al. 2015).

The positive regression between organic C inputs to the soil and soil MBC and the broader SOM probably explains the positive correlations between MBC and crop yields. Soil organic matter improves the soil chemical, physical, and biological properties, which combine to improve soil quality or health for crop productivity. In the 12 years of this trial, SOC stocks in the 0- to 30-cm soil layer increased by 0.48 Mg ha^{-1} y^{-1} in the 5-CONS rotation, which received an average cumulative compost addition of 145 Mg ha^{-1} (Larney et al., 2017). By contrast, SOC stocks in the 3-CONV rotation, which did not receive compost, declined by 0.25 Mg ha^{-1} y^{-1}. There are many examples of other studies in which soil management practices/systems that increased soil microbial biomass and its activity also increased crop yields by increasing SOM. These examples include addition of organic fertilizers (Jannoura et al., 2013; Neufeld et al., 2017), reduced tillage (Perez-Brandán et al., 2012; Nunes et al., 2018), crop rotations (Zuber et al., 2017; Rosenzweig et al., 2018), and use of cover crops (Lupwayi et al., 2018; Schmidt et al., 2018).

The difference in relationships between MBC and yield of wheat grown in rotations (quadratic regression) or wheat grown continuously (linear regression) shows that CONS management was more beneficial in nutrient-poor soil than under relatively nutrient-rich soil conditions. In a multilocation trial in the Canadian prairies, the grain yield of canola correlated positively with soil MBC only at locations where canola yield was less than 4 t ha^{-1}, that is, with low yield potential (Lupwayi et al., 2015). Nutrient-poor soils with little external nutrient inputs rely more on internal cycling of nutrients than soils that receive external, especially inorganic, nutrient inputs. Since neither MBC nor wheat yield was a fixed variable in our study, the relationships between the two variables probably do not necessarily indicate a one-way cause and effect, that is, that increasing soil MBC increased wheat yields without reciprocal effects. The relationships probably indicate interdependence between wheat yields and MBC that results in a positive feedback cycle; that is, high wheat yields (including wheat residue yields) resulted in high soil C inputs, which resulted in high soil MBC and organic C that, in turn, resulted in high wheat yields through nutrient cycling and other organic C effects. A positive relationship between soil C inputs and soil β-glucosidase enzyme activity, indicative of C and nutrient cycling, in this trial was reported by Lupwayi et al. (2017a). Conversely, as was observed for continuous field pea (*Pisum sativum* L.) in Saskatchewan (Nayyar et al., 2009; Lupwayi et al., 2012), a negative feedback cycle can occur when low crop yields (and C inputs into soil) result in low soil MBC, which in turn result in low crop yields. The coefficients of determination (adjusted R^2) in these regressions were always greater with MBC in wheat rhizosphere than in bulk soil; that is, more yield variance was explained by rhizospheric MBC than bulk soil MBC. Therefore, soil microbes in close proximity to wheat roots affected, and were affected by, wheat yields more than microbes farther away from wheat roots. The adjusted coefficients of determination may seem low, but the sample sizes were very large because we used data from individual plots (not replicate means) over a 10-year period.

The quadratic relationships between MBC and wheat yield suggest that other factors related to soil or climate become more important than soil MBC and organic C after a threshold value is reached. In relating soil microbial properties to corn and soybean yields in Brazil, Lopes et al. (2013) calculated threshold values for the contents of each soil microbial property. Adequate contents were defined as contents that corresponded with at least 80% of the crop (corn + soybean) maximum yields, and the threshold value for MBC was 375 mg C kg^{-1} soil. In quadratic regressions in the present study, the threshold values ranged from 645 mg C kg^{-1} soil in bulk soil for wheat grown in all treatments (including 1-CONT) to 750 mg C kg^{-1} soil in wheat rhizophere for wheat grown in rotation with other crops (excluding 1-CONT). Our values were higher than those reported by Lopes et al. (2013) because the methods and crops were different, but also because such values will depend on many factors that include the soils and climate of a location. Whatever the method used, such "calibrations" with yields of economic crops are useful to appreciate the value of soil MBC or other soil microbial properties.

CONCLUSIONS

Soil microbial biomass and its activity are very important for storing and recycling nutrients for sustainable agriculture. Soil conservation management systems that included reduced tillage, addition of compost, crop rotation, and inclusion of cover crops increased MBC and wheat grain yields, presumably due to increased SOM contents resulting from increased organic C inputs. These results confirm the soil-building nature of these management systems in the current and similar regions. Conservation management systems resulted in a positive feedback cycle between MBC (plus other organic C components) and wheat yields.

ACKNOWLEDGMENTS

The authors thank Jim Sukeroff and staff at the Vauxhall Substation for field assistance. They gratefully acknowledge funding contributions from the Alberta Agricultural Research Institute, Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Pulse Science Cluster, and Agriculture and Agri-Food Canada's Matching Investment Initiative.

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ARTICLE

Soil water dynamics over 12 seasons on irrigated dry bean–potato–wheat–sugar beet rotations

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Abstract: Dry bean (*Phaseolus vulgaris* L.), potato (*Solanum tuberosum* L.), wheat (*Triticum aestivum* L.), and sugar beet (*Beta vulgaris* L.) are mainstays of irrigated crop production in southern Alberta. Concerns about soil quality and sustainability instigated a 12 yr (2000–2011) rotation study to compare conventional (CONV) with conservation (CONS) management practices (reduced tillage, narrow-row dry bean, compost addition, and cover cropping). Plant-available water (PAW) was measured using a neutron probe (10–16 count days·season^{-1}, $n = 148$) on all phases of 4 yr (dry bean–potato–wheat–sugar beet) rotations under CONS and CONV management. A visual monitoring approach was used for irrigation scheduling. For dry bean and sugar beet, management allowable depletion (MAD) was exceeded on only 11%–15% of neutron probe count days over 12 yr. However, MAD was exceeded on 30% of count days for wheat and 43% for potato. Significant crop × management interactions showed that PAW was higher with CONS management most frequently on potato, followed by dry bean, wheat, and sugar beet. This order reflected the prevalence of CONS practices directly impacting each crop. Regression analyses showed that potato, wheat, and sugar beet yield increased significantly as mean growing season water table depth (WTD) increased. This was explained by yield suppression due to excessive soil wetness in seasons with high rainfall and shallow WTD. This study provided comparative soil water dynamics for four major irrigated crops in southern Alberta, over a 12 yr period, which included record high and low growing season precipitation.

Key words: crop rotation, irrigation, soil conservation, soil water.

Résumé : Le haricot (*Phaseolus vulgaris* L.), la pomme de terre (*Solanum tuberosum* L.), le blé (*Triticum aestivum* L.) et la betterave sucrière (*Beta vulgaris* L.) sont les principales cultures irriguées dans le sud de l'Alberta. Les préoccupations relatives à la qualité du sol et à sa durabilité ont incité les auteurs à entreprendre une étude de 12 ans (de 2000 à 2011) sur les assolements afin de comparer les pratiques de travail du sol classiques (CLASS) aux pratiques de conservation (CONS) que sont la réduction des labours, la culture du haricot en rangs serrés, l'ajout de compost et la plantation d'une culture-abri. L'eau disponible pour les plantes (EDP) a été mesurée au moyen d'une sonde à neutrons (10–16 journées de relevés par saison, $n = 148$) à toutes les étapes de l'assolement de quatre ans (haricot–pomme de terre–blé–betterave sucrière) avec le régime CONS ou CLASS. Les auteurs ont recouru à un examen visuel pour déterminer quand il fallait irriguer. Dans le cas du haricot et de la betterave sucrière, en 12 ans, l'assèchement tolérable n'avait été dépassé que 11 à 15 % des jours où l'on a procédé à un relevé avec la sonde à neutrons. Cependant, il a été dépassé de 30 % pour le blé, les mêmes jours, et de 43 % pour la pomme de terre. D'importantes interactions culture × pratiques agronomiques indiquent que l'EDP est plus importante plus souvent pour la pomme de terre, puis le haricot, le blé et la betterave sucrière avec le régime CONS. Cet ordre reflète la prévalence des pratiques CONS, qui ont un impact direct sur la culture. Les analyses de régression montrent que le rendement de la pomme de terre, du blé et de la betterave sucrière augmente sensiblement quand la hauteur moyenne de la nappe phréatique s'élève durant la période végétative. La suppression du rendement à la suite d'une teneur en eau excessive du sol les saisons se caractérisant par des précipitations plus abondantes et d'une nappe phréatique peu profonde explique ces résultats. Cette étude compare la

Received 24 April 2020. Accepted 22 September 2020.

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dynamique de l'eau du sol pour quatre grandes cultures irriguées dans le sud de l'Alberta sur une période de 12 ans durant laquelle on a enregistré un maximum et un minimum record de précipitations pendant la période végétative. [Traduit par la Rédaction]

Mots-clés : assolement, irrigation, conservation du sol, eau du sol.

Introduction

Farmers grow a diverse range of crops on ~625 000 ha of irrigated land in southern Alberta, a semiarid region where precipitation is generally <50% of that required for optimum productivity. This crop diversity supports value-added agri-food industries (e.g., potato processing and sugar refining), and it provides feed (grain, hay, and silage) for intensive livestock production. Astute irrigation management aims to control the rate, amount, and timing of applied irrigation water to effectively regulate root zone soil water and promote optimum crop response, minimize soil degradation, and protect water quality (Alberta Agriculture and Forestry 2016). For most crops, yield-reducing water stress occurs at <60% of plant-available water (PAW) (Alberta Agriculture and Forestry 2016). This means irrigation should start just before soil reaches 60% of PAW to permit time for water delivery and application, before depletion to a critical level. This level is called management allowable depletion (MAD), or the maximum amount of PAW an irrigation manager chooses to allow a crop to extract between irrigations.

Crop-specific irrigation management strategies often adjust for differences in effective root zone (ERZ), i.e., the depth to which most plant roots are concentrated. For example, at peak water demand, dry bean and potato have shallower ERZ (0–60 cm) than wheat or sugar beet (0–100 cm). All four crops, however, meet ~70% of seasonal water requirements from the upper half of the ERZ (0–30 cm for dry bean and potato; 0–50 cm for wheat and sugar beet) (Alberta Agriculture and Forestry 2016). In southern Alberta, Efetha et al. (2011) advised dry bean growers to maintain >60% of PAW in the 0–30 cm root zone during the early growing season, switching to the 0–60 cm zone during later growth stages. Sensitivity to water stress and physiological maturity are also important irrigation management parameters. Lynch et al. (1995) reported that early- and mid-season water stress had greater negative impact on potato tuber yield than late-season stress in southern Alberta.

Safeguarding soil health is also considered a vital irrigation management practice and is crucial to the continued success of irrigation farming in the region. Increased areas of dry bean, potato, and sugar beet in the late 1990s led to the establishment of an irrigated rotation study to address sustainability and soil conservation issues. Its overarching objectives were to examine crop sequences and soil management for irrigated land that (*i*) optimized crop response, (*ii*) reduced soil erosion, enhanced soil quality, and promoted long-term sustainability, and (*iii*) minimized weed, insect, and disease pressures. The multi-rotation study ran for 12 yr (2000–2011) with core crops of dry bean, potato, wheat, and sugar beet managed conventionally (CONV) or with bundled conservation practices (CONS) of (*i*) reduced tillage, (*ii*) narrow-row dry bean, (*iii*) compost addition, and (*iv*) cover cropping.

Compared with CONV management, all four CONS practices could potentially increase soil water. Reduced tillage conserves water by minimizing soil disturbance and maintaining crop residue cover that lowers surface evaporation (Larney et al. 1994). Narrow-row dry bean, where individual plants are further apart than with wide-row, offers better utilization of seedbed space (Pfiffner et al. 2014), resulting in less competition for water (Manitoba Agriculture 2014). In contrast, wide-row dry bean requires (*i*) inter-row cultivation for early season weed control and (*ii*) undercutting prior to harvest that leaves unanchored crop residue and loose surface soil. Both practices may increase losses of near-surface soil water. Addition of organic amendments (e.g., compost) improves water retention by increasing soil organic matter, and improving structure, mainly through reduced bulk density and increased porosity (Miller et al. 2015; Eden et al. 2017). Finally, fall-seeded cover crops improve soil water conservation and enhance infiltration (Basche et al. 2016), as long as timely termination precludes water depletion that can negatively affect the following crop (Krueger et al. 2011).

The study was fully phased, i.e., each crop phase of each rotation appeared in each year. This provided an opportunity to address the following objectives: (*i*) to compare PAW dynamics of dry bean, potato, wheat, and sugar beet in 12 growing seasons, (*ii*) to determine if CONS compared with CONV management enhanced soil water, and (*iii*) to elucidate relationships between crop yield and soil water.

Materials and Methods

The study was conducted from 2000 to 2011 at the Vauxhall substation of Agriculture and Agri-Food Canada (50°03′N, 112°09′W, elevation 781 m) in the Bow River Irrigation District of southern Alberta. The soil was Brown Chernozem (Soil Classification Working Group 1998), with a sandy loam (0.52 $kg \cdot kg^{-1}$ sand, 0.35 $kg \cdot kg^{-1}$ silt, and 0.13 $kg \cdot kg^{-1}$ clay) Ap horizon, changing to loam (0.37–0.46 $kg \cdot kg^{-1}$ sand, 0.36–0.42 $kg \cdot kg^{-1}$ silt, and 0.18–0.22 $kg \cdot kg^{-1}$ clay) at depth (25–100 cm). Organic carbon concentration was 12.5 $g \cdot kg^{-1}$ (0–15 cm layer). Precipitation, evaporation (class A pan), and air temperature were obtained from an automated weather station located ~300 m from the study site. Mean annual 30 yr (1971–2000) normals were 303 mm of precipitation, 1230 mm of evaporation, and 5.7 °C air temperature.

Barley (*Hordeum vulgare* L.) was grown in 1999, and fully phased rotations (continuous wheat, 3 yr CONV and CONS, 4 yr CONV and CONS, 5 yr CONS, and 6 yr CONS) were established in spring 2000. Soil water was measured on the two 4 yr rotations only, which had similar crop sequences of dry bean–potato–wheat–sugar beet, one managed under CONV and the other under CONS (2 rotations × 4 phases × 4 blocks = 32 plots). Three full cycles of the 4 yr rotations ran over the 12 yr timeline. Each plot was 10.1 m × 18.3 m (185 m^2), with 2.1 m wide inter-plots and 18.3 m headlands between blocks. Full details of rotation treatments, crop management practices, and yields have been reported (Larney et al. 2015, 2016*a*, 2016*b*, 2018).

Crop management

Across 12 yr, mean planting dates were 2 May (wheat), 3 May (potato), 5 May (sugar beet), and 20 May (dry bean). In fall, the mean date of desiccation/harvest was 1 Sept. (wheat), 2 Sept. (potato), and 8 Sept. (dry bean). The mean date of defoliation/harvest was 28 Sept. for sugar beet. All crop residues were returned to plots at harvest.

Crop management for individual phases began each fall after harvest of the previous crop. The extent of the CONS practices (reduced tillage, narrow-row dry bean, compost addition, and cover crops) on the 4 yr CONS rotation was dependent on crop phase. In preparation for dry bean following sugar beet, both CONV and CONS rotations received one pass of a disk harrow. In spring, CONV dry bean received 1–2 passes with a spring-tine harrow prior to seeding with a disc drill in wide rows (60 cm) at 29 plants·m^{-2}, whereas CONS was seeded with a no-till drill in narrow rows (19–23 cm) at 53 plants·m^{-2}. Wide-row CONV dry bean was inter-row cultivated once in June for weed control (except 2010 and 2011), whereas herbicides alone were used on narrow-row CONS dry bean, further reducing tillage. In fall, wide-row CONV dry bean was undercut (creating soil disturbance) into swaths before harvesting with a plot combine. Narrow-row CONS dry bean was direct cut with a plot combine except in 2003 and 2005 (hand-harvested), and 2010 and 2011 (undercut before combining to reduce harvest losses).

Each fall after dry bean and prior to potato, the CONV rotation was moldboard plowed to 25 cm, followed by levelling with one pass of a chisel plow. On the CONS rotation, straw-bedded beef feedlot manure compost was broadcast at 42 Mg·ha^{-1} (fresh weight). Compost was incorporated by reservoir tillage, which used paddles on a turning wheel to create 15–25 cm depressions on the soil surface (Hackwell et al. 1991), trapping rain and snow, and reducing runoff. In spring, both CONV and CONS potato received two passes of a spring-tine harrow prior to planting. Potato hilling to improve drainage, prevent tuber greening, and facilitate harvest is a common agronomic practice in the region (Harms and Konschuh 2010). Hilling of both CONV and CONS rotations took place when plants were 20–25 cm tall (mean, 11 June; $n = 12$).

After potato harvest and prior to wheat, the reduced tillage CONS practice was not an option due to soil disturbance and low residue cover (Larney et al. 2017*a*), and therefore, fall tillage comprised one pass of a disk harrow on both CONV and CONS rotations. However, the relatively early harvest of potato (mean, 14 Sept.; $n = 12$) was ideal for seeding and establishment of a cover crop on the CONS rotation. Oat (*Avena sativa* L.) was used in the initial 3 yr (fall 2000–2002). However, establishment was poor, providing little or no cover, and fall rye (*Secale cereale* L.) was used from fall 2003 onward. Unlike oat, fall rye did not winterkill and re-grew in spring, before chemical desiccation and incorporation by tillage. There was no difference in spring tillage intensity between CONV and CONS wheat, i.e., disk or spring-tine harrow, or heavy-duty cultivator, depending on soil water content.

Each fall, wheat stubble was shredded with a flail mower (mean, 26 Sept., $n = 12$) on both CONV and CONS rotations in preparation for sugar beet the following spring. When the study was initiated in 2000, fall mouldboard ploughing was no longer conventional practice for sugar beet. Widespread adoption of reduced fall tillage (disking, heavy-duty cultivator) precluded further tillage reduction for the sugar beet phase, and therefore, both CONV and CONS rotations received 1–2 passes of a disk harrow. Similarly, spring tillage for sugar beet consisted of 1–2 passes of a heavy-duty or spring-tine cultivator on both rotations. Both CONV and CONS sugar beet were inter-row cultivated (1–3 times in late June to early July) for weed control, except 2006 (low weed pressure) and 2009–2011 (glyphosate-tolerant cultivars).

The traditional visual monitoring approach was used for irrigation scheduling, whereby the experienced farm manager inspected crop conditions and assessed soil water status. This was the most widely practiced approach at the outset of the study in 2000. In a 2012 survey covering 82% of Alberta's irrigated land area, Wang et al. (2015) found that growers in 48% of the survey area still relied on visual monitoring for irrigation scheduling.

All plots were individually irrigated using four quarter-circle sprinklers on a wheel-move system. The maximum water application rate used in the study was 102 mm in 4 h. The common approach with wheel-move irrigation in Alberta is to "fill-up" the root zone to field capacity (FC, 100% of PAW), with frequent light irrigations (assuming a rainfall deficit) during germination and seedling emergence (Alberta Agriculture and Forestry 2016). This is followed by increased irrigation amounts to replenish PAW during periods of peak

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demand, i.e., flowering and pod-setting (dry bean), full canopy and tuber bulking (potato), heading and flowering (wheat), and full canopy and tap root enlargement (sugar beet).

Volumetric water content

Volumetric water content (θ) was measured with a neutron probe (model 503 DR Hydroprobe, CPN International Inc., Martinez, CA, USA). Each year aluminum neutron probe access tubes (two per plot, 2000–2005; one per plot, 2006–2011) were installed within plant rows to 1.2 m depth in the 32 plots of the 4 yr rotations after all crop phases were established.

For neutron probe counts, the neutron source (50 mCi americium-241/beryllium) was positioned in the access tubes at 13, 38, 63, and 88 cm depths to measure θ at 0–25, 25–50, 50–75, and 75–100 cm, respectively. Neutron probe counts during each growing season were spaced approximately weekly (referred to as count days subsequently), with all four crops measured within 10 h. Initial counts occurred from 19 May (2000, Fig. 1*a*) to 25 June (2010, Fig. 2*e*) with a study mean ($n = 12$) of 6 June. Final counts fell between 14 Aug. (2006, Fig. 2*a*) and 13 Sept. (2002, Fig. 1*c*) with a mean of 30 Aug. Count days per season ranged from 10 in 2006 (Fig. 2*a*) to 16 in 2000 (Fig. 1*a*) and 2001 (Fig. 1*b*), with a total of 148 count days over 12 yr. Neutron probe access tubes were removed before harvest each fall.

The neutron probe was calibrated by sampling soil cores corresponding to count depths from adjacent calibration access tubes (Chanasyk and McKenzie 1986). A total of 40 soil cores were taken in spring 2000 and 63 in spring 2004. A positive linear regression equation ($R^2 = 0.71$, $p < 0.001$) derived from neutron probe count ratio (ratio of count at a given depth to a standard count, y) vs. θ of soil cores (x), using all 103 data pairs consolidated into a single calibration, was used to obtain neutron probe volumetric water content (θ_{NP}).

Plant-available water

In spring 2001, soil cores were taken to 100 cm depth in 25 cm increments close to the locations of each of the two neutron probe access tubes in the 32 plots, for particle size analysis by the hydrometer method (Sheldrick and Wang 1993). Volumetric water content at FC (θ_{FC}) and permanent wilting point (θ_{PWP}) were estimated from sand and clay contents using equations for southern Alberta soils (Oosterveld and Chang 1980). Plant-available water (θ_{PAW}) was obtained as $\theta_{FC} - \theta_{PWP}$. Conversion to millimetres of water and summation of the 0–25 and 25–50 cm layers allowed expression of θ_{NP} as a percentage of PAW at 0–50 cm as follows:

$$(1) \quad \frac{\theta_{NP} - \theta_{PWP}}{\theta_{PAW}} \times 100$$

Mean ($n = 64$) FC water content of the 0–50 cm layer was 139 [±11 standard deviation (SD)] mm, whereas PWP was 50 (±8 SD) mm, resulting in mean PAW of 89 (±4 SD) mm. Treatment effects on PAW for 0–50 cm are reported, as the management effect (CONV vs. CONS) may have been masked for the full 0–100 cm layer. Moreover, McKenzie (2018) advocated an effective irrigation management strategy of building up soil water to near FC in the 0–100 cm layer in spring and early summer and then maintaining it between 60% and 100% of PAW in the 0–50 cm layer throughout the growing season. This corresponds to MAD of 40% of PAW that is recommended for dry bean, wheat, and sugar beet in Alberta (Alberta Agriculture and Forestry 2016). For potato, a MAD of 35% of PAW is used for most growth stages, other than tuber initiation, when 30% is recommended (Alberta Agriculture and Forestry 2016). However, for direct comparison with other crops in this study, a MAD of 40% was used for potato.

Water table depth

Ten wells (38 mm diameter steel, 3 m depth) were installed (four in spring 2000 and six on 20 July 2000) to monitor water table depth (WTD). The wells were located in the 2.1 m wide inter-plot areas and remained in place for the duration of the study. Even though the site slope was <1%, the 10 well locations were chosen to represent high (four wells), low (two wells), and intermediate (four wells) surface elevations. The inter-plots were planted to fall rye each spring, which was mowed to provide continuous surface cover around the wells. Water table depth measurements were taken on all neutron probe count days except 5 (20 July 2001; 9 Aug. 2002; 11 June, 20 July, and 9 Aug. 2004), resulting in a total of 143 WTD measurements over the 12 yr study.

Statistical analyses

Generalized linear mixed models were fitted to the PAW data using SAS PROC GLIMMIX (version 9.4, SAS Institute Inc., Cary, NC, USA). Four categorical variables were included in the CLASS statements of models of within-plots means: crop, management, block, and count day. Count day was treated as a numeric variable that measured time (rounded to weeks) during the growing season. The RANDOM statement structured the variance–covariance matrix, based on the count day where the "SUBJECT" was the block. The type of structure [VC, AR(1), ARH(1), CS, CSH, TOEP, or TOEPH] was selected based on the Schwarz Bayesian information criterion. The interaction effects of management, crop, and count day were removed from the models when the F tests were statistically non-significant, except when removal resulted in the GLIMMIX procedure failing to converge.

Results and Discussion

Weather conditions

Weather data are presented for pre-growing (16 Oct.–30 Apr.) and growing season (1 May–15 Oct.)

Fig. 1. Crop × count day least-squares means (except arithmetic means, 2004 as crop × day effect non-significant) for plant-available water (PAW) (0–50 cm layer); irrigation and precipitation amounts; and average water table depth during the (*a*) 2000, (*b*) 2001, (*c*) 2002, (*d*) 2003, (*e*) 2004, and (*f*) 2005 growing seasons. Count days with asterisks denote a significant ($p < 0.05$) crop effect on PAW. Dashed lines at 100%, 60%, and 50% of PAW indicate field capacity, 40% management allowable depletion (MAD), and 50% MAD. Dotted lines link phase sequences following on the same plots (*i*) dry bean–potato, (*ii*) potato–wheat, (*iii*) wheat–sugar beet, and (*iv*) sugar beet–dry bean, through three cycles of the 4 yr rotations (continued in Fig. 2*a*). Irrigation bars without letters indicate all four crops were irrigated. Irrigation bars with letters indicate specific crops irrigated as follows: DB, dry bean; P, potato; W, wheat; SB, sugar beet.

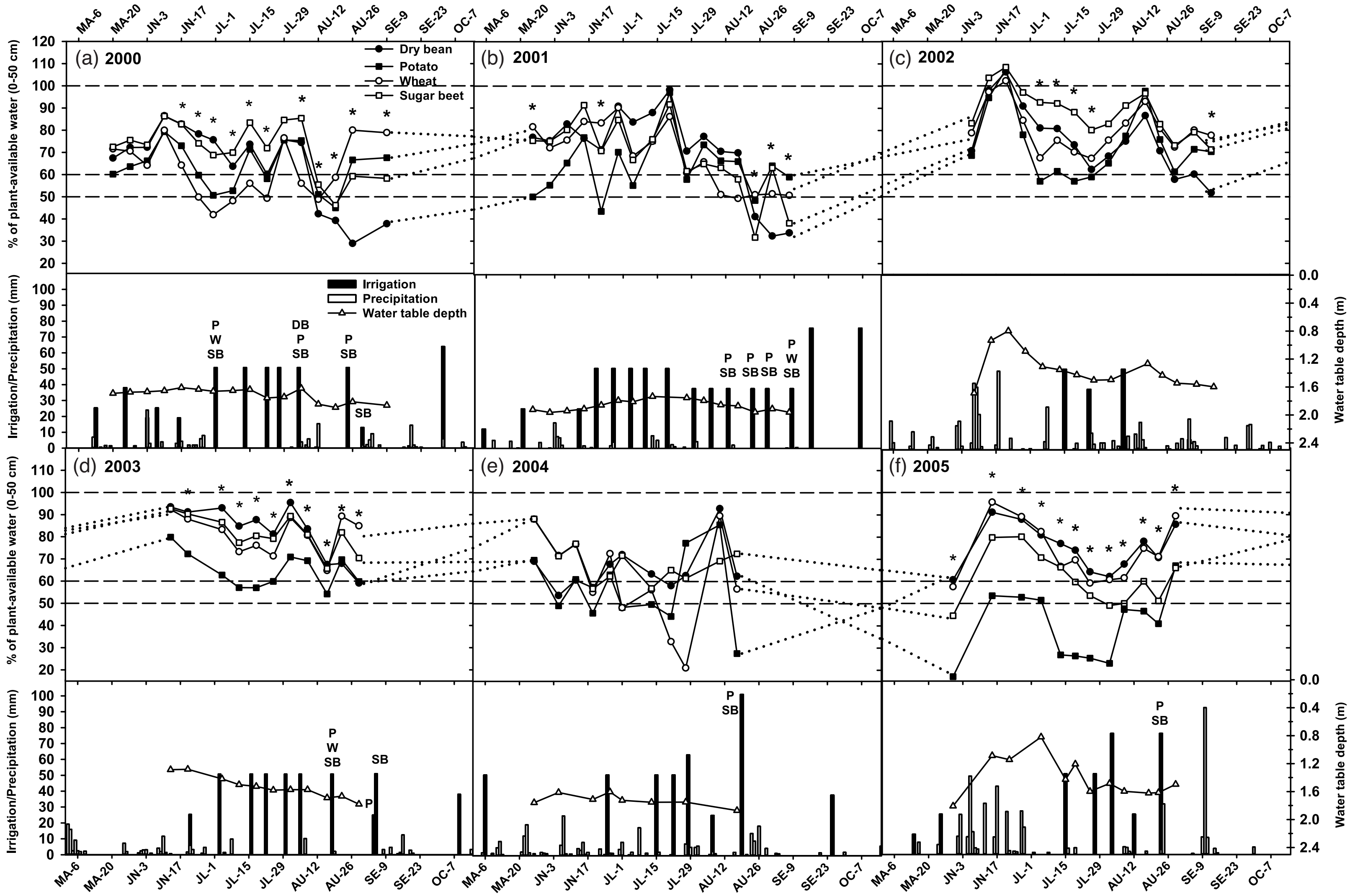

Fig. 2. Crop × count day least-squares means (except arithmetic means, 2009, 2011 as crop × count day effect non-significant) for plant-available water (PAW) (0–50 cm layer); irrigation and precipitation amounts; and average water table depth during the (*a*) 2006, (*b*) 2007, (*c*) 2008, (*d*) 2009, (*e*) 2010, and (*f*) 2011 growing seasons. Count days with asterisks denote a significant ($p < 0.05$) crop effect on PAW. Dashed lines at 100%, 60%, and 50% of PAW indicate field capacity, 40% management allowable depletion (MAD), and 50% MAD. Dotted lines link phase sequences following on the same plots (*i*) dry bean–potato, (*ii*) potato–wheat, (*iii*) wheat–sugar beet, and (*iv*) sugar beet–dry bean, through three cycles of the 4 yr rotations (continued from Fig. 1*f*). Irrigation bars without letters indicate all four crops were irrigated. Irrigation bars with letters indicate specific crops irrigated as follows: DB, dry bean; P, potato; W, wheat; SB, sugar beet.

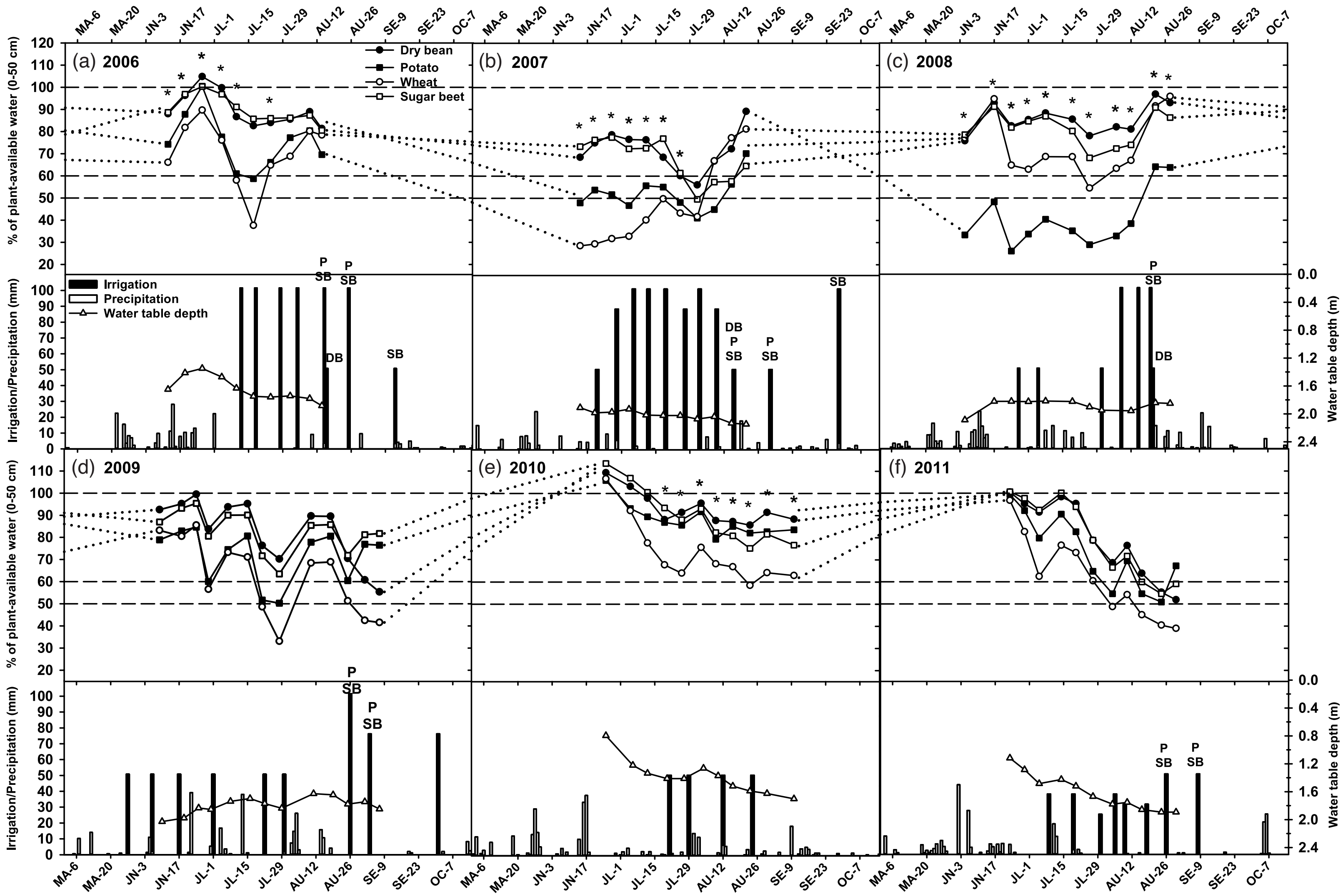

Table 1. Precipitation, evaporation, and air temperature for pre-growing and growing seasons, 1999–2011.

Pre-growing season (16 Oct.–30 Apr.)				Growing season (1 May–15 Oct.)			
Years	Precipitation (mm)	Evaporation (mm)	Mean air temp. (°C)	Year	Precipitation (mm)	Evaporation (mm)	Mean air temp. (°C)
1999–2000	83	41	0.2	2000	150	1123	14.6
2000–2001	65	131	−2.1	2001	94	1205	15.9
2001–2002	100	105	−2.3	2002	465	850	13.8
2002–2003	158	97	−1.5	2003	164	773	15.2
2003–2004	102	290	−1.7	2004	253	1137	14.1
2004–2005	105	225	−0.9	2005	484	979	14.1
2005–2006	133	191	0.6	2006	236	1024	15.7
2006–2007	154	138	−0.8	2007	177	1172	15.4
2007–2008	39	131	−2.3	2008	318	1021	14.5
2008–2009	140	271	−3.2	2009	251	1309	14.2
2009–2010	195	169	−1.7	2010	314	1163	13.9
2010–2011	149	97	−4.8	2011	262	1258	15.1
Mean	119	157	−1.7	Mean	264	1085	14.7

periods (Table 1). The driest pre-growing season was 2007–2008 with 39 mm precipitation, whereas the first two (1999–2000 and 2000–2001) were next driest (65–83 mm). The wettest pre-growing season was 2009–2010 (195 mm precipitation). Pre-growing season evaporation ranged from 41 mm in 1999–2000 to 290 mm in 2003–2004, whereas mean air temperature was highest in 2005–2006 (0.6 °C) and lowest in 2010–2011 (−4.8 °C).

The 30 yr (1971–2000) normal precipitation for a 1 May to 15 Oct. growing season is 220 mm. There was considerable variation in growing season precipitation: ranging from 484 mm (normal × 2.2) in 2005 to 94 mm (normal × 0.4) in 2001 (Table 1; Figs. 1 and 2). In fact, these growing seasons were the wettest and driest since records began at Vauxhall in 1953. The 2002 season was the second wettest (465 mm), whereas 2000 was second driest (150 mm) since 1953. Evaporation during the growing season ranged from 773 mm in 2003 to 1309 mm in 2009 with a study mean of 1085 mm (Table 1). The coolest growing season was 2002 with a mean air temperature of 13.8 °C, whereas 2001 was the warmest (15.9 °C).

Excessively wet early growing seasons in 2002, 2005, and 2010 (April to June precipitation, normal × 2.0–2.4) led to waterlogging and crop failure. Of the 32 plots in the soil water study, two were abandoned in 2002 (one dry bean and one sugar beet), four in 2005 (one of each crop), and eight in 2010 (three dry bean, three potato, and two sugar beet). Abandoned plots were treated as missing values in statistical analyses.

Irrigation management

All irrigation occurred in the growing season period only (1 May–15 Oct.). Initial irrigations took place in May in 5 yr (2000–2001, 2004–2005, 2009), June in 3 yr (2003, 2007, 2008), and July in 4 yr (2002, 2006, 2010–2011), with a range from 5 May (2001) to 21 July (2010), and a mean of 12 June (Table 2). There was no variation in initial irrigation date among crops (Table 2). Initial irrigations took place after potato, wheat, and sugar beet were planted in all 12 yr and after dry bean was planted in 8 yr. However, in 4 yr with dry springs (2000, 2001, 2004, 2005), an initial irrigation preceded dry bean seeding by 5–14 d to help establishment. Mean ($n = 12$) final irrigation dates (Table 2) were of the order: wheat (9 Aug.), dry bean (11 Aug.), potato (27 Aug.), and sugar beet (2 Sept.). Post-harvest fall irrigation was carried out in late September to early October in 5 of 12 yr (Table 2). Fall irrigation is considered a best management practice as it alleviates soil compaction by enhancing wet–dry and freeze–thaw cycles (McKenzie 2010).

Irrigation amounts varied substantially by season (Table 2; Figs. 1 and 2), and to a lesser extent by crop (Table 2). Across all crops, irrigation ranged from 143 mm in 2002 to 813 mm in 2007 (mean, 381 mm, $n = 12$). Across all growing seasons, mean irrigation was of the following order: wheat (329 mm) ≈ dry bean (338 mm) < potato (421 mm) ≈ sugar beet (437 mm). On average, potato and sugar beet received 28% more irrigation water than dry bean or wheat. These values fall in line with maximum evapotranspiration (ET) values (calculated from 1983–2010 Vauxhall weather data) of 419 mm for dry bean, 469 mm for wheat, 548 mm for potato, and 599 mm for sugar beet (Bennett and Harms 2011). Fall irrigation amounts ranged from 38 to 152 mm (190 mm for wheat) (Table 2).

Plant-available water (0–50 cm layer)

Management allowable depletion

Across all four crops, PAW was within MAD range (60%–100% of PAW) for a maximum of 86% of count days in 2003 (Fig. 1*d*), to a minimum of 50% in 2007 (Fig. 2*b*),

Table 2. Irrigation dates and amounts, 2000–2011.

	Irrigation date						Irrigation amount					
	Initial	Final				Fall	Initial to final date					Fall
Year	All crops	Dry bean	Potato	Wheat	Sugar beet	All crops	Dry bean (mm)	Potato (mm)	Wheat (mm)	Sugar beet (mm)	Mean (mm)	All crops (mm)
2000	12 May	3 Aug.	23 Aug.	26 July	29 Aug.	1 Oct.	330	432	330	445	384	64
2001	5 May	6 Aug.	8 Sept.	6 Aug.	8 Sept.	15 Sep./6 Oct.	394	546	394	546	470	152[a]
2002	15 July	9 Aug.	4 Sept.	9 Aug.	4 Sept.	—	140	146	140	146	143	0
2003	21 June	5 Aug.	18 Aug.	18 Aug.	5 Sept.	9 Oct.	279	355	330	381	336	38
2004	6 May	6 Aug.	18 Aug.	6 Aug.	18 Aug.	24 Sep.	317	419	317	419	368	38
2005	14 May	12 Aug.	24 Aug.	12 Aug.	24 Aug.	—	241	318	241	318	280	0
2006	12 July	15 Aug.	25 Aug.	4 Aug.	13 Sept.	—	457	610	405	660	533	0
2007	21 June	16 Aug.	31 Aug.	9 Aug.	28 Sept.	—	775	826	724	927	813	0
2008	26 June	20 Aug.	20 Aug.	14 Aug.	20 Aug.	—	406	457	356	457	419	0
2009	27 May	30 July	3 Sept.	30 July	3 Sept.	1 Oct.	305	483	305	483	394	76
2010	21 July	24 Aug.	24 Aug.	24 Aug.	24 Aug.	—	203	203	203	203	203	0
2011	9 July	18 Aug.	8 Sept.	18 Aug.	8 Sept.	—	203	254	203	254	229	0
Mean	12 June	11 Aug.	27 Aug.	9 Aug.	2 Sept.	—	338	421	329	437	381	—

[a]Wheat received 190 mm.

with a study average of 72% of count days (Table 3). Other years with acceptable MAD compliance (81%–85% of count days) were 2002 (Fig. 1*c*), 2006 (Fig. 2*a*), 2009 (Fig. 2*d*), and 2010 (Fig. 2*e*), with 2002 and 2010 likely due to normal × 2 April–June rainfall. However, 2005 had normal × 2.1 growing season precipitation (Fig. 1*f*), but relatively low MAD compliance (58%, Table 3), due to challenging conditions. The driest April–May (38 mm precipitation, normal × 0.51) led to the driest soil of the study (17% of PAW under potato) on 30 May 2005 (Fig. 1*f*). The dry spring was followed by an extremely wet June (284 mm, normal × 4.8), and subsequent waterlogging precluded irrigation until 15 July (Fig. 1*f*). In turn, the wet June was followed by a dry 36 d period (3 July to 7 Aug.) with only 10 mm of rainfall. Although June rainfall increased PAW under potato to 51%–53% from 15 June to 5 July, irrigation from 15 July to 3 Aug. failed to replenish PAW to >60% (Fig. 1*f*).

For the four crops, average MAD compliance over 12 yr was of the following order: dry bean (84%) > sugar beet (80%) > wheat (68%) > potato (55%) (Table 3). Management allowable depletion was exceeded (Table 3) on only 11% of count days for dry bean and 15% for sugar beet, mostly in the late growing season (Figs. 1 and 2), as crops reached maturity and dry soil conditions were preferred for harvest operations. In addition, frequent irrigation creates a micro-environment conducive to white mould [*Sclerotinia sclerotiorum* (Lib.) de Bary] of dry bean (Efetha et al. 2011; Kader et al. 2018). In contrast, MAD was exceeded for wheat on 30% and for potato on 43% of count days. The behaviour of MAD largely agreed with maximum 10 d average daily ET values in the region, where wheat (7.4 mm·d^{-1}) and potato (6.2 mm·d^{-1}) are higher than dry bean (5.7 mm·d^{-1}) and sugar beet (6.0 mm·d^{-1}) (Alberta Agriculture and Rural Development 2014).

Selection of a specific MAD is not a rigid irrigation management criterion and may be adjusted based on the irrigation system, crop growth stage, water stress sensitivity, PAW in the ERZ, rainfall patterns, or availability of pumped or delivered water (Alberta Agriculture and Forestry 2016, 2019). For example, in terms of irrigation system, for most grain, oilseed or forage crops using centre pivots, the suggested MAD is 35%–40% of PAW. For the same crops grown with surface or wheel-move irrigation, MAD may be adjusted to 50%. In the case of growth stage, MAD may be set to 50% during pod-fill of dry bean, without significant yield loss, if conditions favour white mould. When the MAD threshold was adjusted from 40% to 50% of PAW, MAD was exceeded on 22% vs. 43% of count days for potato and on 17% vs. 30% for wheat (Table 3). In addition, overall MAD compliance increased from 72% to 85%, and MAD was exceeded on only 12% of count days (Table 3).

Management allowable depletion (0–50 cm layer) was exceeded for potato for most of three growing seasons: 2005 (Fig. 1*e*), 2007 (Fig. 2*b*), and 2008 (Fig. 2*c*). However, these seasons differed in precipitation and irrigation

Table 3. Plant-available water status (0–50 cm layer) on the four crop phases (based on crop × count day least-squares means, except 2004 when arithmetic means used, as crop × count day effect non-significant), 2000–2011.

		Count days within MAD range[a] (*n*)					Count days MAD exceeded[b] (*n*)					Count days >100% of PAW (*n*)				
Year	Count days (*n*)	Dry bean	Potato	Wheat	Sugar beet	All (%)[c]	Dry bean	Potato	Wheat	Sugar beet	All (%)[c]	Dry bean	Potato	Wheat	Sugar beet	All (%)[c]
2000	16	12	10	8	12	66	4	6	8	4	34	0	0	0	0	0
2001	16	13	9	11	13	72	3	7	5	3	28	0	0	0	0	0
2002	15	12	11	14	13	83	2	3	0	0	8	1	1	1	2	8
2003	11	10	6	11	11	86	1	5	0	0	14	0	0	0	0	0
2004	11	8	5	5	9	61	3	6	6	2	39	0	0	0	0	0
2005	12	12	1	10	5	58	0	11	2	7	42	0	0	0	0	0
2006	10	9	8	8	9	85	0	1	2	0	8	1	1	0	1	8
2007	11	10	1	3	8	50	1	10	8	3	50	0	0	0	0	0
2008	11	11	2	10	11	77	0	9	1	0	23	0	0	0	0	0
2009	13	12	10	7	13	81	1	3	6	0	19	0	0	0	0	0
2010	11	9	10	9	8	82	0	0	1	0	2	2	1	1	3	16
2011	11	7	8	5	7	64	2	3	6	3	32	2	0	0	2	9
Total	148	125	81	101	118	—	17	64	45	22	—	6	3	2	8	—
Percentage of total	—	84	55	68	80	72	11	43	30	15	25	4	2	1	5	3
Percentage of total count days																
MAD = 50% of PAW		91	76	82	90	85	5	22	17	5	12	—	—	—	—	—

Note: MAD, management allowable depletion.
[a]Within MAD range: management allowable depletion = 60%–100% of PAW.
[b]MAD exceeded: management allowable depletion <60% of PAW.
[c]Sum for all crops expressed as percent of total (*n* count days × 4).

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Table 4. Summary of main and interaction effects on plant-available water (0–50 cm), 2000–2011.

Effect	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Count day	*	*	*	*	NS	*	*	*	*	*	*	*
Crop	*	NS	NS	*	NS	*	*	*	*	NS	*	NS
Management	*	*	NS	*	NS	*	NS	NS	*	*	*	NS
Count day × crop	*	*	*	*	NS	*	*	*	*	NS	*	NS
Crop × management	*	*	NS	*	NS	*	NS	*	*	*	*	*
Count day × management	NS	NS	*	*	NS	NS	NS	NS	NS	NS	NS	NS
Count day × crop × management	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note: *, significant effect at $p < 0.05$; NS, non-significant.

amounts. The 2005 precipitation trend was outlined above, with a dry April–May, followed by an excessively wet June, and dry again in July–August. In 2007, April–May had 143 mm of rainfall (normal × 2), followed by a 36 d mid-season (30 June–4 Aug.) dry period with only 5 mm of rainfall. In addition, July 2007 was the hottest of the study, with a mean air temperature of 22.2 °C (3.8 °C above normal). This necessitated high rates of irrigation (673 mm from 29 June to 9 Aug., Fig. 2*b*; Table 2), which did not replenish soil to >60% of PAW. The 2008 growing season was preceded by the driest pre-growing season of the study with only 39 mm of precipitation between 16 Oct. 2007 and 30 Apr. 2008 (Table 1).

Lower PAW for potato in 2005, 2007, and 2008 may also have been due to lower water inputs for preceding dry bean crops in 2004, 2006, and 2007. In 2004 (Fig. 1*e*), even though all four crops received a fall irrigation of 38 mm (24 Sept.), dry bean (preceding 2005 potato) was last irrigated on 6 Aug. (25 mm), whereas potato (preceding 2005 wheat) and sugar beet (preceding 2005 dry bean) received 102 mm (18 Aug.). In 2006 (Fig. 2*a*), dry bean (preceding 2007 potato) was last irrigated on 15 Aug. (51 mm), whereas potato (preceding 2007 wheat) received 204 mm (15, 25 Aug.), and sugar beet (preceding 2007 dry bean) received 255 mm (15, 25 Aug.; 13 Sept.). A similar scenario arose in 2007 (Fig. 2*b*), when dry bean (preceding 2008 potato) was last irrigated on 15 Aug. (51 mm), whereas potato (preceding 2008 wheat) received 51 mm (31 Aug.), and sugar beet (preceding 2008 dry bean) received 153 mm (31 Aug., 28 Sept.).

Count days with >100% of PAW (i.e., exceeding FC) averaged only 3% of the total (Table 3), and these occurred in 4 yr with high (normal × 1.6–2.5) May–June rainfall: 2002 (Fig. 1*c*), 2006 (Fig. 2*a*), 2010 (Fig. 2*e*), and 2011 (Fig. 2*f*). There was little variation due to crop (1% for wheat to 5% for sugar beet) in count days >100% of PAW (Table 3). The wettest soil in the study was 113.5% of PAW, under sugar beet on the initial count day in 2010 (25 June, Fig. 2*e*).

Main effects (count day, crop, and management)

Over 12 yr, only 2004 was non-significant for all main and interaction effects on PAW (Table 4). Of the three main effects (count day, crop, and management), count day (across all crops and managements), not unexpectedly, was significant in 11 of 12 yr (Table 4). However, in 9 of 11 yr, the count day effect was qualified by significant two-way (count day × crop, count day × management) interactions (Table 4). This left 2 yr (2009, 2011) late in the study when count day was unaffected by interactions, and PAW for all four crops (across managements) trended in unison (Figs. 2*d* and 2*f*), being significantly wetter (near FC) in the early growing season but staying >60% until the late growing season, thereby following the approach of McKenzie (2018).

Crop (across all count days and managements) indicated significant effects on PAW in 7 of 12 yr: 2000, 2003, 2005–2008, and 2010 (Table 4). However, all 7 yr showed significant count day × crop interactions, whereas 6 yr (2006 excepted) showed significant crop × management interactions (Table 4). Management (across all count days and crops) was significant in 7 of 12 yr: 2000–2001, 2003, 2005, and 2008–2010 (Table 4). However, significant crop × management interactions occurred in all 7 yr and a significant count day × management interaction in 2003 (Table 4).

Count day × crop interaction effects

Significant differences in PAW among crops on specific count days (count day × crop interaction) are of interest, showing differential crop water use or residual effects of previous crops in rotation. Count day × crop interactions (across both managements) were present in 9 of 12 yr, the exceptions being 2004, 2009, and 2011, when crop had no significant effect on PAW on any count day during the growing season (Table 4; Figs. 1*e*, 2*d*, and 2*f*). Of 148 count days, 75 (or 51%) showed significant crop effects on PAW, including all 12 count days in 2005 (Fig. 1*f*), all 11 in 2008 (Fig. 2*c*), and all but 1 of 11 in 2003 (Fig. 1*d*).

Carryover of significant effects from final counts of a season to initial counts of the next was evident, e.g., despite fall irrigation, significantly lower PAW under dry bean at the end of 2000 (Fig. 1*a*) rendered PAW under potato significantly lower at the beginning of 2001 (Fig. 1*b*). Similarly, significantly lower PAW under dry bean in fall 2002 was carried over to potato after the initial count in 2003 (Fig. 1*d*). Examples of fall irrigation replenishing the upper soil profile were evident from 2001 (Fig. 1*b*) to 2002 (Fig. 1*c*) and from 2009 (Fig. 2*d*) to 2010 (Fig. 2*e*).

On any specific count day, six pairs of crops could be compared for PAW: dry bean vs. potato, wheat or sugar beet; potato vs. wheat or sugar beet; and wheat vs. sugar beet. When a significant difference occurred in PAW between crops, there were two possible scenarios: crop $x >$ crop y or crop $x <$ crop y. Table 5 summarizes significant differences in PAW for the six crop comparisons. Non-significant effects (crop $x \approx$ crop y) are also shown.

Dry bean had significantly higher PAW than both potato (28% of count days) and wheat (19% of count days), whereas the reverse (dry bean < potato or wheat) was true on only 3%–5% of count days (Table 5). This agreed with maximum 10 d average daily ET values where dry bean is lower than potato and wheat (5.7 vs. 6.2–7.4 mm·d^{-1}; Alberta Agriculture and Rural Development 2014), hence leading to higher PAW under dry bean, given similar irrigation inputs in the early part of the growing season. The crop pair with the greatest similarity in PAW was dry bean and sugar beet, with only 4% of count days showing dry bean > sugar beet, and a further 4% with dry bean < sugar beet, leaving 92% of count days not significantly different (Table 5). This may seem unusual as sugar beet was shown to have higher ET than dry bean at Vauxhall (599 vs. 419 mm, Bennett and Harms 2011), mostly due to its longer growing season. However, in June–July, the ET patterns of both crops are similar and lower than both potato and wheat, e.g., the average ET from 11–20 July for dry bean and sugar beet is 5.4 mm d^{-1}, compared with 5.8 mm d^{-1} for potato, and 7.3 mm d^{-1} for wheat (Alberta Agriculture and Rural Development 2014). All five significantly drier count days under dry bean vs. potato, seven vs. wheat, and six vs. sugar beet (Table 5), were confined to late season, in the initial years (2000–2003; Figs. 1*a*–1*d*), reflecting lower water requirements as dry bean neared maturity.

Potato had significantly lower PAW than wheat on 21% of count days and sugar beet on 28% of count days (Table 5). The least-common PAW status was potato > sugar beet that occurred on only 2 of 148 count days (Table 5) in late 2001 (Fig. 1*b*). The final crop comparison, wheat vs. sugar beet, showed more instances of wheat < sugar beet (22% of count days) than wheat > sugar beet (5% of count days), most likely due to greater ET by wheat during the mid-growing season.

Table 5. Summary of count day × crop effects on plant-available water (PAW) (0–50 cm layer, based on 148 count days presented in Figs. 1 and 2), 2000–2011.

PAW[a]	No. of count days	Percentage of total count days
Dry bean > potato	41	28
Dry bean < potato	5	3
Dry bean ≈ potato	102	69
Dry bean > wheat	29	19
Dry bean < wheat	7	5
Dry bean ≈ wheat	112	76
Dry bean > sugar beet	6	4
Dry bean < sugar beet	6	4
Dry bean ≈ sugar beet	136	92
Potato > wheat	18	12
Potato < wheat	31	21
Potato ≈ wheat	99	67
Potato > sugar beet	2	1
Potato < sugar beet	41	28
Potato ≈ sugar beet	105	71
Wheat > sugar beet	8	5
Wheat < sugar beet	32	22
Wheat ≈ sugar beet	108	73

[a]Significantly > or < at $p < 0.05$; ≈, non-significant.

Crop × management interaction effects

Crop × management interactions on PAW (across all count days in a growing season) were significant in 9 of 12 yr, the exceptions being 2002, 2004, and 2006 (Tables 4 and 6). For dry bean, 4 yr (2000–2001, 2003, 2008) showed significantly higher PAW (9%–17% points) with CONS management (Table 6), whereas only 1 yr (2010) had higher PAW with CONV management (101% vs. 86%). For potato, all 6 yr with significant effects (2000–2001, 2005, 2007–2008, 2010) showed higher PAW (mean, +11% points) under CONS management (Table 6). Wheat had the most years (8) with significant effects (Table 6): with 5 yr (2000, 2007, 2009–2011) showing higher PAW under CONV and 3 yr (2001, 2005, 2008) higher (mean, +12% points) under CONS management (Table 6).

Sugar beet had the least growing seasons (4) with a significant management effect on PAW, with 3 yr (2005, 2008, 2010) higher under CONV and 1 yr (2003) higher under CONS management. In Idaho, Tarkalson and King (2017) found higher θ for 0–30 and 0–120 cm layers for strip (alternating 30 cm wide tilled and untilled soil) vs. conventional tillage for sugar beet in 1 of 3 yr. However, in 2 yr, they hypothesized that sugar beet extracted water to greater depths than measured, resulting in a masking effect of tillage on θ and non-significant differences. In Montana, Stevens et al. (2015) reported no significant difference in θ in the 0–75 cm layer between strip and conventional tillage. Strip tillage would be considered more conservation oriented than CONS management for sugar beet in our study.

In total, there were 14 cases of significantly higher PAW under CONS management in the study that ranked as follows: potato (6) > dry bean (4) > wheat (3) > sugar beet (1). This order reflects the prevalence of CONS practices for each crop. For CONS potato, reduced and reservoir tillage (vs. moldboard plowing with CONV), and compost addition in the previous fall, likely enhanced soil water. For CONS dry bean, a narrow-row production system with reduced soil disturbance (no-till seeding, absence of inter-row cultivation or undercutting at harvest) may have lowered evaporation.

Table 6. Crop × management least-squares means (except arithmetic means, 2002, 2004, and 2006 as crop × management effect non-significant) for plant-available water (PAW) (0–50 cm layer) averaged across count days, 2000–2011.

		Percentage of PAW											
Crop	Management	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Dry bean	CONV	53.9b	63.8b	78.8a	76.3b	63.7a	70.2a	95.5a	70.5a	79.6b	76.7a	100.6a	67.7a
	CONS	70.5a	72.5a	72.6a	86.6a	67.0a	78.6a	84.0a	71.7a	91.6a	85.8a	86.0b	93.4a
Potato	CONV	58.0b	56.4b	68.1a	67.1a	51.9a	28.6b	72.4a	47.7b	37.3b	75.9a	82.1b	53.4a
	CONS	67.9a	70.0a	79.7a	61.7a	60.9a	47.2a	76.5a	55.6a	40.5a	65.5a	93.4a	95.4a
Wheat	CONV	66.7a	59.3b	70.6a	80.4a	64.8a	65.7b	71.8a	50.4a	68.2b	65.8a	89.3a	70.8a
	CONS	55.7b	75.9a	91.7a	81.0a	56.7a	79.0a	65.3a	39.1b	76.8a	61.7b	58.0b	52.6b
Sugar beet	CONV	71.0a	66.8a	85.7a	73.1b	66.0a	64.1a	98.0a	64.1a	84.3a	84.3a	92.2a	66.5a
	CONS	70.5a	65.3a	90.7a	89.7a	70.8a	55.8b	82.3a	69.3a	78.0b	79.6a	86.8b	90.2a

Note: Within year and crop × management pairs, means followed by different lowercase letters are significantly different from each other (least significant difference, $p < 0.05$).

For CONS wheat, a fall-seeded cover crop that increased surface residue (Larney et al. 2017*a*) may have reduced evaporation losses from the soil surface. Of the four crops, CONS practices were least prevalent for sugar beet, which was reflected in only one instance of higher PAW under CONS sugar beet.

At the end of 12 yr, the 4 yr CONS rotation had 20% higher soil organic carbon (SOC) than 4 yr CONV (41.2 vs. 34.4 Mg·ha^{-1}, 0–30 cm, Larney et al. 2017*b*), which may also explain higher PAW with CONS. The 4 yr CONS rotation received 116 Mg·ha^{-1} of feedlot manure compost over 12 yr, which largely drove the increase in SOC, although other CONS practices (reduced tillage, narrow-row dry bean, and cover crop) also contributed. There were nine cases of significantly higher PAW under CONV management, with the remaining 25 comparisons being non-significant (Table 6). A recent global meta-analysis showed that increased SOC had a smaller effect on soil water and hydrological cycling than previously thought (Minasny and McBratney 2018), which may partly explain CONV > CONS and non-significant (CONV ≈ CONS) cases.

Count day × management interaction effects

Across the entire study, there were only two growing seasons when significant count day × management interactions on PAW occurred (Table 4), i.e., across all four crops. In 2002, six count days in the late growing season (26 July; 2, 11, 29 Aug.; 6, 13 Sept.) showed significantly higher PAW with CONS management. Across the 6 d, CONS averaged 78% compared with 65% of PAW under CONV. In 2003, five count days in mid- to late-growing season (18, 25 July; 16, 22, 29 Aug.) also showed higher PAW (mean, 75% vs. 67%) with CONS management across all four crops.

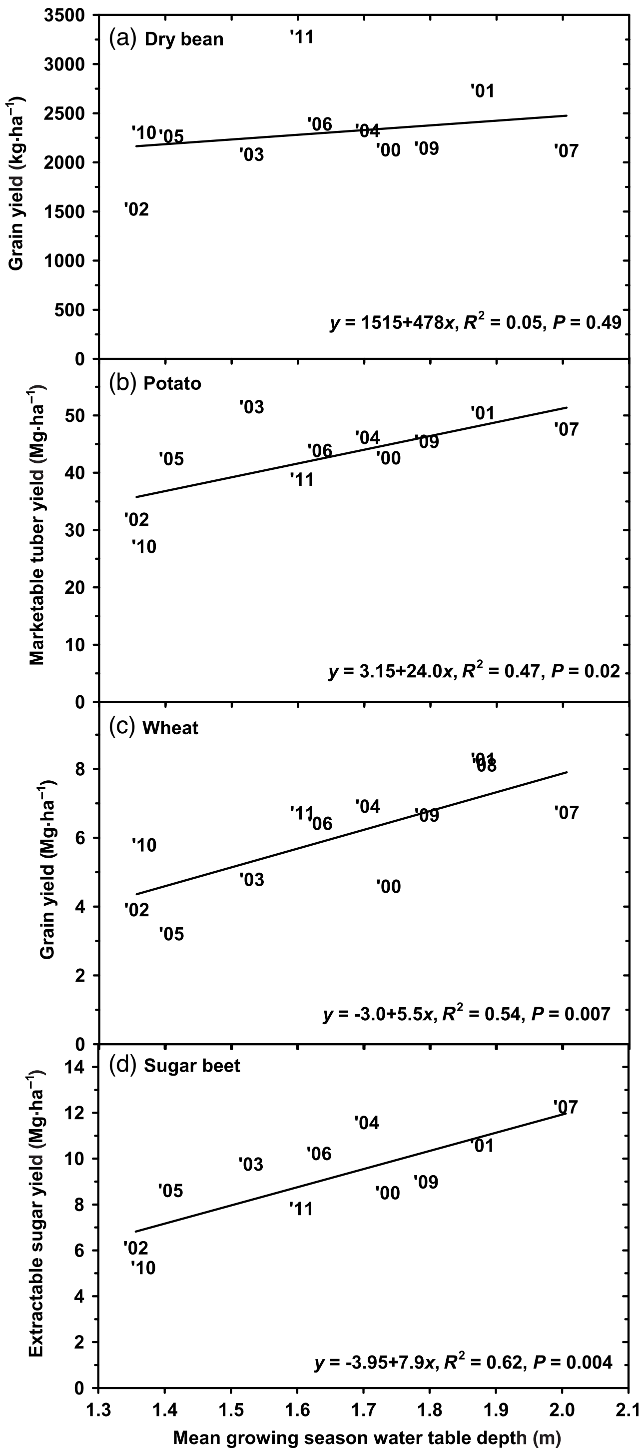
Water table depth and crop yield

The shallowest WTD of the study was 0.78 ± 0.53 m ($n = 10$, ±SD) on 25 June 2010 (Fig. 2*e*), whereas the deepest was 2.13 ± 0.36 m ($n = 10$) on 21 Aug. 2007 (Fig. 2*b*). The shallowest mean growing season WTD was 1.36 ± 0.49 m ($n = 140$) in 2002 (Fig. 1*c*), followed closely by 1.37 ± 0.46 m ($n = 110$) in 2010 (Fig. 2*e*), and 1.41 ± 0.50 m ($n = 120$) in 2005 (Fig. 1*f*), reflecting normal × 2.0–2.4 April–June precipitation in those years. The deepest mean growing season WTD was 2.01 ± 0.33 m ($n = 110$) in 2007 (Fig. 2*b*), followed by tied years: 1.88 ± 0.32 m ($n = 150$) in 2001 (Fig. 1*b*) and 1.88 ± 0.44 m ($n = 110$) in 2008 (Fig. 2*c*).

Annual yields of grain (dry bean and wheat), marketable tubers (potato), and extractable sugar (sugar beet) (Larney et al. 2015, 2016*a*, 2016*b*, 2018) were regressed on mean growing season WTD (Fig. 3). The 2008 yields for dry bean, potato, and sugar beet were omitted as three severe hail storms in early July caused extensive canopy damage to these broadleaf crops, whereas wheat was relatively unscathed. The relationships showed that yield increased significantly for potato, wheat, and sugar beet (Figs. 3*b*–3*d*) as mean growing season WTD increased. The strongest relationship was for sugar beet, where mean WTD explained 62% of the variation in extractable sugar yield (Fig. 3*d*). In 2007, the deepest mean WTD (2.01 m) led to the highest extractable sugar yield (12.3 Mg·ha^{-1}), whereas the shallowest WTDs (1.36–1.37 m) of 2002 and 2010 (due to above-normal rainfall) led to the lowest sugar yields (5.2–6.1 Mg ha^{-1}). This agreed with Benz et al. (1985) who reported significantly lower sugar beet yields with shallow (0.46 m) vs. deep (1.0–2.1 m) water table treatments in North Dakota.

Mean WTD explained 54% of annual yield variation for wheat (Fig. 3*c*) and 47% for potato (Fig. 3*b*), but had no significant effect on dry bean yield (Fig. 3*a*). Satchithanantham et al. (2012) also found that potato yield was significantly positively correlated with seasonal average WTD in Manitoba, i.e., plots with deeper WTD performed better. They concluded that with a deep water table, the vadose zone stayed aerated and conducive to root growth. Satchithanantham et al. (2014) found that during short dry periods, up to 92%

Fig. 3. Relationships between mean growing season water table depth and annual (*a*) dry bean, (*b*) potato, (*c*) wheat, and (*d*) sugar beet yields (mean of CONV and CONS management). $n = 11$ for dry bean, potato, and sugar beet (2008 omitted due to hail damage); $n = 12$ for wheat. Symbols represent growing seasons, e.g., '00 = 2000, '01 = 2001, etc.



of potato water use was contributed by shallow (1.33–1.66 m) groundwater. This observation was corroborated by Abbas and Sri Ranjan (2015) who reported that high potato yield under dry surface conditions was due to upward migration of water from shallow groundwater. The upward water flux to meet crop demand then led to lowering of the water table. In our study, water extraction by potato from >50 cm depth may have compensated for MAD exceedance at 0–50 cm depth, thereby maintaining tuber yield. For example, 2007 recorded the third highest marketable tuber yield of the study (47.6 $Mg\cdot ha^{-1}$; Fig. 3*b*), although MAD was exceeded at 0–50 cm for most of that growing season (Fig. 2*b*).

The above results may justify deficit irrigation, i.e., deliberately applying water below ET requirements, without jeopardizing yield (Geerts and Raes 2009). In Nebraska, sugar beet tolerated moderate late-season deficit irrigation, producing profitable yields (Yonts et al. 2003), whereas moderate-to-severe water stress late in the growing season increased sugar yield by 1.0–1.9 $Mg\cdot ha^{-1}$ (Haghverdi et al. 2017). Yonts et al. (2018) found that applying 25% less water in normal and even dry years did not reduce dry bean yields compared with full irrigation, yet increased water use efficiency by 26%.

Summary and Conclusions

This 12 yr study provided comparative analysis of PAW and its response to CONS management for four major crops in the irrigated region of southern Alberta under a gamut of weather conditions. Even with record-setting rainfall (e.g., 2002, 2005), maintaining soil water at >60% of PAW was a challenge for two of the four crops. Use of the traditional visual monitoring or "crop condition" irrigation scheduling approach in our study was adequate for dry bean and sugar beet, as MAD was exceeded on only 11%–15% of neutron probe count days during 12 yr. The approach was less successful for wheat (MAD exceeded on 30% of count days) and potato (MAD exceeded on 43% of count days). However, adjusting the MAD threshold to 50% of PAW, which is legitimate for wheel-move irrigation, lowered the number of count days when MAD was exceeded to more acceptable levels of 17% for wheat and 22% for potato.

The traditional visual monitoring method, while still the most common scheduling practice in the region (48% of irrigated area, Wang et al. 2015), is often considered unreliable because yield reduction may have already occurred before water stress becomes apparent. The "hand-feel" method is the simplest and cheapest way to improve accuracy of irrigation scheduling over the traditional method (Alberta Agriculture and Forestry 2016), whereby a hand auger, or probe sampler obtains soil from deeper in the profile to estimate PAW by "hand-feel" (soil stickiness, ball strength, and finger staining). Bjornlund et al. (2009) noted increased adoption of the "hand-feel" method in a survey of two irrigation districts in southern Alberta, whereas

Wang et al. (2015) reported that 43% of their survey area used the method.

Over the course of the 12 yr study, 51% of neutron probe count days showed significant crop effects on PAW in the 0–50 cm layer. Dry bean had significantly higher PAW than potato on 28%, and wheat on 19% of count days, that agreed with lower water use requirements of dry bean vs. potato or wheat. However, dry bean and sugar beet had similar levels of PAW at 0–50 cm on 92% of count days, despite these crops having different ERZs (0–60 cm, dry bean; 0–100 cm, sugar beet). This may have been due to similar ET values of dry bean and sugar beet in mid-season and possible extraction of water from deeper than the ERZ of both crops. Because of lower water requirements and earlier maturity and hence irrigation cut-off, dry bean impinged on PAW of the following potato crop. This rotational effect could be negated by (*i*) fall irrigation following dry bean harvest or (*ii*) altering crop sequence to avoid potato after dry bean.

Although adoption of CONS practices led to instances of higher PAW, the magnitude of the effect depended on crop. For the four crop phases (with their specific CONS practices of direct impact), advantages of CONS management on PAW were of the order: potato (reduced tillage, compost addition) > dry bean (reduced tillage, narrow-row) > wheat (cover crop) > sugar beet (any CONS benefits largely residual from previous crop phases). CONS management also elicited gains in PAW (8%–13% points) across all four crops in 2002 and 2003. Advantages of CONS management were also observed on dry bean (Larney et al. 2015), potato (Larney et al. 2016*b*), and sugar beet (Larney et al. 2016*a*) yields but not on wheat (Larney et al. 2018). CONS management also enhanced soil quality (Li et al. 2015; Larney et al. 2017*b*), soil microbial communities (Lupwayi et al. 2017*a*, 2017*b*), and surface residue cover (Larney et al. 2017*a*). In addition, Blackshaw et al. (2015) found that implementing CONS practices posed little risk of increased weed populations. There was no evidence of accrual of a positive CONS effect on PAW with time. The magnitude of the benefit may have been expected to intensify as multiple CONS practices were layered onto three repeated cycles of the 4 yr CONS rotation over 12 yr.

There was a substantial variation in WTD during the study from 0.78 to 2.13 m, or a range of 1.35 m, reflective of precipitation trends over 12 yr. Water table depth was a good indicator of soil water dynamics and is a much simpler and less time-consuming measurement than PAW. Yield suppression from excessive soil wetness in high rainfall years contributed to the positive relationship between crop yield and deeper WTD.

Acknowledgements

We thank Terry Dell (2000–2003) and summer students Jess Senneker (2004), Danyae Hobberstad (2005), Rikki-Lee Brown (2005–2006), Jennifer Pepneck (2007), Tracy Pepneck (2008–2009), Laine Geremia (2010), and Julie Pepneck (2011) for field assistance with neutron probe counts and water table measurements. We appreciate the help of Bruce Woolhouse with neutron probe calibrations and plant-available water estimates; Jim Sukeroff, Dale Reynolds, and Vauxhall Sub-station staff with crop husbandry; and Jennifer Nitschelm (2000–2006) and Peter Regitnig (2007–2011), Rogers Sugar Ltd./Lantic Inc., Taber, AB, Canada, with sugar beet management. Jim Miller kindly reviewed a draft of the manuscript. We thank anonymous reviewers for critiquing the manuscript, especially the one who offered such enthusiastic comments. Funding was provided by the Alberta Pulse Growers, the Potato Growers of Alberta, Lantic Inc., the Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster.

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Soil surface cover on irrigated rotations for potato (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.), and soft white spring wheat (*Triticum aestivum* L.) in southern Alberta

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Abstract: Soil surface cover (crop residue and fall-seeded cover crops) during the nongrowing season is an important tenet of sustainable agriculture, reducing wind and water erosion risk and enhancing soil water conservation. Expansion of irrigated row crop production, namely, potato (*Solanum tuberosum* L.), dry bean (*Phaseolus vulgaris* L.), and sugar beet (*Beta vulgaris* L.), in southern Alberta in the late 1990s prompted a 12-year (2000 to 2011) study to evaluate rotations and soil management systems for improved soil quality. The study compared conservation (CONS) and conventional (CONV) management systems in three- to six-year rotations. Conservation management included cover crops; reduced tillage; feedlot manure compost addition; and solid-seeded, narrow-row dry bean production. Beginning in the third year of the study (2002), surface residue cover was estimated each spring prior to tillage or seeding. Averaged over 10 years (2002 to 2011), residue cover was significantly higher on CONS (15.6%) versus CONV (7.1%) management. Cover was significantly higher where wheat (*Triticum aestivum* L.) was the previous crop (33.7%) compared to narrow-row dry bean (9.7%), which was significantly higher than potato and sugar beet (6.5% to 6.7%), which were in turn significantly higher than wide-row bean (3.6%). Inclusion of a fall rye (*Secale cereale* L.) cover crop after potato or dry bean increased residue cover close to or more than 30%, the threshold required to reduce wind erosion risk. Long-term replacement of cereals with lower residue-producing crops (e.g., potato, dry bean, and sugar beet) on irrigated rotations in southern Alberta should be considered judiciously in light of potential negative effects on surface residue cover.

Key words: crop residue—erosion—irrigated land—rotations—soil cover

Crop residue management is an integral part of conservation tillage systems (Larney et al. 1994) and widely viewed as a key building block for agricultural sustainability (Delgado 2010). Interest in crop residues has primarily been due to their ability to provide surface cover and reduce soil erosion risk by water (Nearing et al. 1989) and wind (Fryrear 1995). Maintaining crop residue cover on the soil surface also reduces exchanges of water, energy, and greenhouse gases with the atmosphere and increases soil organic matter, thereby enhancing a wide range of soil properties (Lobb et al. 2007). Soil or land cover is promoted by the Organization for Economic Cooperation and Development (OECD) as a temporal indicator to assess the environmental performance of agriculture (OECD 2008). Recently, a soil cover days (SCD) indicator model was developed in Canada to monitor the relationship between agricultural production and agri-environmental quality (Huffman et al. 2015). The SCD indicator integrates information on crops, soils, climate, and field activities to estimate the number of days that agricultural soils are covered by crop canopy, crop residue, or snow in a given year.

During the growing season, cover on Canadian cropland is determined by crop residue in the early period until such time as the plant canopy increases sufficiently (Huffman et al. 2012). In the nongrowing season, soil surface cover is influenced by crop residue management postharvest, the presence or absence of a fall-seeded cover crop, and duration of snow cover. Therefore, crop residue is the major provider of soil cover for most of the year. Crop type determines the density of plants, the growth rate, and the amount of biomass produced, and therefore has a major effect on the amount of soil cover (Huffman et al. 2012). Perennial crops, such as hay and pasture, offer almost complete soil cover year-round, while annual row crops tend to leave the soil exposed after planting or fall tillage. Crops such as dry bean (*Phaseolus vulgaris* L.), pea (*Pisum sativum* L.), canola (*Brassica* spp.), and potato (*Solanum tuberosum* L.) tend to have shorter periods of full crop canopy and leave less residue on the soil surface after harvest. Additionally, potato vines are chemically desiccated prior to harvest. The harvest operation for root crops (potato and sugar beet [*Beta vulgaris* L.]) creates a high degree of soil disturbance, which can bury what little residue is produced (Bolinder et al. 2015). Residue management at harvest (e.g., whether cereal straw is chopped and spread on the soil surface as it leaves the combine or baled and removed) also has significant implications for soil cover (Blanco-Canqui and Lal 2009). Additionally, tillage intensity plays a role. As a rule of thumb, conservation tillage leaves >30% of the soil surface covered in crop residue, reduced tillage leaves 15% to 20%, and conventional tillage leaves <15% residue cover (CTIC 2016).

However, as the adoption of conservation tillage has peaked on the Canadian prairies, Huffman et al. (2012) suggested that future soil cover may decline if cropping changes continue (i.e., a decreased area of cereals and concomitant high residue production, and increased area of low residue-producing oilseeds and pulses, coupled with residue harvest for biofuels). There is also the uncertainty of climate change and its potential impact on

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crop productivity and the negative feedback loop to crop/residue cover.

Cover crops have been used in agriculture as far back as Roman times (Dunn et al. 2016), but were largely abandoned in the 1940s and 1950s with advancements in synthetic fertilizers. Although there has been renewed interest since the early 1990s, the total area planted to cover crops in the United States remains <5% of row-crop land (USDA 2014). Nonetheless, cover crops play an increased role in sustainable cropping systems, environmental protection, and ecosystem services (Delgado et al. 2007; Blanco-Canqui et al. 2015). They provide surface cover during the vulnerable wind erosion period, which on irrigated land in southern Alberta can extend from potato harvest (mid-September) to dry bean seeding some eight months later (mid-May). They also act as a source of soil fertility, suppress weeds and pests (Moyer and Blackshaw 2009), and scavenge soil nitrate-nitrogen (NO_3^--N) remaining after harvest, reducing its leaching risk (Weinert et al. 2002; Stark and Porter 2005). Since irrigation reduces competition for water between a cover crop and its follow-up main crop, Snapp et al. (2005) indicated significant niches within irrigated cropping systems where cover crops proved beneficial.

The irrigated land area in southern Alberta's irrigation districts continues to increase. Between 2000 and 2014 there was an 8.5% increase in irrigated land area from 527,000 to 572,000 ha (1,302,000 to 1,413,000 ac) (Alberta Agriculture and Forestry 2015). Specialty crops (mainly potato, dry bean, and sugar beet), grown under irrigation, provide diversification of the local agricultural economy in terms of value-added food processing. In 2014, specialty crops accounted for 18% of the irrigated land area, with cereals and forages at 32% each, and oilseeds at 14% (Alberta Agriculture and Forestry 2015). There is very little information on residue cover provided by typical irrigated row crops (potato, dry bean, and sugar beet) in southern Alberta. Although known to be low, residue amounts from these crops have not been compared to cereals. Moreover, the performance of fall-seeded cover crops (e.g., fall rye [*Secale cereale* L.]) in provision of increased surface cover has not been adequately quantified.

An expansion in area of specialty crops in the late 1990s prompted the establishment of a rotation study in 2000 with a focus on conservation management and maintenance of soil quality on irrigated land. The study ran for 12 years (2000 to 2011) and compared three- to six-year rotations under conventional (CONV) and conservation (CONS) management for potato, dry bean, sugar beet, and soft white spring wheat (*Triticum aestivum* L.). Oat (*Avena sativum* L.) and timothy (*Phleum pratense* L.) were included in the six-year rotation. The effects of rotation and soil management on potato (Larney et al. 2016b), dry bean (Larney et al. 2015), and sugar beet (Larney et al. 2016a) performance have been reported, while Li et al. (2015) found that adoption of CONS management enhanced soil quality attributes (e.g., total, fine and particulate organic matter carbon [C] and N, and aggregate stability).

The specific objective of this paper was to assess soil surface cover (measured in spring) attributed to residue from previous crops (potato, dry bean, sugar beet, and wheat) as well as a fall-seeded fall rye cover crop under CONV and CONS soil management, starting in the third year of the study (i.e., for 10 years [2002 to 2011]).

Materials and Methods

Experimental Design. The study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50°03′ N, 112°09′ W, elevation 781 m [2,562 ft]) on an Orthic Dark Brown Chernozemic soil (Soil Classification Working Group 1998). The 0 to 15 cm (0 to 6 in) depth was sandy loam texture (52% sand, 34% silt, and 14% clay). The 30-year (1971 to 2000) normal mean annual precipitation is 303 mm (11.9 in) and mean annual air temperature is 5.7°C (42°F).

Seven rotations were established in spring of 2000 (table 1): continuous wheat (1-CONT), two conventional rotations (three- and four-years in length: 3-CONV and 4-CONV), and four conservation rotations (three to six-years in length: 3-CONS, 4-CONS, 5-CONS, and 6-CONS). The 3-CONV and 3-CONS rotations had similar crop sequences (potato–dry bean–wheat) as had the 4-CONV and 4-CONS rotations (potato–wheat–sugar beet–dry bean). The longer rotations were only present under CONS management, as increased rotation length was not considered a CONV practice. The 5-CONS rotation included three row crop and two wheat phases (potato–wheat–sugar beet–wheat–dry bean), while 6-CONS was the only one to include a forage (potato–oat–timothy–timothy–sugar beet–dry bean). Four specific management practices were bundled in the CONS rotations: (1) no-till or reduced tillage where possible in the rotation; (2) fall-seeded cover crops (table 1); (3) composted cattle manure as a substitute for inorganic fertilizer (table 1); and (4) solid-seeded, narrow-row (19 to 23 cm [7.5 to 9 in]) dry bean. In contrast, the CONV rotations had conventional tillage, no cover crops, no compost addition, and wide-row (60 cm [23.6 in]) dry bean undercut at harvest.

Each phase of each rotation appeared in each year, resulting in 26 rotation phases: seven of wheat, six each of dry bean and potato, four of sugar beet, two of timothy, and one of oat (table 1). Rotation phases were in a randomized complete block design with four replicates for a total of 104 plots. Individual plot dimensions were 10.1 × 18.3 m (33 × 60 ft). Over the 12 years of the study (2000 to 2011), the shortest three-year rotations completed three full cycles and the longest six-year rotation completed two full cycles (table 1). Precipitation and air temperature were monitored throughout the study period at an automated weather station located ~300 m (328 yd) from the plots.

Harvest Management. Harvest details were outlined for potato (Larney et al. 2016b), dry bean (Larney et al. 2015), and sugar beet (Larney et al. 2016a). Briefly, from 2002 to 2011, wide-row dry bean (3- and 4-CONV) was undercut (average September 6) and allowed to mature in swaths before harvesting (average September 23) with a plot combine. Narrow-row dry bean (3-, 4-, 5-, and 6-CONS) was direct cut with a plot combine except in 2003, 2005, 2010, and 2011. Hand-harvesting was carried out in 2003 due to high weed populations and in 2005 due to wet soil conditions. In 2010 and 2011, narrow-row dry bean was undercut prior to combining in an effort to reduce harvest losses associated with direct cutting (Larney et al. 2015). The average harvest date for narrow-row dry bean was September 24 (undercutting in 2010 to 2011 excepted). After securing harvest samples, the remainder of dry bean plots was harvested with a plot combine and residue left on the soil surface.

For potato, average vine desiccation date was September 2 and average harvest date was September 13. Average sugar beet har-

Table 1
Outline of rotations over 12 years (2000 to 2011), Vauxhall, Alberta.

Rotation*	Crop sequence	No. rotation phases	No. rotation cycles†
1-CONT	Wheat	1	12
3-CONV	Potato–dry bean–wheat	3	4
4-CONV	Potato–wheat–sugar beet–dry bean	4	3
3-CONS	Potato‡–dry bean‡–wheat§	3	4
4-CONS	Potato‡–wheat–sugar beet–dry bean§	4	3
5-CONS	Potato‡–wheat–sugar beet§–wheat–dry bean§	5	2.4
6-CONS	Potato‡–oat/timothy–timothy–timothy–sugar beet–dry bean§	6	2

*Integer refers to length of rotation. CONT = continuous. CONV = conventional management. CONS = conservation management.

†No. rotation cycles = 12 (y) ÷ no. crop phases.

‡Fall-seeded cover crop entry point. See text for details.

§Feedlot manure compost entry point: see Larney et al. (2016b) for application rate details. Applied after harvest except 2003 (postponed to spring 2004 due to wet soil conditions).

vest date was September 30, with mechanical defoliation by a flail mower one to two days prior. After potato and sugar beet harvest samples were extracted, the balance of the plot area was harvested with the same equipment. The average wheat harvest date was September 11. After harvest strips were taken with a plot combine, a large combine, equipped with a straw chopper, harvested the balance of the wheat plots including the wheat straw swaths from the plot combine.

For the oat/timothy phase of 6-CONS, oat was harvested for silage at the milk to early-dough growth stage (average date was July 16) using a forage harvester. Timothy was no-tilled into oat stubble (average date was August 26) and allowed to grow for two years. First- and second-year timothy was harvested twice during the growing season (average first cut was July 5 and average second cut was September 21) and removed as hay.

Fall Tillage Management. Since residue cover is largely dictated by the previous crop species, the 26 rotation phases were grouped by previous crop (table 2) for ease of comparison of fall tillage management. A disk harrow was the main implement used on 17 of the 26 rotation phases (table 2). The disk harrow had four gangs of seven disks (51 cm [20 in] diameter, 18 cm [7 in] spacing), a working width of 3.2 m (10.5 ft), and was operated with two gangs in tandem at 10 cm (4 in) depth. The front gangs had notched disks while the rear gangs had smooth disks. A crazy harrow (2001) or diamond harrow (2002 to 2010) was always towed in tandem with the disk for extra leveling.

Of the 17 disked phases, 11 used one pass exclusively because apart from 1-CONT, which was wheat, all had either potato (3-, 4-, 5-, and 6-CONS), dry bean (3-CONV and 3-CONS), or sugar beet (4-CONV, 4-, 5-, and 6-CONS) as the previous crop (table 2). Phases with a fall-seeded cover crop entry point (after potato and dry bean on 3-CONS, and after potato on 4-, 5-, and 6-CONS; tables 1 and 2) were a subset of this group. Two other phases, with potato as the previous crop (3- and 4-CONV; table 2), differed only slightly from the larger group of 11 disked phases by receiving two disk passes in 2006 only. The remaining four phases where the disk was the main implement had wheat as the previous crop (4-CONV, 3-, 4-, and 5-CONS; table 2) and hence were worked more intensively for residue management. Wheat stubble was shredded with a flail mower (average date was September 26) and the number of disk passes increased to two in most years (three passes on 3-CONS in 2006). Also, other implements were used to augment tillage in some years (e.g., one pass of a Vibra Shank prior to sugar beet [fall 2001 and 2004] on 4-CONV, 4-CONS, and 5-CONS [table 2], or one pass of a chisel plow prior to potato on 3-CONS [table 2] in fall of 2001 to 2002 and 2004 to 2005). The timing of fall disking was dictated by harvest dates of the previous crops. Potato and dry bean were harvested earlier, and hence disked earlier in fall than wheat and sugar beet plots.

A moldboard plow (25 cm [10 in] depth) was used on 3 of the 26 phases (table 2) with an average date of October 5 ($n = 12$). These included potato following wheat on 3- and 4-CONV, augmented with one pass of a chisel plow (2001 to 2002 and 2004 to 2005) or one pass of a disk (2006 to 2010) for further leveling. In addition, moldboard plowing for sugar beet following timothy on 6-CONS commenced in fall of 2002 as wheat replaced second-year timothy (table 2) in 2001 (since timothy was not seeded in August of 1999 [i.e., prior to the start of the experiment] to enable a second year stand in 2001). Moldboard plowing was the only practical tillage option to prevent remnants of timothy sod from interfering with subsequent sugar beet planting in spring, and packers were towed behind the moldboard plow for extra leveling. In addition, this phase received one to three disk passes (all years), one pass of a Vibra Shank (2001 and 2004), or one pass of a chisel plow (2005).

A further three phases following dry bean (4-, 5-, and 6-CONS; table 2) employed a Dammer-Diker (AG Engineering and Development Co. Inc., Kennewick, Washington), a reservoir tillage implement, in preparation for potato in spring. Reservoir tillage uses paddles on a turning wheel, which create depressions (up to 25 cm [10 in] deep) on the soil surface (Hackwell et al. 1991) to trap water that might otherwise be lost to surface runoff, or snow that may be blown off by wind. One pass of the Dammer-Diker was sufficient in five years (2002 to 2003, 2005 to 2006, and 2010) while two passes were required in the other five years (2001, 2004, and 2007 to 2009). Since compost had to be hauled and applied to these phases prior to fall tillage, the average date of Dammer-Diker operations was later (November 4) than phases requiring disking or moldboard plowing.

Two of 26 phases were under no-till: where wheat stubble was shredded on 5-CONS in preparation for dry bean seeding, and where timothy was no-tilled into oat stubble on 6-CONS (table 2). The remaining phase of the study (the one-year old timothy stand on

Table 2
Fall tillage and management details (2001 to 2010) and average spring residue cover on all 26 rotation phases.

Previous crop	Rotation*	Fall tillage†	Tillage substitutions/remarks	Average residue cover contribution (%) Previous crop‡	Fall rye§	Total
Wheat	1-CONT	Disk		39.3b	0.0	39.3b
	3-CONV	Moldboard; +chisel (2001 to 2002, 2004 to 2005); +disk (2006 to 2010)		11.8def	0.0	11.8def
	4-CONV	Disk (×2, 2001 to 2006); +Vibra Shank (2001 to 2004)	Wheat stubble shredded	38.0b	0.0	38.0b
	3-CONS	Disk (×2, 2001 to 2004; 2007 to 2008; ×3, 2006); +chisel (2001 to 2002, 2004 to 2005)	Wheat stubble shredded; compost	26.5c	0.0	26.5c
	4-CONS	Disk (×2, 2001 to 2006); +Vibra Shank (2001 to 2004)	Wheat stubble shredded	33.6bc	0.0	33.6bc
	5-CONS	Disk (×2, 2001 to 2006); +Vibra Shank (2001 to 2004)	Wheat stubble shredded	36.1bc	0.0	36.1bc
	5-CONS	No-till	Wheat stubble shredded	85.2a	0.0	85.2a
Potato	3-CONV	Disk (×2, 2006)	HD cultivator (2001); spike (2005)	4.4ij	0.0	4.4ij
	4-CONV	Disk (×2, 2006)	HD cultivator (2001); spike (2005)	4.2j	0.0	4.2j
	3-CONS	Disk	Spike (2005); fall rye cover crop	8.7efgh	48.9a	57.6b
	4-CONS	Disk	Spike (2005); oat/fall rye cover crop	8.1fgh	20.7bc	28.8cd
	5-CONS	Disk	Spike (2005); oat/fall rye cover crop	7.5gh	22.6b	30.1cd
	6-CONS	Disk	Spike (2005); oat/fall rye cover crop	7.5gh	21.5bc	29.0cd
Dry bean	3-CONV	Disk	HD cultivator (2001)	7.2gh	0.0	7.2gh
	4-CONV	Moldboard; +chisel (2001 to 2002, 2004 to 2005); +disk (2006 to 2010)		1.6k	0.0	1.6k
	3-CONS	Disk	Oat/fall rye cover crop	12.9d	15.3c	28.2cd
	4-CONS	Dammer Diker (×2, 2001, 2004, 2007 to 2009)	Disk (2003); compost	8.3efgh	0.0	8.3efgh
	5-CONS	Dammer Diker (×2, 2001, 2004, 2007 to 2009)	Disk (2003); compost	10.2defg	0.0	10.2defg
	6-CONS	Dammer Diker (×2, 2001, 2004, 2007 to 2009)	Disk (2003); compost	8.1fgh	0.0	8.1fgh
Sugar beet	4-CONV	Disk	HD cultivator (2001)	6.3hi	0.0	6.3hi
	4-CONS	Disk	HD cultivator (2001)	7.0gh	0.0	7.0gh
	5-CONS	Disk	Chisel (2001 to 2002, 2004); spike (2005); compost	6.1hij	0.0	6.1hij
	6-CONS	Disk	HD cultivator (2001)	7.3gh	0.0	7.3gh
Oat/timothy	6-CONS	No-till		75.9a	0.0	75.9a
Timothy	6-CONS	Not applicable	First-year timothy	100.0a	0.0	100.0a
	6-CONS	Moldboard; +disk (×2, 2002 to 2005; ×3, 2006; ×1, 2007 to 2010); +Vibra Shank (2004); +chisel (2005)	Second-year timothy; moldboard included packers; disk (×2 , 2001)	12.0de	0.0	12.0de

Notes: HD = heavy-duty. Within columns means with different letters are significantly different from each other (LSD, p <0.05).

*Integer refers to length of rotation (y). CONT = continuous. CONV = conventional management. CONS = conservation management.

†Tillage consisted of one pass of each implement unless otherwise indicated (×2 = two times; ×3 = three times). Disk included a tandem-towed crazy harrow (2001) or diamond harrow (2002 to 2010). Chisel plow and Vibra Shank included tandom-towed packers for extra leveling.

‡Average of 10 years (2002 to 2011).

§Average of eight years (2004 to 2011).

6-CONS; table 2) was the only one where fall tillage was not applicable.

Tillage substitutions (table 2) during the study included a heavy-duty (HD) cultivator, which replaced a disk on six phases in fall of 2001, a disk that replaced the Dammer Diker on three phases in fall of 2003 when soil conditions were too wet, and a spike cultivator that replaced a disk on seven phases in 2005 (table 2), when soil conditions were too dry. Also following sugar beet on 5-CONS, a chisel-plow, instead of a disk, was used in early years (2001, 2002, and 2004) to incorporate compost. Since residue measurements were taken prior to spring field operations, spring tillage information is not provided here. Larney et al. (2015, 2016a, 2016b) and Li et al. (2015) may be consulted for spring tillage details. In general, CONS rotations had reduced tillage options in spring compared with CONV rotations.

Residue Cover Measurements. Residue cover was not measured in the initial two years (2000 to 2001), during establishment of the study. Starting in spring of 2002, measurements were taken annually before any field work using the line-transect or "rope" method (Laflen et al. 1981). This method is a quick and reliable way to estimate residue cover lying flat on the soil surface and randomly distributed and is preferred for field use (Wollenhaupt and Pingry 1991). The earliest measurement date was March 23 and the latest was April 27 with a mean (n = 10) of April 12 (table 3). The average time span between fall tillage operations (table 2) and residue cover measurement (table 3) was ~6.5 to 7 months for disked, 6 months for moldboard plowed, and 5.5 months for Dammer-Diker phases.

A residue rope was made by making 25 marks at equidistant (15 cm [6 in]) intervals on a length of rope (Wollenhaupt and Pingry 1991), and residue levels on each plot were estimated as follows:

1. A measurement area was randomly chosen by throwing the rope 1 to 2 m (3 to 6 ft) away and sampling where it fell after stretching the rope out.
2. Walking beside the rope and looking straight down, the number of rope marks directly intersecting a piece of crop residue (≥10 cm [4 in] long) was counted. Live or dead weeds or fall rye cover crops were not counted as crop residue.
3. Steps one and two were repeated at three more locations in each plot.
4. The total number of rope marks out of 100 (25 rope marks × 4 locations) intersected by residue represented the percentage residue cover.

Table 3

Residue cover measurement dates (2002 to 2011), and precipitation and air temperature between previous October 1 and measurement date.

Year	Residue cover measurement date	Precipitation (mm)	Mean daily air temperature (°C) Maximum (date)	Minimum (date)	Average
2002	Apr. 12	90	13.7 (Nov. 4)	−28.5 (Mar. 8)	−3.0
2003	Apr. 25	128	14.7 (Apr. 22)	−27.3 (Mar. 9)	−1.2
2004	Apr. 12	96	21.4 (Oct. 21)	−29.5 (Jan. 27)	−1.7
2005	Apr. 11	89	16.2 (Oct. 6)	−29.9 (Jan. 14)	−0.7
2006	Apr. 10	108	14.1 (Oct. 15)	−23.2 (Feb. 16)	0.3
2007	Mar. 23	86	15.4 (Mar. 12)	−24.9 (Nov. 28)	−1.5
2008	Mar. 26	39	17.2 (Oct. 24)	−30.3 (Jan. 29)	−2.3
2009	Apr. 15	131	16.0 (Oct. 3)	−28.7 (Dec. 14)	−3.0
2010	Apr. 22	168	17.2 (Oct. 17)	−27.1 (Dec. 13)	−1.9
2011	Apr. 27	147	17.5 (Oct. 12)	−29.1 (Jan. 31)	−3.7
Average	Apr. 12	108	16.3	−27.9	−1.9

Cover Crops. Initially two fall-seeded cover crops were used: (1) oat to provide fall cover and then winterkill so as to minimize seeding problems in spring, and (2) fall rye, which did not winterkill and regrew in spring, thereby providing protection from wind erosion in both fall and spring (Moyer and Blackshaw 2009).

Cover crops were used at five entry points in CONS rotations only (tables 1 and 2): twice in 3-CONS (between potato–dry bean and dry bean–wheat), once each in 4- and 5-CONS (between potato–wheat), and once in 6-CONS (between potato–oat). Fall rye was used in 3-CONS (between potato–dry bean) from the beginning of the study. The remaining four cover crop entry points used oat in fall of 2001 to 2002. However, oat establishment was suboptimal, providing low to nonexistent cover, and the oat cover crop was dropped from the study. Fall rye was used at all five entry points starting in fall of 2003 (table 1).

Fall rye (cv. AC Remington) was seeded at a rate of 84 kg ha^{-1} (1.34 bu ac^{-1}) at 19 cm (7.5 in) row spacing. Seeding date (table 4) for four of the five entry points, where potato was the previous crop (table 4), ranged from September 3 (2004) to October 13 (2010) with an average date of September 25. At the remaining entry point (3-CONS, between dry bean–wheat), fall rye seeding was delayed in three years by 16 to 28 days due to later dry bean harvest (table 4), compared to potato for the other entry points.

In spring, fall rye was sampled (6 × 0.25 m^2 [2.7 ft^2] plot^{-1}) between April 12 and May 13 (average April 25) on four of the five phases (table 4), the exception being 3-CONS (between potato−dry bean) where it was allowed to grow, on average, 16 days longer (May 11) due to later seeding of dry bean compared to wheat on the other phases. Fall rye biomass yield was determined after oven drying at 60°C (140°F) for five days.

The contribution of fall rye biomass to surface cover was predicted from equation 1 developed by Gregory (1982) and used by Steiner et al. (2000) and van Donk et al. (2008):

$$C_f = 100(1 - \exp^{-bMf}), \tag{1}$$

where C_f is flat residue cover (%); b is the mass-to-cover factor (m^2 kg^{-1}), which is a crop-specific coefficient; and Mf is the flat residue mass (kg m^2). We used a wheat b coefficient of 6.5 m^2 kg^{-1} (31.7 ft^2 lb^{-1}) (van Donk et al. 2008) since none is available for fall rye. Also, equation 1 was developed for nonliving flat residue and, as such, may underestimate the contribution of living standing fall rye biomass. For wind erosion control, although standing crop residue elements provide less cover than flat elements, they reduce the friction velocity of wind at the soil surface, strongly influencing the degree of erosion control achieved (Bilbro and Fryrear 1994).

Daily growing degree days (GDD) for fall rye were estimated from daily mean air temperature (base temperature 4°C [39°F]; Brennan and Boyd 2012) and summed for the following periods: (1) seeding date (table 4) to December 31, (2) January 1 to bio-

Table 4

Fall rye seeding date, biomass sampling date, growing period, and biomass yield, 2001 to 2011. Biomass yield is indicated for various fall rye entry points (between previous crop and next crop) in each rotation.

				Biomass yield (kg ha^{-1}) (dry weight)				
Year	Seeding date*	Biomass sampling date†	Growing period (d)‡	3-CONS Potato–dry bean	3-CONS Dry bean–wheat	4-CONS Potato–wheat	5-CONS Potato–wheat	6-CONS Potato–oat
2001 to 2002	Sept. 24	(May 14)	(231)	669	–§	–	–	–
2002 to 2003	Oct. 10	(May 20)	(221)	1,105	–	–	–	–
2003 to 2004	Oct. 3	Apr. 15 (May 4)	194 (213)	130a	32b	39b	35b	29b
2004 to 2005	Sept. 3 [Sept. 22]	Apr. 19 (May 2)	227 [208] (240)	1,940a	729c	806bc	1,108b	1,029bc
2005 to 2006	Sept. 9 [Oct. 7]	Apr. 24 (May 8)	226 [198] (240)	2,043a	282b	477b	299b	407b
2006 to 2007	Sept. 29	Apr. 23 (May 15)	205 (227)	1,573a	171b	143b	144b	159b
2007 to 2008	Sept. 20	Apr. 12 (May 12)	204 (234)	1,413a	307b	304b	321b	284b
2008 to 2009	Sept. 29 [Oct. 15]	May 5 (May 14)	217 [201] (226)	1,476a	386c	1,049ab	921b	780bc
2009 to 2010	Sept. 28	May 13 (May 19)	226 (232)	754a	318c	419ab	426bc	477b
2010 to 2011	Oct. 13	May 4 (May 17)	202 (215)	604a	53b	180b	172b	127b
Average#	Sept. 25	Apr. 25 (May 11)	211 (227)	1,204	269	394	447	411

Notes: 3-CONS = conservation management, three-year rotation. 4-CONS = conservation management, four-year rotation. 5-CONS = conservation management, five-year rotation. 6-CONS = conservation management, six-year rotation. Within rows means with different letters are significantly different from each other (LSD, $p < 0.05$).

*Later seeding date in brackets is 3-CONS (between dry bean–wheat) due to delayed dry bean harvest (compared to potato harvest for other entry points) in those years.

†Later biomass sampling date in parentheses is 3-CONS (between potato–dry bean) as fall rye allowed to grow longer due to later seeding of dry bean in spring (vs. wheat for other entry points).

‡Shorter growing period in brackets is 3-CONS (between dry bean–wheat) due to later seeding in fall. Longer growing period in parentheses is 3-CONS (between potato–dry bean) due to later biomass sampling in spring.

§Oat cover crop (winterkilled, not sampled for biomass in spring).

#n = 10 (2001 to 2010) for seeding date; n = 8 (2004 to 2011) for biomass sampling date, growing period, and biomass yield.

mass sampling date in spring (table 4), and (3) seeding date to biomass sampling date in spring (table 4).

Statistical Analyses. Residue data were tested for outliers and normality (PROC UNIVARIATE; SAS Institute Inc. 2010) prior to analysis. This indicated that data did not conform to a normal distribution, and they were therefore $\log_e(1 + x)$-transformed and analyzed by year using PROC MIXED with rotation (n = 7; 1-CONT, 3-CONV, 3-CONS, 4-CONV, 4-CONS, 5-CONS, and 6-CONS) as a variable. Orthogonal contrasts compared management effects: CONV (mean, 3-, and 4-CONV rotations) versus CONS (mean, 3-, 4-, 5-, and 6-CONS rotations). Analysis was also conducted by year with previous crop as a variable (n = 8; wheat, potato, wide-row dry bean, narrow-row dry bean, sugar beet, oat/timothy, first-year timothy, and second-year timothy). The least significant difference (LSD) test (α = 0.05) was used to separate means for the rotation and previous crop analyses. Analysis by rotation and previous crop was also performed on residue data averaged over all years (2002 to 2011, n = 10). Ten-year average residue data were also analyzed with rotation phase (n = 26, table 2) as a variable with a Tukey-Kramer adjustment (α = 0.05) for means separation. Fall rye biomass yield was analyzed by year (PROC MIXED), with rotation entry point (n = 5) as a variable.

Results and Discussion

Weather Conditions. October 1 was chosen as a starting date for precipitation and air temperature parameters because all applications of irrigation water were completed by that date across all years, the latest irrigation being September 28, 2007, to facilitate sugar beet harvest due to dry soil conditions. Cumulative precipitation (mostly as snow) from October 1 to residue measurement in spring varied from 39 mm (1.5 in) in 2008 to 2009 to 168 mm (6.6 in) in 2010 to 2011, with a mean (n = 10) of 108 mm (4.3 in) (table 3). The maximum mean daily air temperature between October 1 and spring residue cover measurement ranged from 13.7°C (57°F) in 2002 to 21.4°C (71°F) in 2004 with a mean (n = 10) of 16.3°C (61°F) (table 3). The maximum temperature occurred in October in 7 of 10 years. The minimum mean daily temperature ranged from –23.2°C (–10°F) in 2006 to –30.3°C (–23°F) in 2008 (table 3) with a mean of –27.9°C (–18°F), and occurred in any month from November to March. The warmest overwinter period was 2005 to 2006 (0.3°C [33°F]) and the coldest was 2010 to 2011 (–3.7°C [25°F]) with a mean (n = 10) of –1.9°C (29°F).

Residue Cover. When residue cover was analyzed with rotation as a variable, this compared average residue cover across all crops in a rotation (e.g., the 3-CONS rotation was the average cover of potato, dry bean, and wheat). The rotation effect was significant in 9 of 10 years, the exception being 2011 (table 5). The 1-CONT rotation (continuous wheat) had significantly higher residue cover than at least two (3- and 4-CONV in 2008 and 2009) and up to all six other rotations (2004). However, significant differences among the CONS rotations only occurred in four of nine years where rotation was significant. In 2003, 6-CONS was significantly lower (6%) than 5-CONS (12.7%) because two phases of 6-CONS, with normally higher residue cover (oat, and first-year timothy; table 1), were not measured in 2003 and therefore not included in the overall 6-CONS rotation value. In 2005, 2006, and 2007, significant effects were attributed to the 6-CONS rotation, which was significantly higher than 4-CONS in 2005 (8.7% versus 3.8%) and 2006 (15.1% versus 7.1%), and both 3- and 4-CONS in 2007 (19% versus 6.4% to 7.7%), likely due to the presence of second-year timothy.

Comparing the twin rotations where the same crop sequences were managed under CONV versus CONS practices (i.e., 3-CONV versus 3-CONS and 4-CONV versus 4-CONS), there were only two years when 3-CONS showed significantly higher residue cover than 3-CONV (2006: 11.5% versus 3.9% and 2008: 21.6% versus 4.9%) and one year where 4-CONS was significantly higher than 4-CONV (2008: 19.7% versus 8.2%).

When the rotations were averaged across all 10 years (table 5), there was no significant difference in residue cover among continuous wheat (1-CONT: 39.6%), 6-CONS (19.1%), 5-CONS (17.5%), or 3-CONS (14.5%). However, both CONV rotations (6.9% to 7.3%) were significantly lower than 5- and 6-CONS and 1-CONT. There were no significant differences in average residue cover among the four CONS rotations or between the two CONV rotations (table 5). Also, differences among averages of the twin rotations—3-CONV (7.3%) versus 3-CONS (14.5%) and 4-CONV (6.9%) versus 4-CONS (11.4%)—were nonsignificant.

When rotations were grouped by management, however, (CONV: average of 3- and 4-CONV; CONS: average of 3-, 4-, 5-, and 6-CONS) the management contrast was significant in 8 of 10 years, the exceptions being 2003 and 2011 (table 5). In all cases, residue cover on CONS rotations was significantly higher than on CONV rotations. The largest overall difference was in 2008 (CONS: 23.3% and CONV: 6.6%). Averaged over 10 years, the management contrast showed significantly higher residue cover with CONS (15.6%) versus CONV (7.1%) management (table 5).

Since residue cover is largely influenced by crop species, it was also analyzed by previous crop, averaged over all rotations where that crop appeared (table 5). For the four main crops, residue cover was significantly higher after wheat (11.1% to 53.6%) than after potato, dry bean, or sugar beet (1% to 14.3%) in all 10 years. When averaged over 10 years, wheat was significantly higher (33.7%) than potato, wide or narrow-row dry bean, or sugar beet (3.6% to 9.7%).

Comparing potato and sugar beet as previous crops (all had disking as fall tillage; table 2), there was no significant difference in residue cover in five years, while sugar beet > potato in three years (average 7.1% versus 3.2%; 2007, 2009, and 2010), and potato > sugar beet in two years (average 5.1% versus 2.8%; 2005 and 2011). This led to no significant difference between potato (6.5%) and sugar beet (6.7%) when averaged over 10 years. Narrow-row dry bean (table 5) had significantly higher residue cover (4.6% to 17.3%) than wide-row (1% to 5.3%) in 9 of 10 years (2011 excepted), and this was also true of 10-year average values (9.7% versus 3.6%).

Residue cover was highest (~100%) with first-year timothy as a previous crop (table 5), which was expected as this was a mature stand seeded ~19 months earlier. The second highest cover occurred with oat/timothy as a previous crop, ranging from 27% to 100%, with a 10-year mean of 75.9%—not significantly different from first-year timothy, except in 2011 (table 5). With second-year timothy as the previous crop (table 5), the 10-year average residue cover was significantly lower (12%) than wheat (33.7%) due to moldboard plowing prior to sugar beet (table 2). However, second-year timothy was significantly higher than potato (6.5%), sugar beet (6.7%), and wide-row dry bean (3.6%), and similar to narrow row dry bean (9.7%).

Ten-year average residue cover was also analyzed by rotation phase (n = 26) and grouped by previous crop (table 2). With wheat as a previous crop, significantly higher residue cover (85.2%) was measured on 5-CONS (wheat–dry bean segment) where wheat stubble was shredded in fall in preparation for no-till narrow-row dry bean in spring (tables 1 and 2). Wheat residue cover on 1-CONT, 4-CONV, 4-CONS, and 5-CONS (wheat–sugar beet segment) was lower (33.6% to 39.3%), but these were not significantly different from each other (table 2), even though 4-CONV and 4- and 5-CONS were disked twice (2001 to 2006) and received one pass of a Vibra Shank in 2001 and 2004, compared to 1-CONT, which was disked once. However, wheat residue on 3-CONS (26.5%) was significantly lower (table 2) than 1-CONT (39.3%) and 4-CONV (38%), since it received two passes of a disk in more years and three passes in 2006, as well as chisel plowing in four years (table 2). The lowest residue cover after wheat was on 3-CONV (11.8%; table 2) where moldboard plowing and chisel plowing or disking occurred ahead of the potato crop (table 2).

For potato as the previous crop, there was no significant difference in residue cover (7.5% to 8.7%) among the four CONS rotations, which received one pass of a disk. However, the two CONV rotations, which differed only in receiving an extra disk pass in 2006 (table 2), were significantly lower (4.2% to 4.4%; table 2). For wide-row dry bean as the previous crop, 3-CONV, which was disked once, was significantly higher (7.2%) than 4-CONV (1.6%, the lowest residue cover and significantly so compared with all other 25 phases), which was moldboard plowed and chisel plowed or disked (table 2). For narrow-row dry bean as the previous crop, 3-CONS (12.9%) was significantly higher than 4- and 6-CONS (8.1% to 8.3%) as the latter received a Dammer Diker instead of a disk (table 2). However, 5-CONS (10.2%), which also received a Dammer Diker, was not significantly different than 3-CONS (12.9%). The three rotations (4-, 5-, and 6-CONS) that received a Dammer Diker after narrow-row dry bean (in preparation for potato) were not significantly different from each other (8.1% to 10.2%; table 2) or 3-CONV (after wide-row dry bean, disked, 7.2%). For sugar beet as the previous crop, residue cover was unaffected by rotation (6.1% to 7.3%; table 2) as all four were managed with one disk pass in fall.

Residue levels for oat/timothy, first-year, and second-year timothy as previous crops in 6-CONS were discussed above, except to mention that first-year timothy (100%) and oat/timothy (75.9%) were not significantly different than wheat as previous crop on 5-CONS (85.2%) where wheat stubble was shredded in fall prior to no-till narrow-row dry bean.

Comparing across previous crops where fall tillage was managed similarly, there was a series of nine rotation phases (potato on 3-, 4-, 5-, and 6-CONS; sugar beet on 4-CONV and 4-, 5-, and 6-CONS; and wide-row dry bean on 3-CONV), which were all disked once. None was significantly different from another, ranging from 6.1% to 8.7% in average residue cover. Moldboard plowing, followed by chisel plowing or disking (table 2), was common to wheat (3-CONV), dry

Table 5
Effect of rotation, soil management, and previous crop on surface residue cover, 2002 to 2011.

Treatment	Residue cover (%) 2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Average
Rotation											
1-CONT	70.1a	24.1a	39.5a	18.6a	16.7ab	28.4a	44.6a	43.2a	57.8a	40.3a	39.3a
3-CONV	10.3cd	6.5c	2.6c	3.3bc	3.9c	3.6c	4.9b	10.1bc	4.7c	15.8a	7.3cd
3-CONS	22.9abc	11.6abc	6.2bc	5.4abc	11.5ab	6.4bc	21.6a	14.1abc	13.8bc	18.1a	14.5abc
4-CONV	8.2d	8.0bc	3.0c	3.1c	3.1c	4.4c	8.2b	5.6c	6.3c	13.8a	6.9d
4-CONS	16.0bcd	10.1abc	6.3bc	3.8bc	7.1bc	7.7bc	19.7a	11.9abc	8.8bc	9.9a	11.4bcd
5-CONS	25.5ab	12.7ab	7.7b	7.2ab	10.2ab	14.2ab	27.5a	17.4ab	16.7ab	17.7a	17.5ab
6-CONS	22.7b	6.0c	10.8b	8.7a	15.1a	19.0a	24.6a	18.6ab	17.1ab	17.2a	19.1ab
p-value	0.002	0.03	0.002	0.02	<0.001	<0.001	<0.001	0.04	0.005	0.55	0.001
Management*											
CONV	9.3b	7.3a	2.8b	3.2b	3.5b	4.0b	6.6b	7.8b	5.5b	14.8a	7.1b
CONS	21.8a	10.1a	7.7a	6.3a	11.0a	11.8a	23.3a	15.5a	14.1a	15.7a	15.6a
p-value	<0.001	0.14	0.002	0.03	<0.001	<0.001	<0.001	0.02	0.003	0.91	<0.001
Previous crop											
Wheat	39.1b	19.1a	14.6b	11.1b	14.3b	24.7b	36.8b	53.8b	43.4b	53.6b	33.7b
Potato	10.6cd	6.6b	3.8cd	4.0c	6.5cd	3.4d	11.8c	3.8e	2.5d	6.1e	6.5d
Dry bean wide	5.3a	4.9b	1.4a	1.8d	1.0e	1.2e	2.7d	2.5e	3.3d	9.0de	3.6e
Dry bean narrow	17.3c	14.9a	5.3c	4.6c	4.7d	5.5c	12.6c	7.7d	8.2c	11.5d	9.7c
Sugar beet	7.2de	5.5b	2.3de	1.6d	4.1d	6.3c	14.3c	6.3d	8.7c	4.0f	6.7d
Oat/timothy	100.0a	—	100.0a	90.6a	92.6a	76.2a	48.8ab	59.7ab	80.0ab	27.0c	75.9a
First-year timothy	100.0a	—	100.0a	100.0a	100.0a	100.0a	99.7a	100.0a	100.0a	100.0a	100.0a
Second-year timothy	—	1.5c	1.3de	2.7cd	10.9bc	19.1b	11.6c	28.2c	9.6c	20.7c	12.0c
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Within columns means followed by different letters are significantly different from each other (LSD, $p < 0.05$).
*Management contrast: CONV (average of 3- and 4-CONV); CONS (average of 3-, 4-, 5-, and 6-CONS).

bean (4-CONV), and second-year timothy (6-CONS) as previous crops. While wheat and timothy were not significantly different from each other (11.8% to 12%), they were both significantly higher than dry bean (1.6%).

Cover Crop Biomass. In the eight years (2004 to 2011) with five fall rye entry points, average biomass yield ranged from 53 kg ha^{-1} (47 lb ac^{-1}) in 2004 to 1,122 kg ha^{-1} (1,002 lb ac^{-1}) in 2005 (table 4). The highest yield of the study (2,043 kg ha^{-1} [1,824 lb ac^{-1}]) occurred on 3-CONS (between potato–dry bean) in spring of 2006 (table 4), which was associated with the longest growing period (240 days). The average growing period was 211 days, except for 3-CONS (between potato–dry bean), which was allowed to grow longer in spring due to later seeding of dry bean, averaging 227 days (table 4). This longer growing period (16 days on average) led to significantly higher biomass yields (table 4) than the other four entry points in six of eight years (2004 to 2008 and 2011).

There were three years (2004 to 2005, 2005 to 2006, and 2008 to 2009) when fall rye seeding date on 3-CONS (between dry bean–wheat) was 16 to 28 days later than the other four entry points (table 4). This led to significantly lower biomass yield than 5-CONS (729 versus 1,108 kg ha^{-1} [651 versus 989 lb ac^{-1}]) in 2004 to 2005, and 4- and 5-CONS (386 versus 921 to 1,049 kg ha^{-1} [345 versus 822 to 937 lb ac^{-1}]) in 2008 to 2009. In five years (2003 to 2004, 2006 to 2007, 2007 to 2008, 2009 to 2010, and 2010 to 2011; table 4), growing period durations for fall rye were consistent across four entry points: 3-CONS (between dry bean–wheat) and 4-, 5-, and 6-CONS (where fall rye followed wheat). This allowed an assessment of whether dry bean provided a residual N benefit to fall rye, compared to a nonlegume. However, average biomass yield after dry bean (176 kg ha^{-1} [157 lb ac^{-1}]) was lower than after potato (217 kg ha^{-1} [194 lb ac^{-1}]), showing no apparent residual N benefit.

The average biomass yield (n = 10) on 3-CONS (between potato–dry bean) was 1,204 kg ha^{-1} (1,075 lb ac^{-1}), which was substantially higher than the other entry points due to later sampling in spring. The 3-CONS (between dry bean–wheat, which included three years with later seeding dates) had the lowest average yield (n = 8) at 269 kg ha^{-1} (240 lb ac^{-1}), while average yields (n = 8) for the remaining entry points were 394 to 447 kg ha^{-1} (352 to 399 lb ac^{-1}).

The GDD between fall seeding and December 31 showed the weakest relationship with fall rye biomass ($R^2 = 0.17, p = 0.06$; figure 1a). However, there was a trend of good establishment in fall, which was dependent on cumulative GDD between seeding and winter dormancy, leading to higher biomass yield the following spring. The relationship between GDD from January 1 to biomass sampling date was stronger ($R^2 = 0.35, p = 0.005$; figure 1b), showing that cumulative GDD after winter dormancy provided a greater contribution toward final yield. Also, the rate of dry matter (DM) accumulation was much faster (5.3 versus 1.6 kg ha^{-1} [4.7 versus 1.4 lb ac^{-1}] GDD^{-1}). The relationship between GDD and biomass yield for the total period between seeding and spring sampling (figure 1c) was significant (R^2

= 0.33, p = 0.006), with a DM accumulation rate of 2 kg ha^{-1} (1.8 lb ac^{-1}) GDD^{-1}.

The contribution of fall rye biomass to surface cover, as estimated by equation 1, was most evident (48.9%) on 3-CONS (between potato–dry bean; table 2), where the cover crop was allowed to grow an average of 16 days longer. This increased residue cover from 8.7%, where potato was the previous crop, to 57.6%, which was not significantly different than 1-CONT, 4-CONV, 4-, and 5-CONS, or significantly higher than 3-CONV and 3-CONS, where wheat was the previous crop (table 2). The contribution of fall rye to total residue cover was less (15.3% to 22.6%) on 3-CONS (between dry bean–wheat), and 4-, 5-, and 6-CONS (table 2) due to shorter growing periods, and hence less cumulative GDD. However, fall rye contributions increased total cover (previous crop + fall rye) to 28.2% to 30.1% (table 2), or significantly higher than all other phases without a cover crop where potato, sugar beet, or dry bean was a previous crop, and not significantly different than where wheat was the previous crop on 4- or 5-CONS (wheat–sugar beet segment).

Discussion and Implications. Bare soils with a low proportion of nonerodible aggregates on the soil surface are the most prone to wind erosion (Larney et al. 1997). As soil cover increases, topsoil losses due to wind erosion decrease exponentially (Lyon and Smith 2010) (e.g., soil cover as low as 10% can reduce soil loss to 65% of that of bare soil, while cover of 30% reduces soil loss to 30% of bare soil). At 80% soil cover, soil loss is reduced to only 4% of that on bare soil. In the soil erosion literature, a general rule of thumb is that more than 30% residue cover is required to control wind and water erosion (Blanco-Canqui et al. 2016; Unger 2006). Moreover, more than 30% residue cover remaining on the soil surface is also a criterion for conservation tillage (CTIC 2016; Shelton et al. 1995).

Our residue cover measurements clearly showed the benefits of a cereal in irrigated rotations in terms of maintaining residue cover over 30%, the critical threshold to reduce erosion risk. With wheat as the previous crop, residue cover averaged 33.7% compared to 9.7% with narrow row dry bean, 6.7% with sugar beet, 6.5% with potato, and only 3.6% for wide-row dry bean. Merrill et al. (2006) reported spring residue cover (line-transect method) following different no-till crops in North Dakota. Soil cover ranged from 89% to 98% following crop sequences that included spring wheat and barley (*Hordeum vulgare* L.). Soil cover values were intermediate for spring wheat–alternative crop (sunflower [*Helianthus annuus* L.], pea, and dry bean) sequences, at 62% to 97%. Soil cover values were lowest after two consecutive years of broadleaf crops (pea–sunflower [40%]), or two years of dry bean (46%), safflower (*Carthamus tinctorus* L.; 44%), or sunflower (35%). Although our study was not no-till, the advantage of including a cereal in terms of increased surface cover was similarly evident. Indeed residue cover (85%) after wheat on 5-CONS, which was maintained under no-till for the following dry bean crop (tables 1 and 2), compared favorably with values for spring wheat and barley (Merrill et al. 2006).

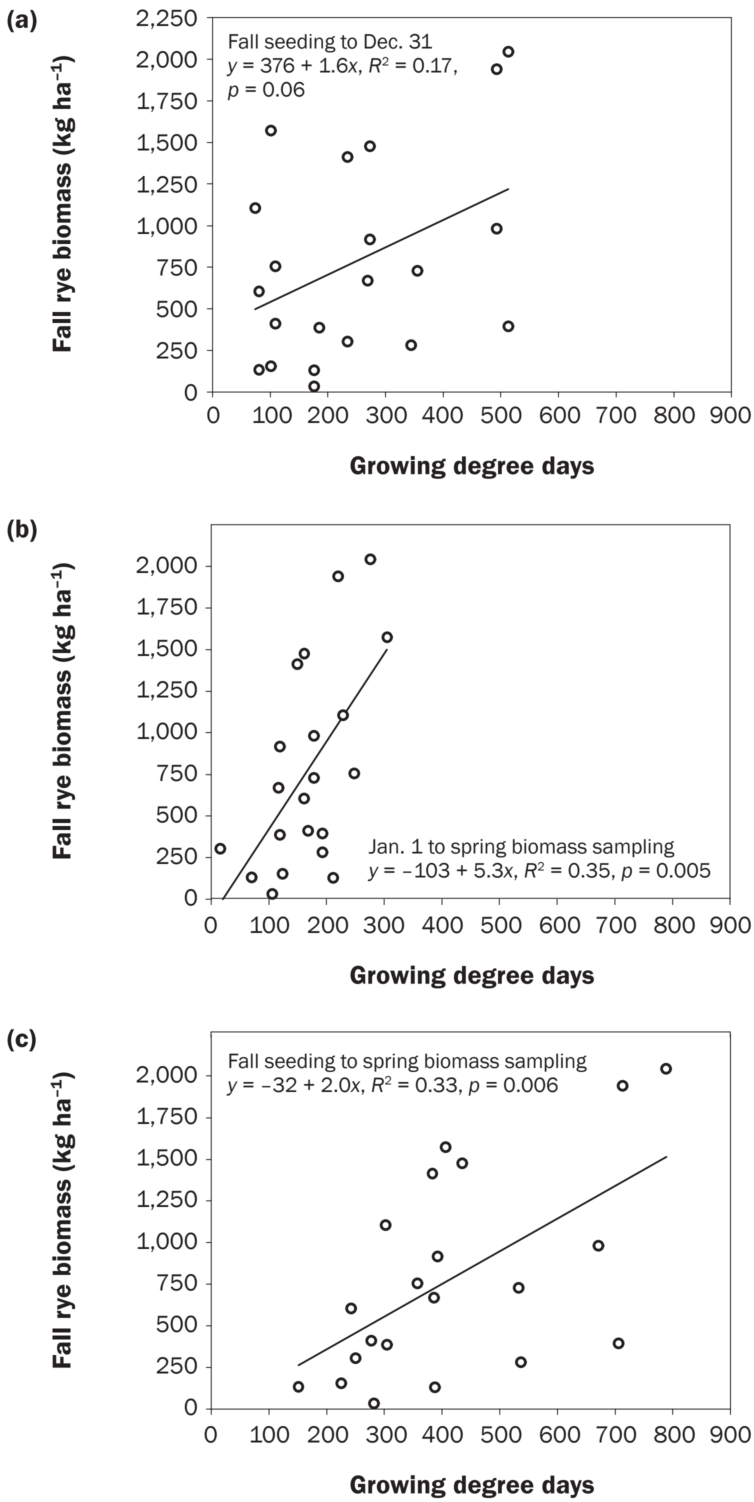
For a barley–potato rotation in Prince Edward Island, mean residue cover of 32.7% was reported (using the rope method after potato planting but before hilling) using a conservation tillage system based on chisel plowing (once in fall after barley harvest and once in spring before potato planting) and fall mulching with wheat straw (after potato harvest, or 18 months before residue measurement) at a rate of 4 Mg ha^{-1} (1.8 tn ac^{-1}) (Carter and Sanderson 2001; Carter et al. 2009). This cover compares closely to our mean value for wheat residue (33.7%; table 5), even though we did not employ fall mulching. Also, in Prince Edward Island, Holmstrom et al. (2006) reported residue cover in spring of 33% to 54% for no-till, 21% to 26% for conservation tillage, and 2% to 8% for conventional tillage (moldboard plowing) after a forage (timothy, alsike clover [*Trifolium hybridum* L.], and red clover [*Trifolium pratense* L.]) and before potato. The moldboard plow levels are similar to those recorded in our study.

The lack of a significant effect on wheat residue cover (33.6% to 39.3%; table 2) among 1-CONT, 4-CONV, and 4- and 5-CONS (wheat–sugar beet segment), even though tillage was less intense on 1-CONT, was likely due to a lower wheat yield on 1-CONT. Averaged over 12 years, wheat yield on 1-CONT was 71% of that on the other rotations due to monoculture (Larney et al. 2017). Therefore, one disking resulted in the same level of residue cover on 1-CONT as two diskings in most years, and Vibra Shank in two years, on the other rotations.

Moyer et al. (2004) reported dry bean residue mass in spring, as affected by fall tillage prior to sugar beet (conventional, minimum, and no-till) in southern Alberta. Conventional tillage included moldboard plowing, while minimum tillage was one pass of a disk + harrows. An equation similar to equation 1, with a different b coefficient (mass-to-cover factor) of 2.7 m^2 kg^{-1} (13.2 ft^2 lb^{-1}) for dry bean (van Donk et al. 2008), was used to convert dry bean residue mass (Moyer et al. 2004) to percentage cover for comparison with our data. Estimated residue cover was 2.4% for conventional, 7% for minimum tillage, and 15.6% for no-till. These values compare favorably to our average dry bean cover of 3.6% for wide-row and 9.7% for narrow row (table 5). Moyer and Blackshaw (2009) reported spring surface cover of 26% after dry bean and 17% after potato where no-till was employed prior to planting wheat. The above findings indicate that even in the absence of tillage (no-till), the maximum surface residue cover attainable is 15% to 26% with dry bean residue and ~17% with potato.

After potato, residue cover was significantly higher on the four CONS rotations (7.5% to 8.7%) than the two CONV rotations (4.2% to 4.4%), even though tillage operations were essentially similar (table 2). This was likely due to the absence of moldboard plowing in the CONS rotations, which allowed residue from preceding crops, especially slower-decomposing wheat, to carry over. Residue from preceding crops, further back in the rotation than one year, has been documented, e.g., Smith et al. (1990) estimated that up to 20% of residue mass after sugar beet was actually from dry bean and corn (*Zea mays* L.), further back in the rotation. This was because sugar beet requires mechanical defoliation just prior to harvest (as in our study) and thin fragile leaves, which are rapidly decomposed, are their primary contribution to surface residue. Similarly, ~30% of residue mass after dry bean was estimated to have originated from a prior corn crop. Smith et al. (1990) concluded that this mixture of residue from various preceding crops explained the weak relationships between residue mass and soil cover for dry bean and sugar beet. Under minimum tillage, Yonts et al. (1989) reported 12.7% residue cover in spring after sugar beet and 23.7% after dry bean for a three-year sugar beet−corn−dry bean rotation in

Figure 1
Relationship between fall rye biomass in spring and (a) growing degree days (GDD) from fall seeding to December 31; (b) GDD from January 1 to spring biomass sampling; and (c) GDD from fall seeding to spring biomass sampling. Data points represent biomass yields from 21 combinations of seeding and sampling dates (2001 of 2011; table 4): ten points from 3-CONS (between potato–dry bean); eight points from mean of 4-, 5-, and 6-CONS; and three points from 3-CONS (between dry bean–wheat).



Nebraska. These cover levels are higher than our average values (table 5) for sugar beet (6.7%) and dry bean (3.6% to 9.7%), likely due to less intense tillage, but also possible carryover of corn residue as reported by Smith et al. (1990).

The 3-CONS (between potato–dry bean) fall rye entry point produced a 10-year average biomass yield of 1,240 kg ha^{-1} (1,107 lb ac^{-1}), substantially higher than 552 to 794 kg ha^{-1} (493 to 709 lb ac^{-1}) previously reported in southern Alberta (Blackshaw 2008). Fall rye cover crops have the potential to produce much higher biomass yields, especially in warmer climates (e.g., yields in Maryland prior to potato were 3,500 to 4,390 kg ha^{-1} [3,125 to 3,920 lb ac^{-1}] when terminated by herbicide in early April [Carrera et al. 2005]). Even in cooler conditions, when allowed to grow to full maturity, yields of up to 15 Mg ha^{-1} (6.7 tn ac^{-1}) have been reported (e.g., Cicek et al. [2014] in Manitoba). The oat cover crop was dropped from our study after 2002 due to very low yields and hence poor provision of surface cover. Blackshaw (2008) also found low yields for fall-seeded oat (40 to 117 kg ha^{-1} [36 to 104 lb ac^{-1}]) or ~12% of those for fall rye.

In Iowa, fall rye with average seeding on October 1 and harvest on April 23 (i.e., 204 days) yielded 1,040 kg ha^{-1} (929 lb ac^{-1}) across eight site years (Pantoja et al. 2016), slightly lower than our average yield of 1,240 kg ha^{-1} (1,107 lb ac^{-1}) produced over 227 days on 3-CONS (between potato–dry bean), most likely due to the shorter growing period. However, the average growing period of 211 days (September 25 to April 25) for the other four entry points (table 4), although similar in length and timeline to 204 days (October 1 to April 23) in the Iowa study, yielded a much lower average biomass of 420 kg ha^{-1} (375 lb ac^{-1}), most likely reflecting lower cumulative GDD in Alberta versus Iowa.

We found significant positive relationships between fall rye biomass in spring and cumulative GDD with a DM accumulation rate of 2 kg ha^{-1} (1.8 lb ac^{-1}) GDD^{-1} between seeding and spring sampling. In California, Brennan and Boyd (2012) reported a DM accumulation rate of 9 kg ha^{-1} (8 lb ac^{-1}) GDD^{-1} (base temperature of 4°C [39°F]). However, their value was based on multiple samplings between December and February/March and biomass yields at termination were 8,000 to 9,000 kg ha^{-1} (7,143 to 8,036 lb ac^{-1}). Also, cumulative GDD during the fall rye growing period ranged from 815 to 1,121 (mean 969, n = 8) compared with 151 to 789 GDD (mean 415, n = 21) in our study (figure 2c).

While threshold amounts of anchored or flat stubble (mostly cereal) to preclude wind erosion have been documented, the amount of living cover crop biomass to effectively prevent erosion has not been quantified to any great extent. The contribution of fall rye biomass raised surface cover levels above or close to the 30% residue cover threshold required for prevention of erosion. Moyer and Blackshaw (2009) reported that planting a fall rye cover crop increased surface cover from 26% to 54% after dry bean and from 17% to 39% after potato, where no-till was employed prior to planting wheat. These increases in cover compare favorably to the contribution of fall rye to surface cover in our study.

As well as surface residue cover, increased surface roughness caused by tillage or large clods is a major factor in reducing wind erosion risk (Chepil 1950; Larney et al. 1997). While we did not measure surface roughness in this study, we observed increased surface roughness after the Dammer Diker, which likely contributed to reduced erosion risk (Hackwell et al. 1991; Salem et al. 2014) on these rotation phases.

In the time since the experiment was initiated in 2000, there have been changes in crop choices and residue management on irrigated land in southern Alberta. First, the area of soybean (*Glycine max* [L.] Merrill) on the Canadian prairies has increased dramatically, especially in Manitoba, and moving westward through Saskatchewan to Alberta. New shorter-season and glyphosate-tolerant varieties have led to increased interest in growing soybean in southern Alberta's irrigation districts (Gabruch and Gietz 2014). In a survey by Fawcett and Towery (2004), 63% of soybean growers cited glyphosate-tolerant technology as a key factor in reducing tillage associated with the crop and thereby increasing residue cover. Perry et al. (2016) found that adoption of conservation tillage was 10% higher and no-till 20% higher, due to the advent of glyphosate-tolerant soybean. If glyphosate-tolerant soybean makes continued inroads in southern Alberta, potentially replacing dry bean in irrigated rotations, then residue cover levels may increase accordingly, although the advent of glyphosate-resistant weed species in western Canada (Beckie et al. 2015) may impact this. Secondly, there has been increased interest in zone tillage (strip tillage and inter-till) for sugar beet in Alberta (Regitnig and Avison 2009). The crop is planted into narrow strips of disturbed soil, and the inter-rows are left undisturbed with higher residue cover. Indications are that strip tillage for sugar beet is being more widely adopted, especially with the advent of glyphosate-tolerant cultivars (Evans et al. 2010).

Summary and Conclusions

Our results quantified soil residue cover for typical row crops in the irrigated region of southern Alberta. They show that wheat is the main provider of residue cover during the nongrowing season on irrigated rotations. The other crops grown in rotation (potato, dry bean, and sugar beet) produced inherently low levels (4% to 10%) of surface residue cover, well below the 30% required to reduce erosion risk. Long-term replacement of cereals with lower residue-producing crops (e.g., potato, dry bean, and sugar beet) on irrigated rotations in southern Alberta should be considered judiciously in light of potential negative effects on surface residue cover. However, addition of a fall rye cover crop after potato or dry bean can raise the level of surface residue close to or above the 30% threshold level and provide cover during the vulnerable fall and early spring periods. We also provided a baseline quantification of the average DM accumulation rate (2 kg ha^{-1} [1.8 lb ac^{-1}] GDD^{-1}) for fall rye on irrigated land in southern Alberta.

The CONS management package, which, in addition to cover crops, included reduced tillage; feedlot manure compost addition; solid-seeded, narrow-row dry bean production; increased wheat frequency (5-CONS); and longer rotations including a forage (6-CONS), led to increased residue cover compared to CONV management (15.6% versus 7.1%, 10-year average). Advantages of CONS management were also observed with respect to potato (Larney et al. 2016b), dry bean (Larney et al. 2015), and sugar beet (Larney et al. 2016a) yields, weed populations (Blackshaw et al. 2015), beneficial insects (Bourassa et al. 2008), and soil quality (Li et al. 2015).

Acknowledgements

Funding contributions from the Alberta Agricultural Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Agriculture and Agri-Food Canada's Matching Investment Initiative, and the Pulse Science Cluster are gratefully acknowledged.

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Conservation Management and Crop Rotation Effects on Weed Populations in a 12-Year Irrigated Study

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Source: Weed Technology, 29(4):835-843.
Published By: Weed Science Society of America
DOI: http://dx.doi.org/10.1614/WT-D-15-00071.1
URL: http://www.bioone.org/doi/full/10.1614/WT-D-15-00071.1

Weed Technology 2015 29:835–843

Conservation Management and Crop Rotation Effects on Weed Populations in a 12-Year Irrigated Study

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Potato, dry bean, and sugar beet production have increased markedly in recent years on irrigated cropland in Alberta, Canada. Concerns exist about declining soil quality and increased soil erosion when these low-residue crops are grown in sequence in short-duration rotations. A 12-yr rotation study was conducted to determine the merits of adopting various conservation practices (reduced tillage, cover crops, composted manure) and longer-duration rotations to develop a more sustainable production system for these row crops. This article reports on weed density and weed seedbank data collected in the study. Weed densities recorded prior to applying postemergence herbicides indicated that conservation compared with conventional management treatments had greater weed densities in 30 to 45% of the cases in 3-, 4-, and 5-yr rotations. In contrast, a 6-yr conservation rotation that included 2 yr of timothy forage resulted in similar or lower weed densities than rotations with conventional management practices. Residual weed densities recorded 4 wk after applying postemergence herbicides were only greater in conservation than conventional rotations in 2 of 12 yr, regardless of rotation length. Weed seedbank densities at the conclusion of the 12-yr study were similar for 3- to 6-yr rotations under either conservation or conventional management. These findings indicate that implementing a suite of conservation practices poses little risk of increased weed populations in the long term. This knowledge will facilitate grower adoption of more sustainable agronomic practices for irrigated row crops in this region.

Nomenclature: Dry bean, *Phaseolus vulgaris* L.; oat, *Avena sativa* L.; potato, *Solanum tuberosum* L.; rye, *Secale cereale* L.; sugar beet, *Beta vulgaris* L.; timothy, *Phleum pratense* L.; wheat, *Triticum aestivum* L.

Key words: Compost manure, cover crop, reduced tillage, soil conservation, weed density, weed diversity, weed seedbank.

La producción de papa, frijol, y de remolacha azucarera ha incrementado en forma marcada en años recientes en zonas agrícolas con riego en Alberta, Canada. Existe preocupación acerca del deterioro de la calidad del suelo y el aumento de la erosión cuando este tipo de cultivos que dejan pocos residuos son producidos en secuencia en rotaciones de corta duración. Un estudio de rotación de 12 años fue realizado para determinar los méritos de la adopción de varias prácticas de conservación (labranza reducida, cultivos de cobertura, estiércol compostado) y rotaciones de mayor duración para desarrollar un sistema de producción más sostenible para estos cultivos. Este artículo reporta los datos colectados de densidad de malezas y banco de semillas en este estudio. Las densidades de malezas registradas antes de aplicar herbicidas postemergentes indicaron que los tratamientos de conservación al compararse con los de manejo convencional tuvieron mayores densidades de malezas en 30 a 45% de los casos, en rotaciones de 3, 4, y 5 años. En contraste, una rotación de conservación de 6 años que incluyó 2 años del forraje *Phleum pratense* resultó en densidades de malezas similares o menores a las prácticas de manejo convencional. Las densidades de malezas residuales registradas 4 semanas después de la aplicación de herbicidas postemergentes fueron mayores en rotaciones de conservación que en rotaciones convencionales solamente en 2 de los 12 años, sin importar la duración de la rotación. Las densidades del banco de semillas al momento de la conclusión del estudio de 12 años fueron similares para las rotaciones de 3 y 6 años bajo cualquiera de los manejos de conservación o convencionales. Estos resultados indican que el implementar una variedad de prácticas de conservación representa poco riesgo de aumentos en las poblaciones de malezas en el largo plazo. Este conocimiento facilitará la adopción por parte de los productores de más prácticas agronómicas sostenibles para cultivos con riego en esta región.

DOI: 10.1614/WT-D-15-00071.1

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Among the crops grown on the 555,000 ha of irrigated land in southern Alberta, Canada, there has been a two- to threefold increase in the area planted to potato, dry bean, and sugar beet in recent years because of good economic returns realized by growers (Alberta Agriculture Rural Development 2014). However, there are concerns about declining soil quality and increased soil erosion when these crops are grown in short-duration rotations with each other. None of these crops return much plant biomass to the soil, and there is considerable inherent soil disturbance with potato and sugar beet harvesting procedures.

Growers are interested in adopting more sustainable production practices, but require information on specific practices such as reduced tillage, cover crops, and manure amendments for these high-value crops. Adoption of no-till practices in the dryland regions of the Canadian prairies has resulted in increased soil organic matter and reduced erosion risk (Larney et al. 1994), but less research has been conducted on irrigated lands and tillage intensity remains high in those areas. Cover crops improve agricultural sustainability by reducing soil erosion, improving soil quality, suppressing pests, and minimizing nitrate and pesticide leaching to groundwater (Blackshaw et al. 2005; Dabney et al. 2001; Sarrantonio and Gallandt 2003; Teasdale 1996). Livestock manure amendments can increase soil carbon, improve soil physical properties such as water retention/infiltration and aggregate stability, and provide a slow release form of nutrients to enhance crop growth (Grandy et al. 2002; Larney et al. 2011; Parham et al. 2002).

Although soil quality and associated crop yield was the main focus of this 12-yr study, it was deemed important to gain knowledge of weed responses to these various conservation management practices and rotations. Cover crops can result in lower or higher weed densities depending on species grown as well as the timing of their planting and termination (Blackshaw et al. 2005; Hartwig and Ammon 2002). Manure, if not properly composed, can add weeds to the cropping system (Cudney et al. 1992; Larney and Blackshaw 2005) and composted manure can increase the competitiveness of weed species that are highly responsive to increased soil fertility (Menalled et al. 2004). Monoculture or short-duration rotations can lead to a proliferation of weeds with similar life cycles to those of the crops (Blackshaw 1994; Liebman and Dyck 1993) although longer, diverse rotations maintain weed diversity by preventing the buildup of a few troublesome weed species and often result in overall lower weed densities (Liebman and Staver 2001).

A 12-yr irrigated rotation study was conducted to determine the merits of utilizing various conservation management production practices (reduced tillage, cover crops, composted manure) in crop rotations that include a high frequency of potato, dry bean, and sugar beet (Li et al. 2015). This article reports on the impact of these conservation practices compared with conventional practices on weed densities and the weed seedbank.

Materials and Methods

Study Location, Design, and Agronomic Practices. A 12-yr (2000–2011) irrigated field study was conducted at the Vauxhall substation of Agriculture and Agri-Food Canada (50.09°N, 112.15°W, elevation 781 m). The soil was an Aridic Haplocryoll with 52% sand, 34% silt, 14% clay, and 2% organic matter (0- to 15-cm depth). The 30-yr (1981 to 2010) mean annual precipitation is 352 mm with a mean annual air temperature of 5.8 C. Irrigation water added during the growing season ranged from 140 to 775 mm, depending on the study year.

The entire plot area was planted to barley (*Hordeum vulgare* L.) in 1999 and treatments were implemented in the spring of 2000. There were seven rotation treatments: continuous spring wheat, two 3-yr rotations, two 4-yr rotations, one 5-yr rotation, and one 6-yr rotation (Table 1). These rotations were managed utilizing conventional (CONV) or conservation (CONS) management practices (outlined below). All crop phases of a rotation were grown each year to account for varying environmental conditions over years. This resulted in 26 rotation phases organized in a randomized complete block design with four replicates. Individual plot size was 10.1 by 18.3 m with a 2.1-m buffer zone between plots.

For the CONS rotations (Table 1), the following four practices were applied as a package: (1) direct seeding and/or reduced tillage whenever possible in the rotation, (2) fall-seeded cover crops, (3) composted cattle manure, and (4) direct-cut

Table 1. Rotation treatments indicating cover crop and composted beef feedlot manure entry points.

Rotation management[a]	Crop sequence	No. crop phases	No. rotation cycles
CONV	Wheat	1	12
CONV	Dry bean–wheat–potato	3	4
CONS	Dry bean[b]–wheat[c]–potato[b]	3	4
CONV	Dry bean–potato–wheat–sugar beet	4	3
CONS	Dry bean[c]–potato[b]–wheat–sugar beet	4	3
CONS	Dry bean[c]–potato[b]–wheat–sugar beet[c]–wheat	5	2.4
CONS	Dry bean[c]–potato[b]–oat/(timothy)[d]–timothy–timothy–sugar beet	6	2

[a] Abbreviations: CONV, conventional management; CONS, conservation management.

[b] Fall-seeded winter rye (oat in 2000 through 2002) cover-crop entry point.

[c] Feedlot manure compost entry points: 28 Mg ha^{-1} fresh weight after wheat harvest in the 3-yr CONS rotation and after sugar beet harvest in 3- and 5-yr CONS rotations; 42 Mg ha^{-1} fresh weight after dry bean harvest in the 4-, 5-, and 6-yr CONS rotations.

[d] Oat was harvested as silage in July and timothy was direct-seeded in late August.

narrow-row dry beans. Conventional management used none of the above practices, and hence the 3- and 4-yr CONV rotations had more intensive tillage, no cover crops, and no manure amendments.

As much as possible, tillage intensity was reduced under CONS vs. CONV management. In the fall preceding potatoes, the 3- and 4-yr CONV rotations were mouldboard plowed 25 m deep. The 3-yr CONS rotation received one pass of a chisel plow and packers or disc harrow, whereas one pass of a Dammer Diker® (AG Engineering & Development Co. Inc., Kennewick, WA) was used on 4-, 5-, and 6-yr CONS rotations. In spring, both CONV and CONS potato plots received two passes of a Triple K spring-tine harrow (Kongskilde Industries Inc., Hudson, IL). Fall tillage prior to dry bean was one pass of a disc harrow with harrows for all rotations. In spring, wide-row dry bean plots on the 3- and 4-yr CONV rotations received one or two passes of a Triple K spring-tine harrow. Dry bean was direct-seeded in the CONS rotations. Fall tillage prior to CONV wheat was one pass of a heavy-duty cultivator or two passes of a disc harrow; CONS wheat had only one pass of a disc harrow. Preseeding tillage for wheat in the spring did not differ between CONV and CONS and was one pass of a disc harrow, Triple K, or heavy-duty cultivator, depending on crop residue levels. Tillage did not differ between CONV and CONS treatments in sugar beet and consisted of one pass with a heavy-duty cultivator.

Two cover crops were used in the CONS rotations only—oats and winter rye—with entry points detailed in Table 1. However, fall establishment of oats was suboptimal, and after an especially poor stand in 2002, it was dropped and winter rye was used from fall 2003 onward. The 3-yr CONS rotation had the greatest proportion of fall-seeded cover crops (8 of 12 yr) with lesser proportions in 4- and 5-CONS (3 of 12 yr), and 6-CONS (2 of 12 yr).

Straw-bedded beef cattle feedlot manure compost [182, 15.4, and 5.4 g kg^{-1} of total C, N, and P, respectively (dry-weight basis)] sourced from the same feedlot each year and produced by active aeration (Larney and Olson 2006) was fall applied in the CONS rotations only (Table 1). A rate of 42 Mg ha^{-1} (fresh weight) was applied after dry bean and before potato in the 4-, 5- and 6-CONS rotations. The shorter 3-CONS rotation received a lower rate (28 Mg ha^{-1}, fresh weight) after wheat and before potato. This lower rate was also applied at a second entry point in the 5-yr CONS rotation, after sugar beet and before wheat.

The fourth conservation management practice was specific to dry bean. The CONV rotations were seeded in wide rows (60 cm), and the CONS rotations were planted in narrow rows (19–23 cm). Wide-row dry bean in the 3- and 4-yr CONV rotations were interrow cultivated in late June for weed control. At maturity, wide-row dry bean was cut below the soil surface, but not windrowed, to facilitate subsequent pickup and threshing with a plot combine. Narrow-row dry beans were direct cut with a plot combine.

Crops were fertilized according to soil test recommendations each year. All crops were irrigated with the use of a wheel-move system to maintain soil water content at $\geq$ 50% field capacity.

Table 2. Herbicides applied in each crop during the 12-yr study.

Crop	Preplant	Rate	Postemergence	Rate
		g ai ha^{-1}		g ai ha^{-1}
Dry bean	Glyphosate	900	Sethoxydim (2000–2007)	200
	Ethalfluralin	840	Bentazon (2000–2007)	840
			Imazamox (2008–2011)	20
Oat	Glyphosate	900	Bromoxynil/MCPA ester	560
Potato	Paraquat	680	Metribuzin	280
Sugar beet	Glyphosate	900	Sethoxydim	200
			Ethofumesate	200
			Phenmedipham/desmedipham	40
			Triflusulfuron methyl	25
Timothy			2,4-D amine	560
Wheat	Glyphosate	900	Tralkoxydim (2000–2003)	200
			Bromoxynil/MCPA (2000–2003)	560
			Clodinafop (2004–2009)	60
			MCPA/mecroprop/dicamba (2004–2009)	400
			Thiencarbazone/pyrasulfotole/bromoxynil (2010–2011)	210

Preseeding, in-crop, and postharvest herbicides were used as required for weed control (Table 2).

Weed Data Collection. Weeds were counted every year by species in 15 randomly chosen 0.25-m^2 quadrats in each plot prior to application of in-crop postemergence herbicides (mid to late June) and approximately 4 wk after postemergence herbicide applications (late July).

Weed seed in the soil seedbank was determined prior to initiating the study (spring 2000), after the first cycle of the 6-yr rotation (fall 2005), and at the conclusion of the study (fall 2011). In 2000, six 10-cm-diameter cores to a depth of 10 cm were randomly taken per replicate. Twelve 10-cm-diameter cores to a depth of 10 cm were taken per plot in 2005. In 2011, 20 5.7-cm-diameter cores to a 10-cm depth were taken per plot. In all instances, soil cores per plot were bulked, air dried, placed in polyethylene bags, and stored for 3 mo at –5 C. Seed determinations were conducted with the use of the greenhouse emergence method (Cardina and Sparrow 1996). Soil was spread onto plastic trays, placed in a greenhouse with a day/night temperature of 24/15 C, and watered as necessary to keep moist. Weed-emergence counts were made twice weekly for 1 mo. Soil was then air dried, remixed, placed in polyethylene bags, and stored at –5 C for a minimum of 1 mo before the second cycle of emergence counts was conducted. The cycle of cool storage/emergence counts were conducted three times and emergence values were combined.

Statistical Analysis. Mean values for weed density and weed seedbank data were calculated over all crop phases within a rotation treatment before conducting the statistical analyses. The UNIVARIATE procedure was used to check the residuals for normality and potential outliers. Outliers were discarded and all data were log-transformed to improve normality and homogeneity of variances before subsequent statistical analyses. Original (nontransformed) data are presented in all tables.

Weed density data were analyzed by year and rotation treatment with the use of the MIXED procedure (SAS Institute) with rotation in the model as a fixed effect and replicate as a random effect. The analyses were done by year because the model failed to converge when year was placed in the model as a repeated measure.

Weed seedbank data were analyzed using the MIXED procedure with rotation treatment, year, and their interaction in the model as fixed effects, and replicate and replicate by rotation treatment as random effects. Year was treated as a repeated measures effect. Various variance–covariance matrices were fitted and the one with the lowest Akaike's information criterion (AIC) value was used for the final analysis.

Additionally, as a measure of weed population diversity among rotation treatments, the Shannon-Weiner index of diversity (H') for both weed density and weed seedbank data was calculated as

Table 3. Weed species enumerated during the 12-yr study.

Scientific name	Common name	Life cycle
Amaranthus retroflexus L.	Redroot pigweed	Annual
Androsace septentrionalis L.	Pygmyflower	Annual
Arctium minus (Hill) Bernh.	Common burdock	Biennial
Avena fatua L.	Wild oat	Annual
Bromus tectorum L.	Downy brome	Annual
Capsella bursa-pastoris (L.) Medicus	Shepherd's purse	Annual
Carduus nutans L.	Nodding thistle	Biennial
Chenopodium album L.	Common lambsquarters	Annual
Chenopdium glacum L.	Oakleaf goosefoot	Annual
Cirsium arvense (L.) Scop.	Canada thistle	Perennial
Descurainia sophia (L.) Webb. ex Prantl	Flixweed	Annual
Echinochloa crus-galli (L.) Beauv.	Barnyardgrass	Annual
Elymus repens (L.) Nevski	Quackgrass	Perennial
Erodium cicutarium (L.) L'Her. ex Ait.	Redstem filaree	Annual
Erucastrum gallicum (Willd.) O.E. Schulz	Dog mustard	Annual
Gallium spurium L.	False cleavers	Annual
Hordeum jubatum L.	Foxtail barley	Perennial
Kochia scoparia (L.) Schrad.	Kochia	Annual
Lolium persicum Boiss. & Hohen. ex Boiss.	Persian darnel	Annual
Malva pusilla Sm.	Round-leaved mallow	Annual
Monolepis nuttalliana (R. & S.) Greene	Spear-leaved goosefoot	Annual
Polygonum aviculare L.	Prostrate knotweed	Annual
Polygonum convolvulus L.	Wild buckwheat	Annual
Polygonum scrabrum Moench	Green smartweed	Annual
Portulaca oleracea L.	Common purslane	Annual
Salsola iberica Sennen & Pau	Russian thistle	Annual
Senecio vulgaris L.	Common groundsel	Annual
Seteria viridis (L.) Beauv.	Green foxtail	Annual
Solanum sarrachoides Sendtner	Hairy nightshade	Annual
Solanum triflorum Nutt.	Cutleaf nightshade	Annual
Sonchus oleraceus L.	Annual sowthistle	Annual
Stellaria media (L.) Vill.	Common chickweed	Annual
Taraxacum officinale Weber in Wiggers	Dandelion	Perennial
Thlaspi arvense L.	Field pennycress	Annual
Tragopogon pratensis L.	Meadow goat's beard	Biennial

$$H' = -\sum P_i(\ln P_i), \qquad [1]$$

where

$$P_i = N_i/N_{total}, \qquad [2]$$

where N_i = number of individuals of species i and N_{total} = total number of individuals (Sosnoskie et al. 2006).

Results and Discussion

Weed Density. We identified 35 weed species over the duration of this 12-yr field study (Table 3). Of these species, 7 were monocots and 28 were dicots. In terms of life cycle, 28 were annuals, 3 were biennials, and 4 were perennials. Seven species (common lambsquarters, redroot pigweed, wild buckwheat, barnyardgrass, green foxtail, hairy nightshade, and shepherd's-purse) accounted for $>$ 60% of the total weed community throughout this study.

There were no differences in weed density prior to applying in-crop postemergence herbicides among the rotation treatments in the first two study years (Table 4). However, in 2002 through 2004, weed densities were markedly higher in the continuous wheat treatment. This result was at least partially due to the choice of herbicide used (Table 2); barnyardgrass was not adequately controlled by tralkoxydim in those years and populations increased substantially. A switch to clodinafop in 2003 controlled barnyardgrass in subsequent years,

Table 4. Weed density in each rotation prior to applying in-crop POST herbicides.

Rotation[a]	2000[b]	2001	2002	2003	2004	2005	2006	2004	2008	2009	2010	2011
	Plants m^{-2}											
CONV W	87 a	2 a	292 a	362 a	282 a	28 a	15 c	15 c	81 ab	28 b	111 a	134 a
CONV B–W–P	34 a	5 a	48 b	24 d	11 c	46 a	24 bc	48 b	83 ab	26 b	13 c	18 c
CONS B–W–P	37 a	6 a	62 b	99 ab	78 b	58 a	65 ab	46 b	150 a	90 a	64 b	35 bc
CONV B–P–W–SB	34 a	6 a	57 b	38 cd	33 c	38 a	40 bc	43 b	65 b	26 b	64 b	23 c
CONS B–P–W–SB	45 a	16 a	107 b	53 bc	80 b	54 a	88 a	79 a	108 a	54 ab	71 b	68 b
CONS B–P–W–SB–W	60 a	18 a	80 b	68 bc	94 b	77 a	74 a	68 a	88 ab	40 b	75 b	61 b
CONS B–P–O–T–T–SB	56 a	10 a	57 b	22 d	34 c	36 a	27 bc	40 b	76 b	42 b	31 c	25 c

[a] Abbreviations: CONV, conventional; CONS, conservation; B, dry bean; O, oat; P, potato; SB, sugar beet; T, timothy; W, spring wheat.

[b] Means within a column followed by the same letter are not significantly different according to the Tukey-Kramer test at $P < 0.05$.

and overall weed densities in continuous wheat were then usually similar to the other rotation treatments until the latter study years, when wheat competitiveness was reduced due to increasing plant disease infestations (D. Pearson, pers. comm.). Previous studies have similarly reported the large effect that herbicides can have on weed communities in long-term cropping studies (Booth and Swanton 2002; Légère and Samson 1999).

One of the main questions of this study was whether weed densities would increase in rotations that included conservation production practices. Weed densities prior to applying postemergence herbicides were greater in the 3-yr CONS compared with the 3-yr CONV rotation in 4 of 12 yr and with the 4-yr CONS compared with the 4-yr CONV rotation in 5 of 12 yr (Table 4). Similarly, the 5-yr CONS rotation had greater weed densities than either the 3-yr or 4-yr CONV treatments in 4 of 12 yr. In other years, weed densities were usually similar in the CONS and CONV rotations. Previous studies have similarly shown that manure applications and reduced tillage intensity can lead to greater weed densities in some situations (Blackshaw 2005a,b; Sosnoskie et al. 2009). In contrast to the results obtained with the 3-, 4-, and 5-yr CONS treatments, the 6-yr CONS rotation consistently had similar or lower weed densities than all CONV rotations. The combined effects of including 2 yr of timothy forage in this rotation (Entz et al. 1995; Schoofs and Entz 2000) plus a longer-duration rotation (Anderson et al. 1998; Liebman and Dyck 1993; Liebman and Staver 2001) likely contributed to this result.

Weed counts in late July reflected residual weed densities remaining after all herbicides were applied. Similar to results of the earlier weed count timing, weed densities were greatest with the continuous wheat treatment in 2002 through 2004 and in the latter study years (Table 5). However, fewer differences occurred between CONS and CONV rotations; greater weed densities in CONS rotations were only recorded in 2 of 12 yr.

Table 5. Residual weed density in each rotation four weeks after applying in-crop POST herbicides.

Rotation[a]	2000[b]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	Plants m^{-2}											
CONV W	17 a	29 a	94 a	155 a	77 a	27 a	5 a	14 a	10 a	14 a	24 a	51 a
CONV B–W–P	30 a	32 a	17 b	4 b	5 c	15 c	6 a	10 ab	5 a	4 b	2 b	1 b
CONS B–W–P	30 a	28 a	25 b	9 b	20 b	24 ab	11 a	9 ab	13 a	5 b	21 a	3 b
CONV B–P–W–SB	26 a	24 a	11 b	4 b	6 c	17 bc	3 a	3 b	8 a	2 b	19 ab	2 b
CONS B–P–W–SB	38 a	26 a	15 b	8 b	9 bc	33 a	11 a	5 b	15 a	3 b	23 a	2 b
CONS B–P–W–SB–W	37 a	21 a	16 b	7 b	18 b	29 a	11 a	3 b	14 a	3 b	17 ab	4 b
CONS B–P–O–T–T–SB	33 a	25 a	7 c	5 b	6 c	12 c	6 a	4 b	11 a	2 b	10 b	1 b

[a] Abbreviations: CONV, conventional; CONS, conservation; B, dry bean; O, oat; P, potato; SB, sugar beet; T, timothy; W, spring wheat.

[b] Means within a column followed by the same letter are not significantly different according to the Tukey-Kramer test at $P < 0.05$.

Table 6. Shannon-Weiner diversity index values (H) for weed count data prior to applying in-crop POST herbicides.

Rotation[a]	2000[b]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
CONV W	1.04 a	0.63 c	0.97 b	0.19 c	0.16 b	0.91 b	1.32 a	0.69 b	0.67 b	0.89 b	0.78 c	0.11 b
CONV B–W–P	1.14 a	1.57 ab	1.56 a	0.93 b	1.40 a	1.77 a	1.72 a	1.70 a	1.87 a	0.96 b	1.09 bc	1.57 a
CONS B–W–P	1.17 a	1.43 ab	1.47 a	1.65 a	1.51 a	1.64 a	1.39 a	1.51 a	1.66 a	1.72 a	1.71 a	1.60 a
CONV B–P–W–SB	1.23 a	1.19 b	1.61 a	1.12 b	1.41 a	1.84 a	1.78 a	1.78 a	1.74 a	1.70 a	1.66 a	1.85 a
CONS B–P–W–SB	1.21 a	1.28 b	1.60 a	1.49 a	1.46 a	1.72 a	1.41 a	1.49 a	1.74 a	1.55 a	1.88 a	1.62 a
CONS B–P–W–SB–W	1.22 a	1.78 a	1.64 a	1.52 a	1.51 a	1.83 a	1.73 a	1.65 a	1.98 a	1.93 a	1.86 a	1.69 a
CONS B–P–O–T–T–SB	1.08 a	1.78 a	1.62 a	1.68 a	1.71 a	1.88 a	1.37 a	1.70 a	1.69 a	1.58 a	1.98 a	1.67 a

[a] Abbreviations: CONV, conventional; CONS, conservation; B, dry bean; O, oat; P, potato; SB, sugar beet; T, timothy; W, spring wheat.

[b] Means within a column followed by the same letter are not significantly different according to the Tukey-Kramer test at $P < 0.05$.

Weed community diversity, as indicated by the Shannon-Weiner index (H'), varied among rotation treatments both before applying in-crop postemergence herbicides (Table 6) and 4 wk after herbicide applications (Table 7). The most consistent result was that H' was often lower for the continuous wheat rotation compared with all other rotations; 8 of 12 yr and 9 of 12 yr for the weed data collected before and after herbicide applications, respectively (Tables 6 and 7). Previous research also reported lower weed diversity in crop monocultures than in more diverse crop rotations (Menalled et al. 2001; Sosnoskie et al. 2009). We hypothesized that H' would be consistently greater for the CONS compared with the CONV rotations, but this only occurred for some comparisons in 4 of 12 yr for weed data recorded both before (Table 6) and after applying postemergence herbicides (Table 7).

Weed Seedbank. The background mean weed seedbank density at the initiation of the study in 2000 was 710 $\pm$ 180 seeds m^{-2} (data not shown). After the first cycle of the longest rotation (2005), the 4-, 5-, and 6-yr CONS rotations had higher seedbank values than either the 3- or 4-yr CONV rotations (Table 8) and were numerically higher than the background density in 2000. The higher seedbank densities noted in these CONS rotations could be due to reduced tillage intensity (Blackshaw 2005b; Sosnoskie et al. 2009) and/or the added composted manure within those rotations (Blackshaw 2005a; Menalled et al. 2004). Additionally, continuous CONV wheat had greater seedbank densities than either the 3- or 4-yr CONV rotations. Previous studies have reported that monoculture cropping often results in higher weed seedbanks compared to more diversified crop rotations (Ball 1992; Cardina et al. 2002; Gulden et al. 2011; Sosnoskie et al. 2006).

At completion of the 12-yr study (2011), the weed seedbank was higher in continuous CONV wheat than all other rotations (Table 8). This result once again confirms that monoculture cropping is a poor practice in terms of weed management. In contrast to the 2005 results, none of the CONS rotation treatments had higher weed seedbank densities compared with the CONV rotations and all values were lower than the background densities present when the study was initiated. This is a

Table 7. Shannon-Weiner diversity index values (H) for weed count data 4 wk after application of in-crop POST herbicides.

Rotation[a]	2000[b]	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
CONV W	1.49 a	1.24 a	0.11 b	0.27 b	0.89 b	1.10 b	0.58 c	0.69 d	0.48 c	0.58 b	0.02 c	0.42 b
CONV B–W–P	1.34 a	1.21 a	1.16 a	1.61 a	1.61 a	1.99 a	1.21 b	1.17 cd	1.47 b	1.53 a	0.54 b	1.55 a
CONS B–W–P	1.37 a	1.48 a	1.28 a	1.55 a	1.51 a	1.86 a	1.67 a	1.63 b	1.79 a	1.43 a	1.33 a	1.68 a
CONV B–P–W–SB	1.32 a	1.20 a	1.60 a	1.61 a	1.72 a	2.11 a	1.40 b	1.58 b	1.71 ab	1.36 a	1.29 a	1.57 a
CONS B–P–W–SB	1.48 a	1.16 a	1.57 a	1.63 a	1.59 a	2.09 a	1.84 a	1.93 a	1.34 b	1.61 a	1.30 a	1.56 a
CONS B–P–W–SB–W	1.45 a	1.35 a	1.40 a	1.85 a	1.90 a	2.23 a	1.75 a	2.00 a	1.83 a	1.59 a	1.37 a	1.48 a
CONS B–P–O–T–T–SB	1.54 a	1.30 a	1.62 a	1.79 a	1.50 a	1.82 a	1.18 b	1.61 b	1.67 ab	1.75 a	1.24 a	1.91 a

[a] Abbreviations: CONV, conventional; CONS, conservation; B, dry bean; O, oat; P, potato; SB, sugar beet; T, timothy; W, spring wheat.

[b] Means within a column followed by the same letter are not significantly different according to the Tukey-Kramer test at $P < 0.05$.

Table 8. Weed seedbank density for each rotation treatment after 6 yr (2005) and 12 yr (2011).

Rotation[a]	2005[b]	2011
	Seed m^{-2}	
CONV W	1,080 b	570 a
CONV B–W–P	481 c	183 b
CONS B–W–P	687 bc	263 b
CONV B–P–W–SB	406 c	275 b
CONS B–P–W–SB	1,589 a	301 b
CONS B–P–W–SB–W	1,135 ab	243 b
CONS B–P–O–T–T–SB	996 b	258 b

[a] Abbreviations: CONV, conventional; CONS, conservation; B, dry bean; O, oat; P, potato; SB, sugar beet; T, timothy; W, spring wheat.

[b] Means within a column followed by the same letter are not significantly different according to the Tukey-Kramer test at $P < 0.05$.

Table 9. Shannon-Weiner diversity index values (H') for weed seedbank data after 6 yr (2005) and 12 yr (2011).

Rotation[a]	2005[b]	2011
CONV W	1.62 ab	0.61 c
CONV B–W–P	1.75 ab	1.29 b
CONS B–W–P	1.69 ab	1.32 b
CONS B–P–W–SB	1.95 a	0.90 c
CONS B–P–W–SB	1.38 b	1.60 a
CONS B–P–W–SB–W	1.72 ab	1.72 a
CONS B–P–O–T–T–SB	1.51 ab	1.78 a

[a] Abbreviations: CONV, conventional; CONS, conservation; B, dry bean; O, oat; P, potato; SB, sugar beet; T, timothy; W, spring wheat.

[b] Means within a column followed by the same letter are not significantly different according to the Tukey-Kramer test at $P < 0.05$.

noteworthy finding as it indicates that conservation agronomic practices can be implemented with no adverse long term effects on weed populations.

There were few differences in Shannon-Weiner index (H') values among the various rotations for weed seedbank data in 2005. H' values were greater in the 4-yr CONV than in the 4-yr CONS rotation but all other rotations had similar values (Table 9). However, in 2011, H' values were higher in the 4-, 5-, and 6-yr CONS rotations compared with all other rotation treatments. This is a positive result, as it indicates that the weed community was not dominated by a few troublesome species. Additionally, maintaining weed species diversity can be beneficial in terms of supporting increased faunal diversity and/or facilitating nutrient retention/cycling (Sturz et al. 2001; Swift and Anderson 1993).

Li et al. (2015) reported on the soil quality attributes of the various rotations at the conclusion of this 12-yr irrigated study. Results indicated that CONS compared with CONV rotation treatments increased particulate organic matter carbon and particulate organic matter nitrogen by > 145%, total carbon by 45%, and aggregate stability by 8%. Of the various CONS management practices, composted manure had the greatest positive effect on soil quality whereas cover crops and reduced tillage intensity contributed to protecting the soil from wind/water erosion.

Overall results of the weed component of this 12-yr study indicate that these desirable CONS management practices can be adopted with little risk of increasing weed densities in the long term. This knowledge will encourage growers to adopt more sustainable practices for production of potato, sugar beet, and dry bean in this irrigated cropping region.

Acknowledgments

We thank the Vauxhall field crew for dedicated technical assistance and Toby Entz for statistical analyses. Funding contributions from the Alberta Agricultural Research Institute, Potato Growers of Alberta, Alberta Pulse Growers, Lantic Inc., Pulse Science Cluster, and Agriculture and Agri-Food Canada's Matching Investment Initiative are gratefully acknowledged.

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Received May 19, 2015, and approved July 23, 2015.

Associate Editor for this paper: Randy L. Anderson, USDA-ARS.

Canadian Journal of Plant Pathology

ISSN: 0706-0661 (Print) 1715-2992 (Online) Journal homepage: http://www.tandfonline.com/loi/tcjp20

Crop rotation effects on Pratylenchus neglectus populations in the root zone of irrigated potatoes in southern Alberta

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Can. J. Plant Pathol., 2015
Vol. 37, No. 3, 363–368, http://dx.doi.org/10.1080/07060661.2015.1066864

Note - Soilborne pathogens/Agents pathogènes telluriques

Crop rotation effects on *Pratylenchus neglectus* populations in the root zone of irrigated potatoes in southern Alberta

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(Accepted 18 June 2015)

Abstract: Root-lesion nematodes (*Pratylenchus* spp.) are important pests of potato (*Solanum tuberosum* L.), particularly in sandy soils and in the presence of *Verticillium dahliae*. We assessed the effects of crop rotation and soil management practices (reduced tillage, cover crops and composted manure applications) on population densities of *P. neglectus* on potato in a sandy loam soil in southern Alberta. Crops in rotation included potato (P), dry bean (DB, *Phaseolus vulgaris* L.), wheat (W, *Triticum aestivum* L.), sugar beet (SB, *Beta vulgaris* L.), oats (O, *Avena sativa* L.) and timothy (T, *Phleum pratense* L.). The rotations included 'conventional' and 'conservation' versions of 3-year (DB-W-P) and 4-year (W-SB-DB-P) rotations, as well as 5-year (W-SB-W-DB-P) and 6-year (O/T-T-T-SB-DB-P) rotations. Conservation practices included autumn cover crops and incorporation of compost as a substitute for inorganic fertilizer. Population densities of *P. neglectus* in the potato phase of each rotation were assessed in autumn of 2006 and 2007, and at the beginning, middle and end of 2008, 2009 and 2010 growing seasons. *Pratylenchus neglectus* populations were affected by rotation length but not soil management practices; population densities in the 3-year rotations were larger than in most other rotations at most sample dates. Potato yields in the 3-year conventional rotation were consistently lower than in longer rotations. In the 3-year rotation, potato was preceded by wheat, which is known to be a good host for *P. neglectus*. We speculate that greater population build-up on wheat in the year before potato, rather than rotation length or crop diversity *per se*, was the cause of the larger population densities in the 3-year rotations than in longer rotations.

Keywords: nematode population dynamics, potato early dying, root lesion nematodes, *Solanum tuberosum*, wheat

Résumé: Les nématodes des racines (*Pratylenchus* spp.) sont d'importants ravageurs des pommes de terre (*Solanum tuberosum* L.), particulièrement de celles qui poussent dans des sols sablonneux, en présence de *Verticillium dahliae*. Nous avons évalué les effets des rotations des cultures et des pratiques de gestion des sols (travail réduit du sol, plantes de couverture et applications de fumiers compostés) sur les densités de population de *P. neglectus* sur la pomme de terre poussant dans les loams sableux du sud de l'Alberta. Les rotations des cultures incluaient les pommes de terre (PT), le haricot (H, *Phaseolus vulgaris* L.), le blé (B, *Triticum aestivum* L.), la betterave à sucre (BS, *Beta vulgaris* L.), l'avoine (A, *Avena sativa* L.) et la phléole des prés (PP, *Phleum pratense* L.). Les rotations incluaient les versions « traditionnelle » et « axée sur la conservation » de trois ans (H-B-PT) et de quatre ans (B-BS-H-PT), de même que les rotations de cinq ans (B-BS-B-H-PT) et de six ans (A/PP-PP-PP-BS-H-PT). Les pratiques axées sur la conservation incluaient les plantes de couverture automnales et l'incorporation de compost comme engrais biologique. Les densités des populations de *P. neglectus* durant la phase « pomme de terre » de chaque rotation ont été évaluées à l'automne 2006 et à l'automne 2007, ainsi qu'au début, au milieu et à la fin des saisons de croissance de 2008, 2009 et 2010. Les populations de *P. neglectus* ont été perturbées par la durée des rotations, mais pas par les pratiques de gestion des sols. Les densités des populations au cours des rotations de trois ans étaient plus élevées que durant les autres types de rotations, et ce, à la plupart des dates d'échantillonnage. Les rendements de pommes de terre obtenus de la rotation traditionnelle de trois ans étaient invariablement plus bas que

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ceux des autres types de rotations. Dans la rotation de trois ans, les pommes de terre étaient précédées par le blé qui est reconnu comme étant un hôte de prédilection de *P. neglectus*. Nous avançons l'hypothèse voulant que la plus grande augmentation de populations chez le blé au cours de l'année précédant la pomme de terre, plus que la durée de la rotation ou que la variété de culture en soi, a engendré les densités plus élevées de populations au cours des rotations de trois ans plutôt qu'au cours des rotations plus longues.

Mots clés: blé, dynamique des populations de nématodes, flétrissure verticillienne de la pomme de terre, nématode des racines, *Solanum tuberosum*

Introduction

Root-lesion nematodes (*Pratylenchus* spp.) can be serious pests of potato. *Pratylenchus penetrans* (Cobb) Schuurmans-Stekhoven has been the focus of most research on the role of root-lesion nematodes in potato production, as it is known to interact with *Verticillium dahliae* Kleb. to cause the Potato Early Dying (PED) disease complex (e.g. Rowe & Powelson 2002). *Pratylenchus neglectus* is often associated with potato production in western North America (e.g. Davis et al. 1992; Hafez et al. 1992; Umesh & Ferris 1994; Mahran et al. 2010). In greenhouse and microplot studies, this species has been shown to reproduce on potato and reduce its growth (Olthof 1990; Umesh & Ferris 1994; Hafez et al. 1999), although there appears to be some geographical variation in the association, with populations in Manitoba and Idaho showing apparently limited capacity to reproduce on potato (Hafez et al. 1999; Mahran et al. 2010). The role of *P. neglectus* in PED has not been studied extensively, although one study suggests that there may be variation among geographically isolated populations of *P. neglectus* with respect to their ability to contribute to PED (Hafez et al. 1999).

Potato production on irrigated, sandy soils in southern Alberta has grown rapidly, with acreage planted to potatoes expanding from 5182 ha in 1998 to 16 582 ha in 2003 (Alberta Agriculture Rural Development 2013). This increase in potato production has occurred in tandem with similar increases in production of dry beans and sugar beets, and producers are interested in identifying rotations and production practices for these crops that will conserve soil resources. Cereal crops are commonly used in rotations with potato, dry beans or sugar beets in western Canada. *Pratylenchus neglectus* has a wide host range (Castillo & Vovlas 2007), but it is most often associated with cereal and grain legume crops (Riley & Kelly 2002; Castillo & Vovlas 2007; Smiley & Machado 2009). Population densities of *P. neglectus* have been positively associated with frequency of cereal cropping (Riley & Kelly 2002) and damage to those crops (Smiley & Machado 2009).

In order to assess the economic and environmental aspects of a range of crop rotations and production practices, a multifaceted long-term rotation experiment was established in southern Alberta in 2000 (Li et al. 2015). As a component of this broader study, the objective of the research presented here was to compare the effects of preceding crop rotations and conservation verses conventional production practices on population densities of *P. neglectus* on potato.

Materials and methods

Field experiment

The crop rotation experiment was established in spring of 2000 at the Agriculture and Agri-Food Canada Vauxhall Substation (50°03′N, 112°09′W, elev. 781 m) on an Orthic Brown Cherozemic soil (Chin series). Texture in the 0–15 cm depth was sandy loam (0.52 kg kg^{-1} sand, 0.34 kg kg^{-1} silt, 0.14 kg kg^{-1} clay). The 30 year normal (1981–2010) mean annual precipitation was 352 mm with a mean annual air temperature of 5.8°C. The principal crops were 'Russet Burbank' potato (P), dry bean (DB), wheat (W), sugarbeet (SB), oats (O) and timothy (T) grown in four basic rotation sequences with lengths of 3–6 years, with 'conventional' and 'conservation' versions of the 3- and 4-year rotations, for a total of six rotations that included potato (Table 1). Each crop of each rotation sequence was represented in any given year in the experiment, which enabled us to sample the potato phase of each rotation in every year. Each rotation was replicated four times in a randomized complete block design. Plot dimensions were 10 × 18.3 m with a 2.1 m buffer zone between each plot.

Conservation rotations were characterized by the following practices: (1) use of autumn-seeded cover crops of rye (*Secale cereale* L.); (2) incorporation of composted cattle manure as a substitute for inorganic P fertilizer prior to potato, (3) direct seeding or reduced tillage where possible, and (4) narrow-row direct harvested dry beans (Li et al. 2015). The reduced tillage included the use of a single pass chisel plough (3-year conservation) or dammer-diker (4-, 5- and 6-year conservation rotations) the autumn before potato in conservation rotations whereas the conventional rotations were moldboard ploughed to a depth of 25 cm (Table 1). The compost

Table 1. Characteristics of crop rotations and soil-nutrient management practices preceding potato, and average marketable and total potatoes for the period 2001–2009.

Rotation	Crop sequence	Nutrient inputs kg ha^{-1}	2001–2009 average marketable yield Mg ha^{-1}	2001–2009 average total yield Mg ha^{-1}
3-year Conventional	B-W-P	112N-67P-67K	27.9b	35.8c
3-year Conservation	B-W-P	62N-28P-67K +28 t/ha compost	31.2a	41.1ab
4-year Conventional	W-SB-B-P	112N-67P-67K	31.5a	40.5b
4-year Conservation	W-SB-B-P	37N-0P-67K +42 t/ha compost	30.1ab	39.9b
5-year Conservation	W-SB-W-B-P	37N-0P-67K +42 t/ha compost	31.9a	43.2a
6-year Conservation	O(t)-T-T-SB-B-P	37N-0P-67K +42 t/ha compost	31.5a	40.9ab

W = wheat; P = potatoes; B = beans; SB = sugar beet; O(t) = oats harvested as green feed in July; T = timothy.

was derived from straw-bedded feedlot manure and had been turned multiple times with a tractor-pulled windrow turner over a 3 month active thermophilic phase and then allowed to cure for a further 3 months before use (Larney & Olson 2006). The compost was applied at 42 Mg ha^{-1} wet weight in the autumn prior to potatoes in the 4- and 5-year conservation rotations, and to the 6-year rotation. Compost was applied to the 3-year conservation rotation at a lower rate of 28 Mg ha^{-1}.

Nematode sampling

Nematode sampling commenced in the autumn of 2006 after a complete cycle of the 6-year rotation and two full cycles of the 3-year rotation. Only the potato phases of the six rotations were sampled each year. Plots were sampled immediately after potato harvest in 2006 and 2007. In each of 2008, 2009 and 2010, samples were taken in the early season (just before or after potato planting, May–early June), mid-season (late July–early August), and immediately after potato harvest (late September). At each sample date, twenty 2-cm diameter cores were taken to a 25 cm depth from each plot and composited. The samples were kept refrigerated and shipped to the Pacific Agri-Food Research Centre in Agassiz, BC, where nematode populations were analysed. Nematodes were extracted from 50 mL soil subsamples using Baermann pans (Forge et al. 2007) and *Pratylenchus* nematodes were enumerated using an inverted microscope. In 2008 and 2009, potato root fragments were picked from the mid-season samples and endoparasitic nematodes were extracted over 7 days in a mist chamber (Ingham 1994).

The population of *Pratylenchus* was identified as *P. neglectus* on the basis of morphological characteristics, particularly the presence of two lip annules, lack of spermatheca and absence of males in the population (Castillo & Vovlas 2007; Yu 2008). The morphology-based identification was confirmed by molecular analyses. A portion of the 28S region of rDNA was amplified using nematode-specific forward and reverse primers D2A (CAAGTACCGTGAGGGAAAGTTG) and D3B (TCGGAAGGAACCAGCTACTA), respectively (De Ley et al. 1999). Amplicons were sequenced and compared with sequences for *P. neglectus* in GenBank. The sequence data were also filed with GenBank (accession numbers KM200578, KM200579).

Data analyses

Nematode counts were expressed as nematodes per 100 mL soil and transformed to log(x + 100) before final analyses to correct heteroscedasticity. For data from the 3-year and 4-year rotations only, the main-factor and interaction effects of production practices (conventional vs. conservation), rotation length and sample date were analysed using Proc Mixed in SAS (SAS, Inc., Cary, NC). Sample dates were treated as repeated measures and blocks were designated as random variables. Subsequently, data from all rotations were separated by season of sampling (spring, summer, autumn) and for each season, the main-factor and interaction effects of rotation length and year were analysed. The analysis for autumn included 2006 and 2007 data whereas analyses for spring and summer were based on 2008–2010 data only. The SLICE procedure was used to test the effect of rotation length and compare means at each sample date.

Results and discussion

Rotation system effects on P. neglectus *population densities*

There were no significant effects of production system (conventional vs. conservation) on *P. neglectus* population densities, either alone or as an interaction with length of rotation (3-year vs. 4-year) (data not shown). The conservation rotations differed from the conventional rotations in that a rye cover crop was planted each autumn, there was less tillage, and compost was applied each autumn preceding potato. The conservation and conventional rotations thus differed in several ways that could have had competing influences on *P. neglectus* populations and therefore resulted in no net effect. For example, the compost amendments and general enhancement of soil organic matter in the conservation rotations (Li et al. 2015) could have fostered a more suppressive soil food web leading to suppression of *P. neglectus* as has been observed in other systems (e.g. Abawi & Widmer 2000; Oka & Yermiyahu 2002; Forge & Kempler 2009; Oka 2010). In contrast, the autumn rye cover crop would likely have promoted *P. neglectus* population build-up by extending the season with a host species, thereby negating any suppression due to organic matter and soil food web enhancement.

Because there was no significant effect of production system or system × rotation length interaction, subsequent analyses were conducted on 3-year and 4-year data pooled over the two production systems. The 3-year rotation (B-W-P) resulted in the greatest population densities on potato. There was a significant date × rotation effect, with significant ($P < 0.05$) effects of rotation length on six of the 10 sample dates (Table 2). At all of these dates, population densities in the 3-year rotation were significantly greater than in at least one other rotation, and there were few significant differences among the 4-, 5- and 6-year rotations. There was also a significant rotation effect for each season of sampling (Fig. 1). Population densities in the 3-year rotation were significantly greater than in 4-year and 6-year rotations in all three seasons, and greater than in the 5-year rotation in spring and autumn samples.

Table 2. Effect of rotation length on population densities of *Pratylenchus neglectus* in soil (nematodes per 100 mL soil) planted to potato, by sample date. Analyses were conducted on log (X + 100) transformed data; data presented are means of raw data.

		Rotation length			
Sample date	P[1]	3-year[2]	4-year[2]	5-year	6-year
Autumn 2006	0.025	241a[3]	165abc	228ab	106 c
Autumn 2007	0.077	129	99	59	56
Spring 2008	<0.001	262a	23c	72b	74b
Summer 2008	0.22	35	7	14	5
Autumn 2008	0.036	77a	24b	44b	59b
Spring 2009	<0.001	176a	23c	80b	33bc
Summer 2009	0.002	101a	21b	61ab	38b
Autumn 2009	0.075	112	69	61	127
Spring 2010	0.005	70a	7b	15b	6b
Summer 2010	0.66	19	3	11	2

[1] Effect of rotation length on the sample date, from SLICE command of PROC MIXED.
[2] Data are means of Conservation and Conventional systems.
[3] Means within a row labelled with the same letter are not significantly different at $P \leq 0.05$.

The effect of the 3-year rotation on *P. neglectus* population densities was manifest as significantly greater numbers of nematodes per g potato root in the 3-year rotation than in other rotations in 2008 but not in 2009 (Fig. 2). There have been conflicting reports on the host status of potato for *P. neglectus* (Mahran et al. 2010). Our root sample data included population densities in excess of 3000 nematodes per g root, which strongly suggests that potato was a good

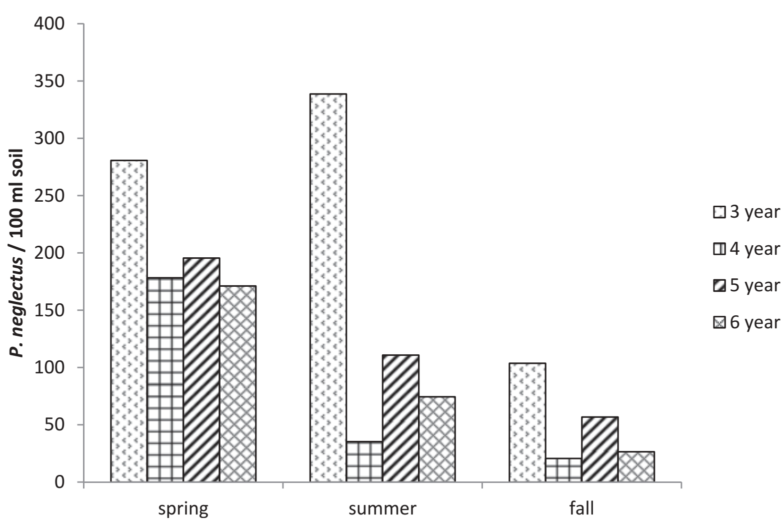

Fig. 1 Effect of rotation length on population densities of *P. neglectus* in soil planted to potato (nematodes per 100 mL soil), by season of sampling. Analysis of variance and mean separations were conducted on log(X + 100) transformed data.

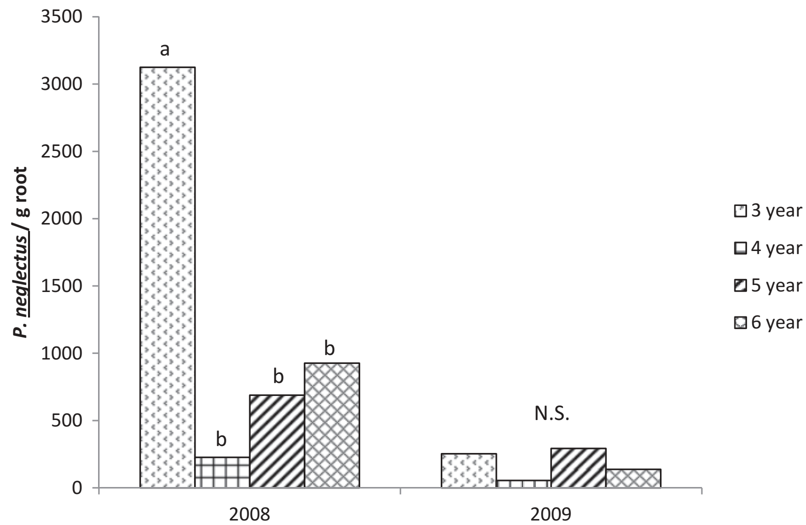

Fig. 2 Effect of rotation length on population densities of *P. neglectus* in roots of potato (nematodes g^{-1} root). Analysis of variance and mean separations were conducted on log(X + 100) transformed data. N.S. = non-significant effect of rotation in analysis of variance.

host for the population of *P. neglectus* at the test site. This is consistent with most previous studies of the potato–*P. neglectus* interaction (Olthof 1990; Umesh & Ferris 1994; Hafez et al. 1999), although a more recent study in Manitoba indicated there was no population increase on potato and very low population densities in roots from field plots (<50 nematodes g^{-1}) (Mahran et al. 2010), leading the authors to speculate that 'Russet Burbank' potato may be a poor host for *P. neglectus*.

In addition to being longer rotations with a greater diversity of crops, the 4-, 5- and 6-year rotations differed from the 3-year rotation in that dry beans rather than wheat immediately preceded potato. As *P. neglectus* is well known to parasitize and multiply rapidly on wheat, we speculate that the sequence of wheat-potato was the primary cause of the increased population densities measured in potatoes in the 3-year rotation. All of the crops used in this experiment can host *P. neglectus* (Castillo & Vovlas 2007), but there are no data directly comparing reproductive potential of the nematode on wheat to any of the other crops. The 5-year rotation fostered significantly greater population densities than the 6-year rotation in autumn 2006 and the 4-year rotation in spring 2008 and spring 2009 (Table 2). It is worth noting that the 5-year rotation had wheat-bean in the 2 years preceding potato whereas the 4- and 6-year rotations both had sugar beet-bean in the 2 years preceding potato. This specific effect of wheat is significant, as it indicates that it may not be necessary to rotate away from potato for a significant length of time as long as wheat does not immediately precede the potato crop.

Alternatively, the lower *P. neglectus* population densities could be the result of the greater diversity of crop species, perhaps fostering beneficial changes in soil microbial ecology resulting in nematode suppression. Further experimentation with long rotations with wheat at differing positions in the rotations, relative to potato, would help elucidate the cause of high population densities in the 3-year rotation observed in this study.

Relationships with potato yields

The damage potential of *P. neglectus* on potato is not well understood as the majority of research on interactions between root-lesion nematodes and potato has focused on *P. penetrans*. Population densities of *P. neglectus* were generally inversely correlated with yields across the rotations, with the 3-year rotations having lower cumulative yields than other rotations, and with the highest yields on the 5-year conservation rotation which was significantly greater than all rotations except the 4-year and 6-year conservation rotations (Table 1). Attempts to correlate *P. neglectus* population densities with yields across individual plots did not yield significant correlation coefficients as a result of high plot-to-plot variability. Symptoms of Potato Early Dying (PED) were evident, particularly in the 3-year conventional plots in 2007. PCR with primers specific for the ITS1 and ITS2 regions of *Verticillium dahliae* rDNA confirmed the presence of

V. dahliae in the plots (L. Kawchuk, personal communication). We speculate that because root-lesion nematodes can act synergistically with *V. dahliae* to cause PED, the lower *P. neglectus* pressure in the longer rotations contributed to reduced intensity of PED relative to the 3-year rotation. Additional research using controlled inoculation of microplots under field conditions to further elucidate relationships between *P. neglectus* population densities, *V. dahliae* and potato yields under Alberta growing conditions is warranted.

In conclusion, our data demonstrate that short rotations with wheat can significantly increase population densities of *P. neglectus* in fields subsequently planted to potato. It is not possible to draw firm conclusions about whether this effect is the direct result of having wheat as the crop immediately preceding potato or some other aspect of the shorter and less diverse rotation, such as shifts in nematode-antagonistic soil microflora. The well-recognized affinity of *P. neglectus* with cereal crops leads us to speculate that greater population build-up on wheat the year before potato was the primary cause of the greater population densities on potato in the 3-year rotations than in the longer rotations. We also speculate that the greater population densities in the 3-year rotations contributed to the greater incidence of PED and lower potato yields than in the longer rotations.

Acknowledgements

We thank Jim Sukeroff, Dale Reynolds and Vauxhall Substation staff and summer students for field assistance.

Funding

Project funding was provided by the Potato Growers of Alberta, the Alberta Pulse Growers, Lantic Inc., the Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada's Matching Investment Initiative, Agriculture and Agri-Food Canada's GAPS programme and the Pulse Science Cluster.

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Am. J. Potato Res. (2016) 93:448–462
DOI 10.1007/s12230-016-9522-8

Economic Comparison of Conventional and Conservation Management Practices for Irrigated Potato Production in Southern Alberta

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Published online: 13 May 2016

Abstract Conventional (CONV) potato (*Solanum tuberosum* L.) production in Alberta has relied on high levels of soil disturbance which may result in long-term degradation of soil resources. A 12-yr (2000–2011) study was conducted to address issues with the CONV system and to evaluate the effects of conservation (CONS) practices on the economics of irrigated potato production. Potato was grown in 3- to 6-yr rotations which included dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.), soft wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), and timothy (*Phleum pratense* L.). CONS included reduced tillage, cover crops, compost addition, and solid-seeded bean. Averaged over 12-yr, potato yields for 4-yr CONV rotations (potato–wheat–beet–bean) were lower than those for CONS systems. However, the decreased costs associated with not using compost in 4-yr CONV offset the losses in yield, thereby resulting in an overall net income higher than that of CONS systems.

Resumen La producción convencional de papa (CONV, *Solanum tuberosum* L.) en Alberta se ha respaldado en altos niveles de alteraciones del suelo, que pudieran resultar en su degradación a largo plazo. Se condujo un estudio de 12 años (2000–2011) para enfatizar temas con el sistema CONV y para evaluar los efectos de prácticas de conservación (CONS) en aspectos económicos de la producción de papa de riego. Se cultivó la papa en rotaciones de 3 a 6 años, que incluían frijol (*Phaseolus vulgaris* L.), remolacha (*Beta vulgarins* L.), trigo suave (*Triticum aestivum* L.), avena (*Avena sativa* L.) y el pasto bohordillo o hierba timotea (*Phleum pratense* L.). CONS incluyó labranza mínima, cultivos de cobertura, agregado de composta y frijol en alta densidad. Promediando sobre 12 años, los rendimientos de la papa en rotaciones CONV por 4 años (papa, trigo, remolacha, frijol) fueron más bajos que los de los sistemas CONS. No obstante, la disminución de costos asociada con no usar composta en 4 años de CONV compensa la pérdida en rendimiento, resultando entonces en un ingreso neto total más alto que el de los sistemas CONS.

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Keywords Crop rotation · Compost · Irrigation · Soil conservation · Cost · Net income · Monte Carlo simulation

Introduction

The province of Alberta is a cornerstone of the Canadian agricultural sector. Alberta is the second-highest contributor to cash receipts from crop production in Canada (following Saskatchewan), totalling $6.3 billion in 2013 [20.6 % of Canada's total crop cash receipts (Statistics Canada 2014a)]. Alberta accounts for 22 % of total potato production in Canada, 29 % of coloured bean and soft white wheat production, 20 % of oat production, and is the only source of sugar beet production nationwide (Statistics Canada 2014b, c). With the arrival of large potato processing plants in southern Alberta, potato production showed a rapid rise in the late 1990s, nearly doubling from a harvested area of 13,030 ha in 1998 to 24,680 ha in 2003; however, potato harvested area declined in 2004 and 2005. Since 2005, potato harvested area has been fluctuating between 18,210 and 22,260 ha. Potato growth and expansion in southern Alberta is limited by market constraints, including the current capacity of potato processing plants. If another large processing plant were to open nearby, the area planted to potatoes could easily grow to accommodate the increased demand. Thus, it is important to investigate practices which could further improve crop production efficiency and operational profitability in this region.

Expansion of commercial value-added processing and irrigated cropping in Alberta offered a dual challenge: producing high value crops (e.g. potato, bean, sugar beet); while overcoming limited nutrient returns to the soil in the form of residue, which if not dealt with may have long-term detrimental effects on soil resources in terms of diminished soil quality and increased erosion risk. Studies have shown that irrigation is able to dramatically improve yields and economic performance of crop systems in Alberta. Nicol (2005) stated that irrigation provides three key benefits to crop systems: increased crop yields, the ability to introduce new crops that would not normally be grown due to the region's semiarid climate, and greater economic stability through diverse agricultural production and reduced weather dependency. Klein et al. (2012) determined that, compared to the same crops grown without irrigation, irrigated cereals (barley (*Hordeum vulgare* L.), durum wheat, hard wheat, oat, and canola (*Brassica napus* L.)) in southern Alberta had yield increases ranging from 77 % to 178 %, and an increased gross margin per hectare by an average of $495. Wood (2013) compared net profit for different crops and reported that irrigated soil, as compared to non-irrigated soil, can potentially increase net profit by 32 % to 321 %.

Careful selection of crops and their sequence in a rotation can have significant effects on crop yields. Khakbazan et al. (2010) performed an 8-yr rotation study in Manitoba, using six different rotations (potato-canola, potato-wheat, potato-canola-wheat, potato-oat-wheat, potato-wheat-canola-wheat, and potato-canola-alfalfa (*Medicago sativa* L.)-alfalfa), and found that the potato-canola and the potato-canola-wheat rotations produced the highest average annual net income. An agronomic follow-up study by Mohr et al. (2011) determined that longer-term rotations (3- or 4-yr), that alternated crops or included forages, helped maintain long-term field productivity. The authors recommended the potato-canola-wheat and potato-canola-alfalfa-alfalfa rotations for maximized potato production over a long period. Legume and perennial forage crops, such as field pea, bean, lentil, or alfalfa have also been found to improve the yields and profitability of subsequent crops by providing additional N to the soil; thereby, reducing input requirements, suppressing crop diseases, and providing greater soil water conservation (Stevenson and van Kessel 1996; Zentner et al. 2011; O'Donovan et al. 2014; Khakbazan et al. 2014).

Conventional potato production uses significant tillage operations and inputs which may result in long term degradation of soil resources, including that of soil organic matter. Traditionally, conventional potato production has relied on high levels of soil disturbance (e.g. fall moldboard plowing, which leaves the soil surface exposed to wind erosion until spring), multiple tillage passes in the spring for a fine smooth seedbed, and hilling in the early growing season for weed control. Tiessen et al. (2007) quantified significant soil displacement associated with potato planting, hilling, and harvesting which led to increased soil translocation and erosivity, especially on sloping land. Soil erosion losses of 22 to 34 Mg ha^{-1} were reported with conventional tillage for potato in Prince Edward Island (Carter and Sanderson 2001). Compared to cereals, potato returns low levels of residue to the soil (Carter and Sanderson 2001; Li et al. 2015), which has implications for the maintenance of organic matter and soil quality, particularly if potato is rotated with other low-residue crops (e.g. dry bean or sugar beet).

Potato production also tends to require higher levels of fertilizer than other crops, with fertilizer often comprising upwards of 20 % of operating costs (Hopkins et al. 2014). As a result of this high nutrient requirement, potato crops regularly receive fertilizer rates in excess of requirements, leading to problems of leaching or runoff of excess nutrients (Davenport et al. 2005; Munoz et al. 2005). In light of these drawbacks, alternatives to conventional soil and nutrient management practices are desired. Studies have shown that the use of organic amendments, such as livestock manure, adds N, P, and trace elements to the soil, while also improving soil physical properties such as water retention, aggregate stability, and infiltration (Larney et al. 2011). This is especially relevant on lighter-textured irrigated land where soil organic matter may be depleted by intensive cultivation and lower amounts of crop residue returned to the soil (Grandy et al. 2002; Porter et al. 1999).

This study was initiated in 2000, in Vauxhall, Alberta, to address issues with conventional (CONV) potato production and to examine the impact of alternative conservation (CONS) rotations on irrigated potato production. Given the issues with CONV potato production practices described above, this study sought to evaluate the effects of CONS management practices and rotations on the economics of irrigated potato production.

Materials and Methods

Field Experiment

The 12-yr (2000–2011) agronomic study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50° 03′ N, 112° 08′ W, elevation 769 m). The study site had predominantly Orthic Brown Chernozemic soils. All plots were planted to spring wheat for several years before 1999.

In 1999, they were planted to spring barley with uniform yields across the experimental site. Growing-season (April 1 to September 30) precipitation averaged 290 mm and air temperature averaged 13.8 °C. This section provides only a brief description of the design and implementation of the experiment, as specifics are provided in Larney et al. (2016).

Rotations used either CONS or conventional CONV crop management practices. CONS management centered on the following four practices: 1) direct seeding or reduced tillage where possible in the rotation, 2) fall-seeded cover crops where possible, 3) composted cattle manure as a substitute for inorganic fertilizer, and 4) straight cutting of solid seeded narrow-row (19–23 cm) bean. CONV management used none of these practices, hence the CONV rotations had more intensive fall tillage, no cover crops, no organic amendments and dry bean was grown in wide rows (60 cm). Of the four practices, reduced tillage and manure compost application apply most directly to potato crop production, while cover cropping and solid-seeded narrow-row planting pertain to the production of bean crops. Details of CONS management treatments on the CONS rotations were provided by Larney et al. (2016).

Potato was grown in six rotations under CONV or CONS management: two 3-yr (3-yr CONV and 3-yr CONS) rotations, two 4-yr (4-yr CONV and 4-yr CONS) rotations, one 5-yr (5-yr CONS), and one 6-yr (6-yr CONS) (Table 1). The 3-yr CONV and 3-yr CONS rotations had similar crop sequences (potato–dry bean–wheat), as did the 4-yr CONV and 4-yr CONS (potato–wheat–sugar beet–dry bean). The 5-yr CONS rotation comprised two phases of wheat interspersed with the three row crops (potato–wheat–sugar beet–wheat–dry bean), while oat and timothy were included in the 6-yr CONS (potato–oat–timothy–timothy–sugar beet–dry bean). A seventh continuous wheat (1-yr CONT) treatment was also included. Each phase of each rotation appeared in each year, resulting in a total of 26 phases (Table 1) in a randomized complete block design with four replicates (104 plots). Individual plots were 10.1 × 18.3 m (185 m^2), with a 2.1 m inter-plot between plots. The number of rotation cycles at the end of the 2011 growing season (12 years) ranged from 4 (3-yr rotations) to 2 (6-yr rotation) (Table 1). All crops were grown to maturity, except oat in the 6-year rotation, which was harvested as silage in mid- to late July to allow for timely planting of timothy in late August. Potato harvest took place between August 30 (2005) and September 25 (2002), with a mean date of September 14 ($n = 12$), using a single-row digger (Grimme Group GmbH, Damme, Germany). Tubers were graded on size, weight, colour, and texture (Larney et al. 2016, Table 2). Marketable potato yield was defined as total yield minus 9 % of dockage and 6 % of shrinkage (Manitoba Agriculture Food and Rural Development 2016).

Potato plots were fertilized (receiving 135 kg ha^{-1} N; 67 kg ha^{-1} of P_2O_5; and 67 kg ha^{-1} of K_2O) for the 3- and 4-yr CONV rotations in the previous fall, except for 2000, which were fertilized in the spring (Table 1). Potato plots on CONS rotations received a lower rate of N (37 kg ha^{-1}) and zero P, to account for the N and P in compost. Compost, derived from beef feedlot manure, was fall-applied (except 2003 when it was postponed by wet conditions until spring) at five entry points (four of which preceded potato, while one preceded wheat) in the CONS rotations (Table 1). On the shorter 3-yr CONS rotation compost was applied at 28 Mg ha^{-1} (fresh wt.) between wheat and potato. In the longer 4-yr CONS, 5-yr CONS and 6-yr CONS rotations, a higher rate (42 Mg ha^{-1} fresh wt.) was used between dry bean and potato. Compost was sourced from the same feedlot each

Table 1 Crop rotations under CONV or CONS crop management practices from 2000 to 2011

Rotation[a]	Crop sequence[b]	# of phases	# of plots	No. rotation cycles[b]
1-yr CONT	Wheat	1	4	12
3-yr CONV	Potato–Dry bean–Wheat	3	12	4
3-yr CONS	Potato[c]–Dry bean[c]–Wheat[d]	3	12	4
4-yr CONV	Potato–Wheat–Sugar beet–Dry bean	4	16	3
4-yr CONS	Potato[c]–Wheat–Sugar beet–Dry bean[d]	4	16	3
5-yr CONS	Potato[c]–Wheat–Sugar beet[d]–Wheat–Dry bean[d]	5	20	2.4
6-yr CONS	Potato[c]–Oat/(Timothy)[e]–Timothy–Timothy–Sugar beet–Dry bean[d]	6	24	2
Total		26	104	

[a] Integer refers to length or rotation; CONT, continuous; CONV, conventional management; CONS, conservation management

[b] No. rotation cycles = 12 (yr)/no. crop phases

[c] Fall-seeded cover crop entry point: fall rye [except oat, 2000–02, on 3-yr CONS (between dry bean and wheat), 4-yr, 5-yr, and 6-yr CONS]

[d] Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-yr CONS; 5-yr CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-yr CONS; 5-yr CONS after dry bean; 6-yr CONS) applied after harvest, except 2003 (postponed to spring 2004 due to wet soil conditions)

[e] Oat harvested as silage in July, timothy direct seeded in late August

Table 2 Unit price for inputs and potato product from 2000 to 2011

	Price ($\$ kg^{-1}$ or L^{-1})		Price ($\$ kg^{-1}$ or L^{-1})
Product		Herbicide	
Potato	0.22	EPTC	19.00
		Paraquat	23.50
Seed		Gglyphosate DMA salt	6.55
Potato	0.47	Sethoxydim	44.22
		Diquat	28.95
Fertilizer		Glyphosate K+ salt	10.50
Nitrogen	0.70[a]	Metribuzin	72.40
Phosphorous	0.77[b]	Glyphosate K+ salt	10.50
Potassium	0.61[c]		
Compost	0.027[d]	Fungicide	
		Chlorothalonil	10.30
Insecticide		Cymoxanil	34.22
Imidacloprid	86.00	Copper hydroxide	16.70
Permethrin	100.00	Boscalid	161.13
Cypermethrin	211.38	Mancozeb	12.83
Chlorpyrifos	23.95		
Methamidophos	36.41		
Spirotetramat	260.50		
Spinosad	68.75		

[a] Based on 46-0-0

[b] Based on 11-51-0

[c] Based on 0-0-60

[d] Costs for transportation to and application in the field are also included

Source: Wood 2013; Manitoba Agriculture Food and Rural Development 2016; and https://www.afsc.ca/Default.aspx?cid=82&lang=1 under risk management/price lists

year and had average concentrations (dry wt., n = 11, fall 2000–10) of 182 g kg^{-1} total C, 15.4 g kg^{-1} total N, and 5.4 g kg^{-1} total P. There was no significant effect of potato rotation on residual N levels in the soil profile to 100 cm depth. Pesticide chemical information and prices are shown in Table 2. Irrigation water was assumed to be applied to the plots via a low pressure pivot system to maintain soil water content at ≥50 % field capacity. Amounts of irrigation water varied according to crop demand and prevailing weather conditions. None of the cover crop entry points preceded potato and they therefore did not directly impact potato establishment (Table 1).

Economic Analysis

Net income (NI), for both potato and entire rotations, was defined as the income remaining after paying for all monetary costs (i.e. seed, nutrients, weed and disease control, transportation, fuel and oil, repairs, miscellaneous expenses, land taxes and land investment, and interest costs on variable inputs), ownership costs on machinery and buildings (depreciation, interest on investment, and insurance and housing), and labour, as described by Zentner et al. (2002) and Khakbazan et al. (2010). No allowance was made for interest costs associated with land equity. Labour cost was assumed to be \$20 hr^{-1} to represent opportunity cost for higher-skilled labour required for agricultural production. Agronomic data from the field trials, combined with price and cost data for machinery and inputs, were used to develop crop budgets. The economic analysis included all inputs used in field operations from pre-seeding to harvest and post-harvest activities. All purchased inputs used in each treatment, including variable and fixed costs for all field operations, nutrient application, weed and disease control, irrigation, harvesting, storage, and transportation of saleable products, were included in the analysis. Input prices from various sources were used to represent the crop production implemented. The total cost for compost was estimated at \$27 Mg^{-1} including composting (\$15 Mg^{-1}), truck loading (\$2 Mg^{-1}), handling and hauling (5 km, \$5 Mg^{-1}), and field application (\$5 Mg^{-1}). Additionally, a scenario was developed assuming a total cost of \$15 Mg^{-1} for compost including composting, truck loading, handling and hauling, and field application, to examine a scenario where improved technologies reduced compost production costs, or where producers had access to cheaper compost materials. A detailed discussion of the paper focused on assuming the current cost of compost (\$27 Mg^{-1}) and risk analysis was only reported for this scenario because it was more relevant to the true cost of compost. The price of \$219 Mg^{-1} was used for marketable potato (Manitoba Agriculture Food and Rural Development 2016). Table 2 provides a summary of prices of inputs and output.

Field operation schedules and equipment used were determined for irrigated potato production and other crops of each rotation based on practices followed by producers in western Canada. Farm machinery sizes and work rates were calculated based on an average potato farm size of 315 ha and grain farm size of 907 ha (Manitoba Agriculture Food and Rural Development 2016; Saskatchewan and Food and Rural Revitalization 2014). The analysis included the costs and returns for each crop and rotation for each year. Please check Tables if captured and presented correctly.Tables were checked and I have added some comments. Please check my corrections and comments.

The total cost and NI of irrigated potato production were expressed in CAN\$ ha^{-1} for each crop and rotation. The Proc MIXED procedure of SAS software (SAS/STAT 9.3 User's Guide), that fits a variety of mixed linear models to data and enables the use of these fitted models to make statistical inferences about the data, was conducted to determine the impact of crop CONV and CONS management practices on potato tuber yield, total cost, gross income, and NI for irrigated potato production. With the MIXED procedure, the management practice was used as a fixed effect variable, while blocks and replicates were used in the random effect variables. Contrast statements were used in the MIXED procedure to test for both impacts of wheat or bean being the preceding crop (PC) and impacts of CONV compared to CONS practices on potato tuber yields, total cost, and NI over all 12 years (2000–2011). The impacts of PC, wheat or bean, were done for 3-yr rotations (3-CONV, 3-CONS) vs. 4-yr rotations (4-CONV, 4-CONS); therefore, if the impacts of PC on potato were significant, it may be due to residual N from PC, or due to 1 year length difference in 3- and 4-yr rotations, or a combination of both. Overall management practice effects and contrast effects between PCs and between CONV and CONS management practices, were considered significant at $P<0.05$. In addition, comparisons of NI for an individual potato crop phase and cumulative years were conducted with the MIXED procedure to test gradual impact of management practices over time at $P<0.01$, $P<0.05$, and $P<0.10$.

Simulation and Stochastic Efficiency with Respect to a Function

Stochastic budgets of costs and returns were developed for 3-yr CONV, 4-yr CONV, 3-yr CONS, 4-yr CONS, 5-yr CONS, and 6-yr CONS management practices to evaluate how the profitability and risky alternatives of the CONS management practices compared with the CONV management practices. A Monte Carlo technique was used to capture the random year-to-year variation of costs, returns, and profitability of these practices (Richardson and Mapp 1976; Richardson et al. 2000). This is a computerized mathematical technique using repeatedly random numbers in a simulation function to compute corresponding results with a certain distribution. The technique allows researchers to account for risk in quantitative analysis and decision making. Stochastic values were randomly generated from an empirical cumulative distribution function (CDF) to approximate the true probability distributions of costs, returns, and profitability. The profitability of potato production was influenced by yields, prices of potato, and cost factors. Stochastic variables included yields and historical prices of potato product, potato seed, and N fertilizer, from 2000 to 2011. Following Anderson et al. (2004), the yields and historical prices of potato product, potato seed, and N fertilizer defined the parameters of normal distributions, where 10,000 yields and prices of potato product, potato seed, and N fertilizer were simulated from the distributions by 3-yr CONV, 4-yr CONV, 3-yr CONS, 4-yr CONS, 5-yr CONS, and 6-yr CONS management practices, respectively.

Stochastic efficiency with respect to a function (SERF) was used in this study to evaluate risk-efficient alternatives (Hardaker et al. 2004) for 3-yr CONV, 4-yr CONV, 3-yr CONS, 4-yr CONS, 5-yr CONS, and 6-yr CONS management practices. The SERF method uses a utility function and calculates certainty equivalents (CE) for a range of alternatives based on a set of different individual risk preferences (e.g. risk neutral, risk preferring, moderately risk averse or extremely risk averse) (Ascough et al. 2009). The SERF method is applied to determine the most profitable management alternatives of potato production under different individual risk levels. To rank risk levels for 3-yr CONV, 4-yr CONV, 3-yr CONS, 4-yr CONS, 5-yr CONS, and 6-yr CONS management practices, we followed the approach adopted by Anderson et al. (2004) and used a constant absolute risk aversion utility function to convert return values of potato production to utility estimates.

Utility values were calculated for absolute risk averse coefficient (ARAC) ranging from 0 (risk neutral) to 0.002 (highly risk averse). For a given level of utility and risk aversion coefficient, the CE is calculated using the equation published in Hardaker et al. (2004). CE is a measurement of a payoff that a decision maker would have to receive to be indifferent between the certain payoff and a more risky alternative (Hardaker et al. 2004). Thus, if $CE_1 > CE_2$ at a given risk averse (r), then alternative 1 is preferred to 2.

Microsoft Excel add-in software SIMETAR, initially developed by Texas A&M University, was used to conduct

CDF simulation, risk analysis and implement the SERF technique, thereby allowing for simultaneous rather than pairwise evaluation of risky alternatives (Richardson et al. 2008).

Results

Potato Tuber Yield

The 5-yr and 6-yr CONS management practices produced significantly higher potato yields than CONV practices. The 12-yr (2000–11) average potato yield (Mg ha^{-1}) was highest for the 5-yr CONS rotation (37.8 Mg ha^{-1}) and significantly lower for the 3-yr CONV rotation (31.9 Mg ha^{-1}) (Table 3). The 5-yr CONS management practices produced 18 % higher potato yields than the 3-yr CONV practices. Compost application may have caused significant potato yield improvement, as the 5-yr CONS system received compost at two entry points, one of which preceded potato. Average potato yield was the same in 4-yr CONV and 3-yr and 4-yr CONS rotations; however, the yields were 10 % higher than 3-yr CONV rotation. Averaged over 12 years, CONS management practices provided higher average potato yields (36.0 Mg ha^{-1}) than CONV practices (33.5 Mg ha^{-1}) (Table 3). Potato crops showed a trend with higher average yields when preceded by bean (35.2 Mg ha^{-1}), as compared to PCs of wheat (33.6 Mg ha^{-1}) (Table 3).

The highest yields by specific year were found in 2001 and 2003, for CONV (41.5 Mg ha^{-1}) and CONS (44.9 Mg ha^{-1}) practices respectively, while the lowest yields were measured in 2008 and 2010, for CONV (19.8 Mg ha^{-1}) and CONS (21.4 Mg ha^{-1}) managements respectively (Table 4). The largest significant difference in potato yield occurred in 2009, with CONS management yielding 5.4 Mg ha^{-1} more potato crop than CONV management. Of the 12 experimental years, statistical differences in potato yield between CONV and CONS systems occurred only in 2005, 2008, 2009, and 2011 (Table 4).

The greatest difference in potato yield, based on PC, was found in 2005, where potato crops preceded by bean yielded an average of 9 Mg ha^{-1} more potato than those preceded by wheat (Table 5). Additionally, in 7 of the 12 study years, crops preceded by bean provided higher potato yields than those preceded by wheat, although differences in potato yields

Table 3 Comparisons of means for yields and net incomes of potato over 12-years (2000–2011) as affected by rotation under CONV or CONS practices and preceding crops

	Tuber yield[a] (Mg ha^{-1})	% Change of yield compared to 3-yr CONV	Compost = \$27 Mg^{-1}		Compost = \$15 Mg^{-1}	
			Net income[a] (\$ ha^{-1})	% Change of net income compared to 3-yr CONV	Net income[a] (\$ ha^{-1})	% Change of net income compared to 3-yr CONV
Rotation[b]						
3-yr CONV	31.9c	0	1251b	0	1251b	0
3-yr CONS	35.3b	10	1389b	11	1706a	36
4-yr CONV	35.1b	10	2044a	63	2044a	63
4-yr CONS	35.2b	10	1211b	−3	1685a	35
5-yr CONS	37.8a	18	1570b	25	2044a	63
6-yr CONS	35.6ba	11	1465b	17	1940a	55
P-value	0.006		0.004		0.004	
Contrast between management practice						
CONV	33.5	–	1648	–	1648	–
CONS	36.0	–	1409	–	1844	–
P-Value	0.0043	–	0.0451	–	0.0926	–
Contrast between preceding crops wheat and bean						
Wheat	33.6	–	1320	–	–	–
Bean	35.2	–	1672	–	–	–
P-Value	0.0827	–	0.0278	–	–	–

[a] Values with same letters in a column are not significantly different ($P > 0.05$)

[b] 3-yr CONV = 3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr CONS = 3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr CONV = 4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr CONS = 4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr CONS = 5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr CONS = 6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

Table 4 Annual comparisons of tuber yields and net incomes of potato between CONV and CONS management practices (compost = \$27 Mg^{-1})

Year	Yield				Net income			
	CONV[a] Mg ha^{-1}	CONS[a]	Contrast test[b]	% change	CONV[a] \$ ha^{-1}	CONS [a]	Contrast test[b]	% change
2000	38.0	36.4	NS	−4.12	2873	2530	NS	−11.94
2001	41.5	42.1	NS	1.46	3067	2353	NS	−23.28
2002	28.3	27.1	NS	−3.96	670	−379	**	−156.57
2003	42.1	44.9	NS	6.67	3559	3260	NS	−8.40
2004	39.1	42.6	NS	9.16	3004	2898	NS	−3.53
2005	29.6	34.4	**	16.27	1024	1275	NS	24.51
2006	35.5	37.5	NS	5.78	2014	1608	NS	−20.16
2007	37.0	41.5	NS	11.96	2310	2274	NS	−1.56
2008	19.8	22.7	**	14.44	−1090	−1318	NS	−20.92
2009	34.1	39.5	***	15.83	1880	2090	NS	11.17
2010	20.5	21.4	NS	4.54	−1125	−1466	NS	−30.31
2011	31.3	36.1	***	15.38	1619	1765	NS	9.02

[a] CONV = Conventional management; CONS = Conservation management

[b] *significant at the 10 % level; **significant at the 5 % level; *** significant at the 1 % level and NS not significant

between PCs were only statistically significant in 2 of the 12 years (Table 5).

Cumulative potato yields were shown to be higher in crops utilizing CONS practices. Cumulative yields show a gradual impact of CONS practices over time. There is no significant difference in cumulative potato yield between CONV and CONS practices in the first 5 years of the experiment (2000–2004), likely because it took time for CONS management to begin to influence the plant-soil system and thereby crop yields; however, greater significant difference is found in later years (Table 6). Starting in 2005, CONS practices yielded significantly more potato than CONV practices. The average cumulative potato yield difference between CONV and CONS practices, from 2005 to 2011, was approximately 7 %, with potato in CONS practices consistently higher than CONV practices. This trend indicates the gradual impacts of CONS practices on improved potato yield. The greatest significant difference in cumulative potato yield between CONV and CONS practices occurred in the 2000–2009 period (8.2 % difference), while the smallest difference of significance was found between 2000 and 2005 (5.5 %). Furthermore, PC bean gradually contributed more positively to potato yield than PC

Table 5 Annual contrasts of means for yields and net incomes of potato as affected by preceding crop (compost = \$27 Mg^{-1})

Year	Yield				Net income			
	After wheat Mg ha^{-1}	After bean	Contrast test[a]	% change	After wheat \$ ha^{-1}	After bean	Contrast test[a]	% change
2000	38.3	36.2	NS	−5.32	2907	2464	NS	−15.24
2001	39.0	42.9	NS	9.94	2217	2894	NS	30.54
2002	27.9	27.1	NS	−2.91	298	−28	NS	−109.40
2003	43.9	43.8	NS	−0.21	3589	3426	NS	−4.54
2004	41.4	39.2	NS	−5.29	3133	2563	NS	−18.19
2005	26.7	35.7	***	33.67	230	2074	***	801.74
2006	35.2	37.3	NS	5.84	1684	1968	NS	16.86
2007	37.5	40.5	NS	7.97	1964	2493	NS	26.93
2008	20.6	19.9	NS	−3.76	−1254	−1521	NS	−21.29
2009	32.4	38.6	***	19.38	1262	2376	***	88.27
2010	19.5	23.0	NS	17.71	−1719	−729	**	57.59
2011	32.5	33.1	NS	1.60	1553	1532	NS	−1.35

[a] *significant at the 10 % level; **significant at the 5 % level; *** significant at the 1 % level and NS not significant

Table 6 Comparisons of average yields and net incomes of potato among years between CONV and CONS management practices from year 2000 to 2011 (compost = \$27 Mg^{-1})

Average year	Yield				Net income			
	Conv.[a] Mg ha^{-1}	Cons.[a]	Contrast test[b]	% change	Conv.[a] \$ ha^{-1}	Cons.[a]	Contrast test[b]	% change
2000–2001	40.3	39.2	NS	−2.52	2970	2442	NS	−17.78
2000–2002	35.7	35.4	NS	−0.63	2203	1501	***	−31.87
2000–2003	37.4	37.9	NS	1.55	2542	1941	**	−23.64
2000–2004	37.7	38.8	NS	3.10	2651	2139	**	−19.31
2000–2005	36.4	38.4	**	5.58	2379	1993	*	−16.23
2000–2006	36.1	38.3	***	6.00	2316	1937	**	−16.36
2000–2007	36.1	38.7	***	7.05	2315	1980	**	−14.47
2000–2008	34.2	36.7	***	7.40	1932	1612	**	−16.56
2000–2009	34.2	37.0	***	8.22	1926	1660	**	−13.81
2000–2010	33.7	35.9	**	6.48	1649	1375	**	−16.62
2000–2011	33.5	36.0	***	7.23	1648	1409	**	−14.50

[a] CONV = Conventional management; CONS = Conservation management

[b] *significant at the 10 % level; **significant at the 5 % level; *** significant at the 1 % level and NS not significant

wheat. The average cumulative potato yield was near 4 % higher for PC bean than PC wheat between 2005 and 2011 (Table 7). The experimental period of 2000–2010 showed the greatest difference in cumulative potato yield amongst PCs (5 %), with 2000–2011 providing the lowest difference of significance (4.6 %), as potato crops preceded by bean showed greater yields than those following wheat PCs in both cases.

Findings indicate that potato crops grown through CONS practices, along with bean PCs, are likely to produce significantly higher yields than those produced through CONV management and preceded by wheat.

Potato Total Cost

On average, production costs for one ha of potato totaled \$6, 340. Storage including maintenance, building and climate control, investment cost, depreciation, and insurance (17.6 %), seed (15.2 %), machinery including repairs, investment cost, depreciation, insurance, and fuel cost (14.2 %), compost (10.1 %), and pesticide (8.7 %) were the highest costs of production (Table 8). Labour costs at \$20 hr^{-1} as an opportunity cost for higher skilled agricultural labour requirement was added. The same labour costs for manipulation of

Table 7 Contrasts of average yields and net incomes of potato among years as affected by preceding crop from year 2000 to 2011(compost = \$27 Mg^{-1})

Average year	Yield				Net income			
	After wheat Mg ha^{-1}	After bean	Contrast test[a]	% change	After wheat \$ ha^{-1}	After bean	Contrast test[a]	% change
2000–2001	39.1	39.6	NS	1.12	2562	2679	NS	4.57
2000–2002	35.2	35.4	NS	0.71	1807	1777	NS	−1.66
2000–2003	37.5	37.5	NS	−0.10	2253	2189	NS	−2.84
2000–2004	38.2	38.0	NS	−0.59	2431	2291	NS	−5.76
2000–2005	36.8	37.7	NS	2.56	2060	2254	NS	9.42
2000–2006	36.4	37.6	NS	3.15	2007	2200	NS	9.62
2000–2007	36.5	37.8	NS	3.66	2000	2240	NS	12.00
2000–2008	34.6	35.7	NS	3.35	1639	1814	NS	10.68
2000–2009	34.4	36.0	**	4.86	1601	1870	*	16.80
2000–2010	33.7	35.3	*	5.01	1298	1633	**	25.81
2000–2011	33.6	35.2	*	4.60	1320	1627	**	23.26

[a] *significant at the 10 % level; **significant at the 5 % level; *** significant at the 1 % level and NS not significant

Table 8 Costs for crop rotations under CONV or CONS potato crop management practices from 2000 to 2011 (compost = $27 Mg^{-1})

Rotation[a]	Seed potato	Machinery	Labour	Chemical fertilizer	Compost at $27 Mg^{-1}	Pesticide	Irrigation	Transport	Storage	Other	Total cost when compost at $27 Mg^{-1} [b]	Total cost when compost at $15 Mg^{-1} [b]
	$ ha^{-1}											
3-yr CONV	952	874	356	342	0	547	423	184	1103	948	5730e	5730d
3-yr CONS	952	919	359	188	693	551	423	199	1103	964	6352c	6035b
4-yr CONV	952	902	356	342	0	541	423	205	1103	949	5773d	5773c
4-yr CONS	952	884	354	125	1040	541	423	201	1103	971	6595b	6121a
5-yr CONS	952	897	354	125	1040	541	423	211	1103	972	6619a	6144a
6-yr CONS	952	893	354	125	1040	541	423	208	1103	972	6611ab	6136a
Mean of rotation	952	895	356	208	635	544	423	201	1103	963	6280	5990
% of total cost	15.2	14.2	5.7	3.3	10.1	8.7	6.7	3.2	17.6	15.3	-	-

[a] 3-yr CONV = 3-year rotation under conventional crop management practice; 3-yr CONS = 3-year rotation under conservation crop management practice; 4-yr CONV = 4-year rotation under conventional crop management practice; 4-yr CONS = 4-year rotation under conservation crop management practice; 5-yr CONS = 5-year rotation under conservation crop management practice; 6-yr CONS = 6-year rotation under conservation crop management practice

[b] Values with same letters in a column are not significantly different (P > 0.05)

compost were included in the two compost cost scenarios. Intensive management of potato, compared to other crops, including more frequent use of chemicals and the requirement for compost, tillage, hilling, and harvesting equipment, contributed to increased costs, particularly in short rotations where potato is grown more frequently (Table 8).

Throughout the study, potato costs associated with CONS management practices were significantly higher than those of CONV practices, mainly due to higher compost costs associated with CONS practices (Table 8). Average potato total cost over the 12 years was highest for the 5-yr CONS rotation ($6,619 ha^{-1}) and significantly lower for the 3-yr CONV rotation ($5,730 ha^{-1}) (Table 8). Additionally, total costs for CONS rotations exceeded those of CONV rotations in each of the 12 study years with the greatest difference occurring in 2005 ($6,364 ha^{-1} vs. $5,467 ha^{-1}, for CONS and CONV, respectively) (data not shown). The average potato cost difference between CONV and CONS practices over the 2000–2011 period, was approximately 14 % ($6,544 ha^{-1} CONS vs. $5,751 ha^{-1} CONV). On average, potato crops preceded by wheat, as compared to bean, had lower total costs in 11 of the 12 years (data not shown). The largest difference amongst PCs in average cumulative total cost ($143 ha^{-1}) was seen in the 2000–2011 span (data not shown), as bean exceeded all cumulative cost totals of wheat. The results suggest that the use of CONV practices and wheat PCs result in lower average costs of potato production than that of CONS practices and PCs of bean.

Potato Net Income

Despite higher potato yield under CONS practices, the study found that rotations incorporating CONV practices tended to produce higher average NIs than those using CONS methods, as a result of higher compost costs ($27 Mg^{-1} Table 3, Scenario 1) associated with CONS practices. Average NI was economically significant and higher for 4-yr CONV management ($2,044 ha^{-1}) than all other forms of crop management (Table 3). The second highest NI was found in the 5-yr CONS system ($1,570 ha^{-1}), while the lowest NI came from the 4-yr CONS system ($1,211 ha^{-1}). Although, there were no statistical differences among 3-yr CONV and 3-yr, 4-yr, 5-yr, and 6-yr CONS systems, the large differences, on average, could have significant economic impacts on farm profitability and may require further investigation with a bigger sample size. Only the NI of the 4-yr CONV system was significantly different from all others and was 63 % higher than that of the 3-yr CONV rotation. The 4-yr CONV rotation was also 49 % higher in 12-yr average NI than the average of all other potato rotation methods over the 12-yr period. Rotation affected both potato yield ($P = 0.006$) and potato net income ($P = 0.004$). Additionally, comparison of 12-yr averages found that overall, CONV practices produced significantly more NI ($1,648 ha^{-1}) than that of CONS practices ($1,409 ha^{-1})

(Table 3). The 12-yr average NI was also higher for crops preceded by bean (\$1,627 ha^{-1}), as opposed to wheat crops (\$1,320 ha^{-1}) (Table 3).

Over study years, CONV practices steadily yielded higher NIs than CONS practices, but the differences were not generally significant. Only 2002 showed a statistically significant difference between the two systems, where CONV management exceeded that of CONS management (\$670 ha^{-1} vs -\$379 ha^{-1}) (Table 4). The highest NI for both practices was seen in 2003, where CONV systems produced an average of \$3,559 ha^{-1}, while CONS systems yielded an average of \$3, 260 ha^{-1}.

Earlier years of the study saw higher NIs for potatoes preceded by wheat, while the later years produced higher incomes for those utilizing bean PCs (Table 5). The highest NI for crops employing either PC occurred in 2003, where crops following wheat PCs averaged \$3,589 ha^{-1} and those using bean PCs averaged \$3,426 ha^{-1} (Table 5). The NI for potato preceded by bean in 2005, 2009, and 2010 was significantly higher than the NI for potato after wheat. Both 2008 and 2010 saw crops using either PC produce a deficit in average NI.

Cumulative net potato incomes mirrored those found over average years. From 2001 to 11, crops grown through CONV practices yielded higher average cumulative NIs than those utilizing CONS practices, with differences of significance in 10 of the 11 cumulative measures (Table 6). The largest difference in cumulative NI was seen in the 2000–2002 period, where CONV practices yielded a 31.8 % higher cumulative NI than CONS practices (Table 6). The cumulative net potato income differences between CONV and CONS practices were significant in later years of the experiment, but remained at around 15 % (Table 6).

Potato incorporating the use of bean PCs tended to show higher average cumulative NIs over the years, with the largest difference (24.5 %) occurring over the last two cumulative periods, where bean PCs yielded higher potato crop NIs than wheat PCs (\$1,630 ha^{-1} vs \$1,310 ha^{-1}) (Table 7).

Study findings suggest that when the full cost of compost is taken into account, the use of a 4-yr CONV rotation and bean PCs are likely to yield higher potato crop NI values than those employing shorter 3-yr CONV or CONS practices with wheat PCs.

Overall, results of the study indicate that a significantly higher yield is obtained in potato crops grown through CONS practices and preceded by bean. However, crops grown in CONS rotations also had higher total costs, associated with higher compost application costs, than those grown through CONV practices. The results therefore suggested that the use of 4-yr CONV management systems yielded potato production with higher NIs than crops grown through CONS practices. While higher total costs were associated with the use of bean PCs, these costs were offset by the income they generated, as potato crops which followed bean PCs produced higher NIs than those following wheat PCs. Therefore, given that the objective of the study was to determine the best practices associated with economic gains, findings suggest the use of 4-yr CONV rotations, along with bean PCs, are preferred when attempting to maximize economic returns in potato crop production.

Assuming \$15 Mg^{-1} compost costs, CONV and CONS practices produce statistically equivalent potato NI, with the exception of the 3-yr CONV rotation, which produced significantly less potato NI than any other rotation (Table 3). Additionally, when \$15 Mg^{-1} compost cost was assumed, comparison of 12-yr averages found that overall there is a trend ($P = 0.09$) of CONS rotations producing higher potato NI than CONV rotations (Table 3).

Economic Performance of Entire Rotations

Annual NI of the six potato rotations varied from \$279 to \$642 ha^{-1} (Table 9), compost cost was assumed at \$27 Mg^{-1} and NI was averaged over the period 2000 through 2011. Based on these 12 years of data, the 4-yr CONV rotation generated the highest annual NI (\$642 ha^{-1}) followed by the 3-yr CONV and 3-yr and 4-yr CONS rotations. The statistical differences were mainly due to the frequency of potato in longer rotations relative to shorter rotations, along with income from other crops in the rotations. Potato was the key determinant of NI or profitability of all rotations. When compost cost was assumed at \$15 Mg^{-1}, the annual NI of the 4-yr CONV rotation was still significantly higher than all other rotations, with the exception of the 4-yr CONS system. However, other than 4-yr CONV, the NI of rotations was statistically the same. When \$15 Mg^{-1} compost cost was assumed, the results of annual NI of entire rotations were somewhat different than that of potato alone. Potato NI increased in all CONS rotations, but the average annual NI of the rotation was still highest for the 4-yr CONV system (Table 9).

Management Rankings

The Cumulative Distribution Function (CDF)

Thus far, analysis has been based on point estimates, such as potato mean NI. A risk ranking procedure, that does not rely on summary statistics or point estimates, is the CDF of all simulated outcomes of the potato NI for all six rotations. The CDF chart shows that the 4-yr CONV system is the most preferred management form for potato NI, as this rotation has the highest probability of achieving a greater profit than the other rotations (throughout the range of distributions analyzed), as the 4-yr CONV distribution of NI lies furthest to the right (Fig. 1). Alternatively, the least preferred treatment is potato in 4-yr CONS (lies furthest to the left). Additionally, CDF values for the 5-yr CONS rotation lie closest to those of

Table 9 Comparisons of 12-year (2000–2011) average annual total cost and net income of entire potato rotations

Rotation[a]	Compost = \$27 Mg^{-1}		Compost = \$15 Mg^{-1}	
	Total cost[b] \$ ha^{-1}	Net income[b]	Total cost[b] \$ ha^{-1}	Net income[b]
3-yr CONS	3191a	400bc	3085a	505b
3-yr CONV	2885c	468b	2885c	468b
4-yr CONS	3094b	391bc	2976b	510ab
4-yr CONV	2834c	642a	2834c	642a
5-yr CONS	2843c	279c	2685d	437b
6-yr CONS	2601d	323c	2519e	405b

[a] 3-yr CONV = 3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr CONS = 3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr CONV = 4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr CONS = 4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr CONS = 5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr CONS = 6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

[b] Values with same letters in a column are not significantly different (P > 0.05)

the 4-yr CONV system, while the three alternative rotation practices have values in the middle range (Fig. 1). Therefore, for a given return, the 4-yr CONV system has the lowest risk of return when compared to the other five rotation methods. Based on the CDFs of the six rotations, producers would be least likely to use the 4-yr CONS rotation system. However, as each individual producer may have different risk preferences, the potato system that a producer would choose or adopt cannot be evaluated by the CDF analytical framework alone. Therefore, the concept of SERF is an analytical technique of greater preference.

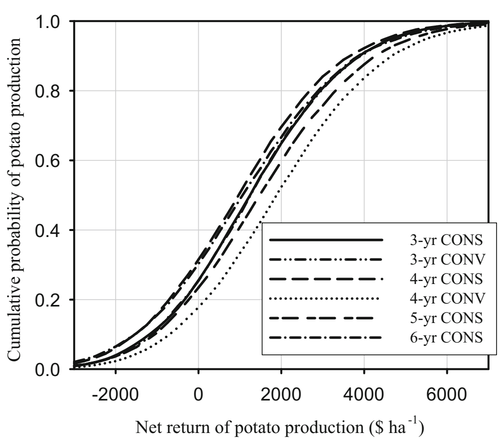

Fig. 1 The cumulative probability of potato net income for different management practices, indicating that the 4-yr CONV system is the most preferred management form for potato net return, as this rotation has the highest probability of achieving a greater profit than the other rotations (throughout the range of distributions analyzed), as the 4-yr CONV distribution of net return lies furthest to the right. 3-yr CONV = 3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr CONS = 3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr CONV = 4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr CONS = 4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr CONS = 5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr CONS = 6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

The Stochastic Efficiency with Respect to a Function (SERF)

Figure 2 presents the SERF approach using a negative exponential utility function. This method identifies the most efficient alternatives for a range of risk preferences by ranking alternatives in terms of certainty equivalents (Khakbazan et al. 2014). The higher CE with the same level of ARAC determines the best potato management alternatives under different individual risk preferences (e.g. risk preferring, risk neutral, moderately risk averse or extreme risk averse).

When ARAC values range from 0 to 0.0018, the 4-yr CONV system reports the highest CE values, indicating 4-yr CONV management is most preferred, as it is the highest utility efficient alternative system (Fig. 2). At this range of ARAC, the 5-yr CONS ranks second, after the 4-yr CONV. At an ARAC value 0.0018, potato growers are indifferent between 3-yr CONV and 3-yr and 5-yr CONS systems (break-even risk aversion coefficient). The 4-yr and 6-yr CONS rotations have the lowest CE values when producers are neutral to moderately risk averse, indicating these rotations would be the least preferred choices (Fig. 2). When potato growers display moderately to very risk averse behavior, their choice of rotation, in terms of rotation length and conservation management practice, may change. For example, when ARAC values are at levels representative of potato farmers with extreme risk averse preferences, the 3-yr CONS system reports the highest CE values. Therefore, among the SERF utility efficient alternatives, the 4-yr CONV rotation represents the risk

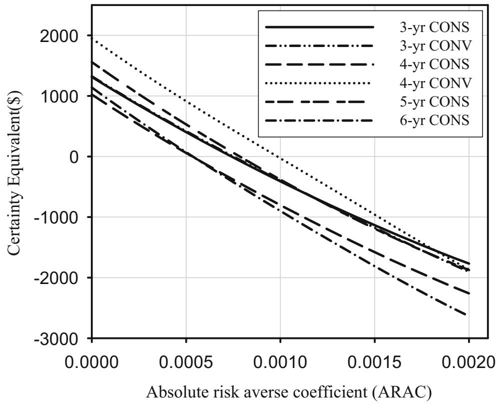

Fig. 2 Stochastic efficiency with respect to a function results over the absolute risk aversion range from 0 to 0.002. The higher certainty equivalent (CE) with the same level of absolute risk aversion coefficient (ARAC) determines the best potato management alternatives under different individual risk preferences. 3-yr CONV = 3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr CONS = 3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr CONV = 4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr CONS = 4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr CONS = 5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr CONS = 6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

preferences of potato farmers who are risk neutral to moderately risk averse preferring.

Discussion

The higher yields associated with CONS practices are in large part a result of the use of manure compost to replace some of the inorganic fertilizer inputs, as organic amendments are known to increase soil quality, in addition to directly providing nutrients for crop development (Zingore et al. 2008). Moore et al. (2011) and Rees et al. (2014) reported increased tuber size when using compost as compared to inorganic fertilizer treatments. Organic amendment use has further been shown to reduce the incidence of potato pathogens, leading to higher crop yields (Molina et al. 2014; Conn and Lazarovits 1999). Through decreased erosion, the reduced levels of tillage found in CONS practices are also likely to result in more fertile soil, thereby improving potato yield (Tiessen et al. 2007). Accordingly, the 5-yr CONS rotation ranked highest for soil quality, with 3- and 4-yr CONV rotations ranking substantially lower (Li et al. 2015).

The larger yields of potato, preceded by bean, as compared to wheat, may be partially due to the ability of legumes to fix N, resulting in greater soil N concentrations than when using wheat as a PC. High soil N concentrations are important in potato production as potato returns of residue to the soil are relatively limited (Carter and Sanderson 2001; Li et al. 2015). Accordingly, higher soil N likely produced larger potato tubers, leading to increases in overall potato weights. Additionally, in 2001, the hottest and driest year on average, the higher yield found in crops using bean PCs (Table 5) may have been a result of the ability of legumes to return moisture to the soil (Stevenson and van Kessel 1996; O'Donovan et al. 2014). In addition to PC type, potato yield and net income variations found amongst 3-yr rotations (3-CONV, 3-CONS) with PC wheat vs. 4-yr rotations (4-CONV, 4-CONS) with PC bean may be due to the 1 year difference in rotation length, or a result of the combination of differences in PC and rotation length. Abnormally low yields may be explained by environmental and/or pathogenic factors, as is described by Larney et al. (2016).

Higher costs involved in the implementation of CONS practices are primarily due to the use of compost over chemical fertilizer. Various costs are similar across rotation methods, with the exception of differences in compost and fertilizer costs found amongst CONS and CONV practices (Table 8). Across all rotations, the use of compost comprises approximately 11 % of the total cost distribution (compared to 3 % for fertilizer) (Table 8), reflecting the higher total costs found amongst rotations utilizing compost application.

The cost of compost greatly exceeds the savings incurred through a reduction in fertilizer use, thereby resulting in an overall increase in costs for CONS systems. Therefore, higher costs of composting and application used in CONS systems, largely exceeds that of the fertilizer in CONV systems, thereby yielding a higher total cost. However, it should be noted that the costs accorded to compost use may be influenced by the source of manure, as producers may have access to more feasible manure outlets.

Though, on average, yields for CONV practices were lower than those for CONS systems, the decreased total costs associated with CONV rotations (Table 8) offset the losses in yield, thereby resulting in a higher overall average NI than that of CONS systems (Table 3). This relationship between CONV and CONS could change if fuel and fertilizer prices (e.g., carbon prices) were to increase. Conversely, the higher yields associated with bean PCs offset the higher costs of potato after bean, relative to wheat, resulting in a higher average NI for potato preceded by bean (Table 3). Thus, use of CONV rotations with bean PCs is likely to produce the highest average NI.

When taking into account the hypothetical situation of \$15 Mg^{-1} compost cost, NI values amongst 4-yr CONV and 3-, 4-, 5-, and 6-yr CONS rotations narrow, as CONS total costs are substantially reduced (Table 3). At this lower compost cost, the mean potato NI of the 5-yr CONS rotation comes to match that of the 4-yr CONV rotation (\$2044 ha^{-1}). As such, a potato producer having access to more feasible compost sources (i.e. advanced technology, cheaper manure compost, compost produced on-farm) may be more likely to utilize CONS management for potato production, than producers limited to the use of higher cost compost (i.e. \$27 Mg^{-1}). These findings further highlight the influence of compost costs on the overall NI of potato production.

Reduced compost costs are also associated with greater similarity in NI of entire rotations. Entire rotations using the 4-yr CONV system produce a substantially higher NI than any CONS rotation when \$27 Mg^{-1} compost is used (Table 9). However, a decrease in the price of compost to \$15 Mg^{-1} greatly reduces this difference, as total costs of CONS rotations are reduced (Table 9). However, the entire 4-yr CONV rotation still produces a significantly higher NI than the entire rotations of all other methods, suggesting the 4-yr CONV system in economically preferred when accounting for the NI of each crop in the rotation.

Results indicate that the 4-yr CONV rotation is the most preferred system, based on CDF values (Fig. 1), and would be most preferred amongst producers who are risk neutral to moderately risk averse (Fig. 2). Alternatively, the 4-yr CONS rotation is least preferred based on CDF values, and one of the least preferred systems throughout the SERF value range. These findings support those of NI measures, which found that the 4-yr CONV rotation had the highest average NI amongst rotations, while the 4-yr CONS rotation had the lowest (Table 3). Therefore, findings of production preferences appear to be in-line with those of economic production values, and suggest that on average, the 4-yr CONV system is most preferred amongst rotation methods.

Conclusions

The economic performance of an irrigated potato rotation study in southern Alberta, Canada was assessed from 2000 through 2011. Results of the study indicated that a significantly higher yield was obtained in potato crops grown through CONS practices and preceded by bean. However, crops grown in CONS rotations also had higher total costs, associated with higher compost application costs, than those grown through CONV practices. The results therefore suggested that the use of 4-yr CONV (potato–wheat– sugar beet–dry bean) management systems yielded potato production with higher NI than crops grown through CONS practices. The risk ranking and risk efficiency alternatives also showed that the 4-yr CONV system was the most preferred management form for potato NI, as this rotation had the highest probability of achieving a greater profit than the other rotations and potato growers with risk neutral to moderately risk averse preferring would prefer this rotation. Potato was the key determinant of NI or profitability of all rotations. The NI differences were mainly due to the frequency of potato in longer rotations relative to shorter rotations, along with income from other crops in the rotations. Therefore, given that the objective of the study was to determine the best practices associated with economic gains, findings suggest the use of 4-yr CONV rotations, along with bean PCs, are preferred when attempting to maximize economic returns in potato crop production.

Assuming a hypothetical scenario where composting technology is improved, or where opportunity cost of labour for composting is zero (if family labour is mostly being used), or producers have access to more feasible and cheaper manure compost outlets (\$15 Mg^{-1} compost costs), CONV and CONS practices produce statistically equivalent potato NI, with the exception of the 3-yr CONV rotation, which produced significantly less potato NI than any other rotation. However, the annual average NI of the 4-yr CONV rotation was still significantly higher than all other rotations, with the exception of the 4-yr CONS system.

While these findings suggest that the 4-yr CONV rotation is the preferred economic choice, a paper from the same experiment showed the 5-yr CONS rotation ranked highest for soil quality, with 3- and 4-yr CONV rotations ranking substantially lower (Li et al. 2015). This study considered only the direct contribution of compost in improving crop yields. Compost application provides additional benefits to soil fertility and soil quality. It may potentially improve or change long-term plant-soil systems and reduce harmful pathogens as rotations continue to mature. Although this study did not take into account these benefits, a connection between soil quality in alternative management systems and economic value was explored by Belcher et al. (2003). Furthermore, while our results show the 4-yr CONV rotation as dominant under most reasonable conditions, this could change if carbon-based inputs become more expensive or if compost becomes relatively less expensive. Previous studies of 2-, 3- and 4-yr rotations in Manitoba have demonstrated significant losses of soil and soil organic matter in shorter conventional rotations (Khakbazan et al. 2009; Mohr et al. 2011). As such, economic gain must be weighed against the long-term economic and environmental sustainability of rotations. Soil losses may contribute to nutrient movement into the environment while declines in soil quality may lead to reduced soil productivity. For capital intensive ventures like potato production, sustained productivity and economic returns may be necessary to cover costs for land, equipment, and storage facilities, which may be amortized over decades. In addition to soil losses, increases in disease prevalence and losses in productivity may be associated with shorter conventional rotations (Carter and Sanderson 2001). Current findings suggest that potato growers will likely be better-off economically by using the 4-yr CONV rotation with bean as PC, provided growers are willing to ignore the long-term contribution of compost to improve productivity of plant-soil systems.

Acknowledgments We thank Nathan Barry, Jim Sukeroff, Dale Reynolds, staff and summer students at the AAFC Vauxhall Sub-station and Brandon Research and Development Centre for field and technical assistance. Ron Gregus assisted with potato management. Jenifer Nitschelem (2000–2006) and Peter Regiting (2007–2011), Rogers Sugar Ltd./Lantic Inc. (Taber, AB) managed sugar beet husbandry. Funding contributions from the Alberta Agricultural Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers; Lantic Inc., Agriculture and Agri-Food Canada, and the Pulse Science Cluster are greatly appreciated.

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Am. J. Potato Res. (2017) 94:105–119
DOI 10.1007/s12230-016-9551-3

Energy Use Efficiency of Conventional versus Conservation Management Practices for Irrigated Potato Production in Southern Alberta

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Published online: 30 December 2016

Abstract A 12-yr. (2000–2011) study was conducted in Alberta, Canada to compare the energy use efficiency (EUE) of conventional (CONV) and conservation (CONS) potato (*Solanum tuberosum* L.) management practices. Potato was grown in 3- to 6-yr. rotations which included dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.), soft wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), and timothy (*Phleum pratense* L.). CONS included compost application, reduced tillage, cover crops, and solid-seeded bean. Findings suggested that potato in 5-yr. CONS produced the highest EUE compared to the other CONS or CONV rotations. CONS can be used as a means of reducing the reliance on non-renewable energy inputs and improving overall EUE of potato production when less than 21% of the N content of compost applied was counted toward energy input use of potato production. At more than 21%, potato in the 4-yr. CONV became more favorable compared to potato in other rotations.

Resumen Se condujo un estudio de 12 años (2000–2011) en Alberta, Canadá, para comparar la eficiencia en el uso de energía (EUE), en prácticas de manejo convencional (CONV) y de conservación (CONS) en papa (*Solanum tuberosum* L.). Se cultivó la papa en rotaciones de 3 a 6 años, que incluía frijol (*Phaseolus vulgaris* L.), remolacha azucarera (*Beta vulgaris* L.), trigo suave (*Triticum aestivum* L.), avena (*Avena sativa* L.) y el pasto fleo (*Phleum pratense* L.). El CONS incluía la aplicación de composta, labranza mínima, cultivos de cobertura y frijol de semilla sólida. Lo que se encontró sugirió que la papa, en un CONS de 5 años, producía la más alta EUE, comparada con las otras rotaciones CONS o CONV. El CONS puede usarse como un medio para reducir el respaldo en la aportación de energía no renovable, y mejorando la EUE en general de la producción de papa cuando se contaba con menos del 21% del contenido de N de la composta aplicada, hacia el uso de la aportación de energía de la producción de papa. A más del 21%, la papa en los 4 años de CONV, se volvía más favorable en comparación a la papa en otras rotaciones.

Keywords Potato crop rotation · Compost · Irrigation · Soil conservation · Energy use indicators · Greenhouse gas emission

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Introduction

The non-renewable energy inputs (EI) of crop production systems play a prominent role in resultant energy outputs (EO). While EO may be measured in terms of yield produced, inputs include fuel expenditures, equipment manufacturing, seeding, and fertilizer application, among others. The difference in EI and EO determines the net energy of cropping systems, and may be used to calculate the energy use efficiency (EUE) of various forms of crop management. As EI correlates with monetary expenditures, it is imperative that crop producers attain the greatest EUE in order to maximize economic gains.

In the last two decades, the potato industry has served a prominent role in agricultural production in Alberta, Canada (Carew et al. 2009), contributing over $1 billion of economic value to the Alberta economy (Market Analysis and Information Section 2015; Mehr 2016). In 2013, Alberta growers planted over 20,000 ha of potato, which produced more than 828,850 t. The province has become the largest exporter of seed potato in Canada, and a major contributor of potato to the food processing industry (Mehr 2016). Given the influence of potato production on Alberta's agriculture industry, knowledge regarding the most energy efficient means of potato production is of current benefit to growers. While CONV methods of potato management have traditionally been employed, interest in CONS practices have been gaining ground as growers seek more efficient methods of production. Additionally, recent demand in Canadian organic potato production has outpaced levels of supply (Lynch et al. 2008), buttressing support for further study into the most energy efficient practices available to potato producers.

Energy expenditures in crop production are influenced by the means in which crops are managed. Conventional potato management has traditionally relied on high inputs of inorganic fertilizer, while CONS systems utilize organic amendments (e.g. manure compost) in place of synthetic fertilizer sources. In Western Canada, inorganic fertilizer and fuel usage can account for >80% of the non-renewable energy expended in crop management (Zentner et al. 2004). Furthermore, N fertilizer, the primary fertilizer type applied to agricultural crops, has increased nearly 80-fold since the 1920s (Gellings and Parmenter 2004). Given the high costs, energy requirements, and negative environmental impacts associated with inorganic fertilizer production (Gellings and Parmenter 2004), the use of organic alternatives has garnered significant interest. Palmer et al. (2013) reported that potato crops utilizing manure as fertilizer produce lower yields than those employing synthetic fertilizer, mainly due to a reduction in available soil N when manure is used. As organic fertilizer regularly contains less nutrients per unit weight when compared to inorganic sources, energy demands associated with compost transportation and application are often higher than inorganic fertilizers (Gellings and Parmenter 2004). Alternatively, Eid and El-Sayed (2012) conducted a field experiment during the two summer seasons of 2009 and 2010 in sandy soil in Egypt to study the effect of using 100% compost and 50% compost + nitrogen fixing bacteria on potato growth and yield as compared to the conventional mineral fertilization treatment. They found no significant differences in tuber yields when comparing compost- and mineral fertilizer-fed potato crops; however, mineral fertilization produced a significantly high yield per hectare than using 50% + any biofertilizer treatment. Furthermore, compost addition benefits crops in a two ways; (1) through the direct provision of nutrients, and (2) by improving soil quality through the introduction of microorganisms and increasing water-retention ability (Gellings and Parmenter 2004).

Energy usage in crop production is also indicative of the level of tillage employed. In contrast to CONV systems, CONS practices are associated with an absence or reduction in the levels of tillage involved in crop management. One drawback of reduced tillage is a tendency for increased occurrences of in-crop weeds, resulting in losses of CONS crop yields (Mundy et al. 1999). As a result, higher rates of pesticides may need to be applied to limit crop loss, thus increasing the energy expenditure of production (Zentner et al. 2004). Alternatively, reducing tillage can have a number of benefits, including: increased soil organic matter and improved soil structure (Carter et al. 2009), reduced soil erosion (Ivany et al. 2007), and increased soil water content (Mundy et al. 1999). Zentner et al. (2004) found that cropping systems utilizing reduced tillage lowered energy use through decreases in fuel consumption and machinery operation. Such findings were consistent with other North American studies that reported modest to moderate reductions in energy use when conservation tillage was used (Lockeretz 1983; MacRae et al. 2010; Nagy 2000; Smolik et al. 1995; Zentner et al. 1998). Some studies (Borin et al. 1997) outside of North America have reported significant energy savings and/or improvements in energy use efficiency when minimum and zero tillage practices have been used. However, Khakbazan et al. (2015) showed tillage practices seem to have a minimal impact on energy use efficiency when compared to other nitrogen management practices.

The rotation and sequence in which crops are planted can affect net energy measures of crops involved. In fact, studies suggest that of all the aspects of crop management, rotation decisions may have the greatest impact on crop energy inputs (Bullock 1992). Furthermore, crop sequences can influence soil nutrient concentrations, and thus, yields of subsequent crops. While Angers et al. (1999) found that continuous potato production depleted the soil of vital nutrients, Nelson et al. (2009) found that organic potato production utilizing extended rotations resulted in improved soil quality over potato systems which lacked such rotations. Similar soil benefits were also identified in a study by Carter et al. (2009), who found that rotations restored soil nutrients lost during the potato phase of production. Lynch et al. (2008) suggest that the incorporation of legumes into potato rotations provides the benefit of returning N to the soil, a finding consistent with that of Khakbazan et al. (2015) who highlighted the effect of legume crops on the success of subsequent crops. Thus, legume crops and rotations play an important role in the overall production of potato crops.

The objective of this study was to evaluate energy input, energy output, and EUE for CONV and CONS potato management practices over a 12-yr. period in southern Alberta in an effort to determine the production method with the greatest environmental and economic benefits. Conservation management involved the implementation of cover crops, reduced tillage, compost manure application, and where dry bean occurred, narrow-row seeding.

Materials And Methods

Field Experiment

The 12-yr. (2000–2011) agronomic study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50° 03′ N, 112° 09′ W, elev. 781 m). The study site had predominantly Orthic Brown Chernozemic soils, and was cropped uniformly in 1999 to spring barley. Growing-season (April 1 to September 30) precipitation averaged 295 mm, and air temperature averaged 13.7 °C (Table 1). This section provides only a brief description of the design and implementation of the experiment, as specifics are provided in Larney et al. (2015).

Rotations used either CONS or CONV crop management practices. CONS management centered on the following four practices: 1) direct seeding or reduced tillage where possible in the rotation; 2) fall-seeded cover crops where possible; 3) composted cattle manure as a substitute for inorganic fertilizer; and 4) straight cutting of solid seeded narrow-row (19–23 cm) bean. CONV management used none of these practices, and hence the CONV rotations had more intensive fall tillage, no cover crops, no organic amendments and dry bean was grown in wide rows (60 cm). Of the four practices, reduced tillage and manure compost application apply most directly to production of the potato crop, while cover cropping and solid-seeded narrow-row planting pertain to the production of the bean crops. Details of the management treatments used in the CONS rotations were provided by Larney et al. (2015).

Potato was grown in six rotations under CONV or CONS management: two 3-yr. (CONV and CONS) and two 4-yr. (CONV and CONS) rotations, one 5-yr. (5-CONS), and one 6-yr. (6-CONS) rotation (Table 2). The 3-yr. CONV and CONS rotations had similar crop sequences (potato–dry bean–wheat), as did the 4-yr. CONV and CONS rotations (potato–wheat–sugar beet–dry bean). The 5-yr. CONS rotation was comprised of two phases of wheat interspersed with the three row crops (potato–wheat–sugar beet–wheat–dry bean), while oat and timothy were included in the 6-yr. CONS (potato–oat–timothy–timothy–sugar beet–dry bean). Each phase of each rotation appeared in each year, resulting in a total of 26 phases (Table 2) arranged in a randomized complete block design with four replicates (104 plots). Individual plots were 10.1 × 18.3 m (185 m^2), with a 2.1 m wide inter-plot between plots. The number of rotation cycles at the end of the 2011 growing season (12 years) ranged from 4 (3-yr. rotations) to 2 (6-yr. rotation) (Table 2). All crops were grown to maturity, except oat in the 6-year rotation, which was harvested as silage in mid- to late July to allow for timely planting of timothy in late August. Potato harvest took place between 30 August (2005) and 25 September (2002), with a mean date of 14 September (n = 12). Potato plots were fertilized (receiving 135 kg N ha^{-1}; 67 kg P_2O_5 ha^{-1}; and 67 kg K_2O ha^{-1}) for the 3- and 4-yr. CONV rotations in the previous fall, except for 2000, when potato plots were fertilized in the spring. Potato plots in CONS rotations received a lower rate of N (37 kg N ha^{-1}), and zero P, to account for the N and P in compost. Compost, derived from beef feedlot manure, was fall-applied (except 2003 when application was postponed by wet conditions until spring) at five entry points (four of which preceded potato, while one preceded wheat) in the CONS rotations (Table 2). In the shorter 3-yr. CONS rotation, compost was applied at a rate of 28 Mg ha^{-1} (fresh wt.) between wheat and potato. In the longer 4-yr. CONS, 5-yr. CONS and 6-yr. CONS rotations, a higher rate (42 Mg ha^{-1} fresh wt.) was applied between dry bean and potato. Compost was sourced from the same feedlot each year and had average concentrations (dry wt., n = 11, fall 2000–10) of 182 g kg^{-1} total C, 15.4 g kg^{-1} total N, and 5.4 g kg^{-1} total P. Energy content of seed potato was subtracted from harvested tuber potato yield. Estimated energy coefficients associated with production of fuel, fertilizer, compost and pesticide are shown in Table 3. Irrigation water was applied to the plots using a wheel-roll sprinkler system to maintain soil water content at ≥50% field capacity. However, irrigation costs were estimated based on a low pressure pivot sprinkler system which is the most common

Table 1 Weather conditions at Vauxhall from 2000 to 2011

Year	Precipitation (mm)		Air temperature (°C)	
	Growing season (Apr – Sept)	Year total	Growing season (Apr – Sept)	Year total
2000	171.6	227.1	14.0	5.4
2001	117.7	183.6	15.0	6.6
2002	466.2	560.9	12.6	4.9
2003	230.4	342.9	14.2	5.5
2004	255.8	340.7	13.3	5.9
2005	506.7	590.6	13.4	6.3
2006	274.4	285.0	14.7	6.3
2007	205.7	348.7	13.7	7.1
2008	316.8	391.8	12.9	5.1
2009	245.1	341.4	13.7	4.2
2010	346.2	469.8	12.7	5.1
2011	246.3	340.7	13.6	5.0
Average	281.9	368.6	13.7	5.6

Source: Environment Canada 2016

Table 2 Crop rotations under CONV or CONS crop management practices from 2000 to 2011

Rotation[a]	Crop sequence[b]	# of phases	# of plots	No. rotation cycles[b]
1-yr. CONT	Wheat	1	4	12
3-yr. CONV	Potato–Dry bean–Wheat	3	12	4
3-yr. CONS	Potato[c]–Dry bean[c]–Wheat[d]	3	12	4
4-yr. CONV	Potato–Wheat–Sugar beet–Dry bean	4	16	3
4-yr. CONS	Potato[c]–Wheat–Sugar beet–Dry bean[d]	4	16	3
5-yr. CONS	Potato[c]–Wheat–Sugar beet[d]–Wheat–Dry bean[d]	5	20	2.4
6-yr. CONS	Potato[c]–Oat/(Timothy)[e]–Timothy–Timothy–Sugar Beet–Dry bean[d]	6	24	2
Total		26	104	

[a] Integer refers to length or rotation; CONT, continuous; CONV, conventional management; CONS, conservation management

[b] No. rotation cycles =12 (yr)/no. crop phases

[c] Fall-seeded cover crop entry point: fall rye [except oat, 2000–02, on 3-yr. CONS (between dry bean and wheat), 4-yr., 5-yr., and 6-yr. CONS]

[d] Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-yr. CONS; 5-yr. CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-yr. CONS; 5-yr. CONS after dry bean; 6-yr. CONS) applied after harvest, except 2003 (postponed to spring 2004 due to wet soil conditions)

[e] Oat harvested as silage in July, timothy direct seeded in late August

irrigation practice in Alberta. Amounts of irrigation water varied according to crop demand and prevailing weather conditions. Cover crops did not immediately precede potato in any rotation, and therefore did not directly impact potato establishment (Table 2).

Energy Statistical Analysis

Process analysis was used to assess the energy performance of management systems (Fluck and Baird 1980). This involved identifying all direct and indirect non-renewable energy going

Table 3 Energy content of potato, as well as estimate of energy associated with production of fuel, fertilizer, and pesticide

Potato tuber, fuel and fertilizer	Energy content	Pesticide trade name	Pesticide common name	Energy content (a.i or a.e.)[a]
	MJ kg^{-1}			MJ L^{-1} or MJ kg^{-1}
Product		Admire	Imidacloprid	68.69
Potato	3.60	Ambush	Permethrin	160.50
		Bravo 500	Chlorothalonil	252.00
Machinery		Curzate 60 DF	Cymoxanil	129.60
Fuel (diesel)	43.99	Cymbush	Cypermethrin	38.52
Lubricants	43.80	Dithane or Manzate	Mancozeb	162.00
		Eptam-8E	EPTC	144.38
Fertilizer		Gramoxone	Paraquat	63.10
N	70.88	Kocide	Copper hydroxide	64.80
P	12.44	Lance WDG	Boscalid	151.20
K	11.15	Lorsban	Chlorpyrifos	117.60
		Maverick III[b]	Gglyphosate DMA salt	217.92
		Monitor 480	Methamidophos	128.40
		Movento 240 SC	Spirotetramat	77.04
		Poast Ultra	Sethoxydim	146.12
		Reglone Desiccant	Diquat	83.23
		Roundup[b]	Glyphosate K+ salt	245.16
		Sencor	Metribuzin	109.50
		Success	Spinosad	154.08

[a] a.i. or a.e. = chemical active ingredient

[b] Roundup also includes products such as R/T540, Roundup Transorb HC, Roundup Ultra2 and Roundup WeatherMax., and Maverick III includes products such as Matrix and Vantage Plus MAX II

Source: Alluvione et al. 2011; Houshyar et al. 2010; Nagy 1999, 2000; Zentner et al. 2004, 2011 into manufacturing, formulation, packaging, transportation, maintenance, and application of all purchased inputs used for potato in each phase of the cropping system, and the energy content of all products removed from the fields for each management system. The physical quantities of inputs used were converted to energy values using the most recent energy coefficients taken from literature (Table 3) and adjusted for manufacturing technology improvements as described by Nagy (1999, 2000). Rates of fuel and lubricant use for tractors and other powered machinery were reported by Saskatchewan Agriculture, Food and Rural Revitalization (2014). Recommended work rates and travel speeds were assumed for all field operations. Definitions of the major energy terms used were listed in Table 4. Non-renewable energy input, gross energy output, net energy, output energy/input energy ratio, potato tuber yield per unit of energy input, quantity of potato produced per unit of greenhouse gases (GHG) emitted from inputs, and cost Mg^{-1} of carbon retained for potato production were analyzed in terms of effects of cropping rotations, and crop conventional and conservation management practices in southern Alberta.

Seed potato was not included as energy input; instead, the seeds were subtracted from the harvested potato. Energy associated with human labor, changes in soil organic matter or plant nutrients were not included in the analysis as these sources of energy were considered negligible, and while energy received directly from the sun is large, differences between cropping systems would be minimal (Zentner et al. 2004, 2011). Storage, including maintenance, building and climate control, transportation, and fuel related to transportation, was classified under "other" energy input. Subsequent processing of the potato beyond the point of initial sale was not included in energy use.

Gross energy output was calculated as gross energy content of the harvested tuber yield less the seed requirements. Energy in the crop straw was not included as energy output of the treatments since the straw was returned to the land except for calculation of cost Mg^{-1} of carbon retained indicator where total carbon retained in potato tuber and above ground residue was required.

Energy content of compost was calculated based on N and P content of compost. The following formula was used to calculate energy content of compost.

$$C_e = \text{compost}^* C_n {}^*13\%^* 70.88 + \text{compost}^* C_p \ {}^*60\%^* 12.44$$

Where C_e is energy content in compost, compost is kg of compost applied to each treatment, C_n is N content of compost measured to be 1.54%, 13% is the percentage of total N contained in compost that is available to crops for uptake during the compost application year (Olson et al. 2010), 70.88 is energy content in N (Nagy 1999), C_p is P content of compost measured to be 0.54%, 60% is percentage of total P contained in compost available to crops during the compost application year for uptake (Olson et al. 2010), and 12.44 is energy content of P (Nagy 1999).

Liu (1995) estimated carbon intake for various crop types, using dry matter as the primary factor. A modified version of Liu's procedure was used in the current study to estimate carbon intake by potato. We divided carbon intake into two parts; carbon intake for crop residues that remain in the field and carbon intake for potato tuber that is removed. Total C intake for potato tuber and residues was estimated using the following equation:

$$EC_i = \frac{1\text{−HI}}{\text{HI}} {}^*Y_i {}^*(1{-}W_i) {}^*\text{CC} + Y_i {}^*(1{-}W_i) {}^*\text{CC}$$

where EC_i is the intake of carbon by $_i$th potato crop in kg ha^{-1}, HI the harvest index for potato at 0.56 (Helgason et al. 2005; Janzen et al. 2006), Y_i the yield of $_i$th potato crop in kg ha^{-1}, W_i the water content, expressed as a proportion of plant biomass, and CC the carbon content of dry plant matter. Moisture content of the potato was assumed to be 75%. Carbon content on a dry matter equivalent basis of C fixation was set at 0.45 g

Table 4 Major energy terms used and their definitions

Energy term	Definition
Direct energy	Energy inputs used in production when such inputs can be directly converted into energy units (e.g., diesel fuel and lubricants).
Indirect energy	Energy used in producing inputs used in the crop production process when such inputs cannot be converted directly into energy units (e.g., manufacturing of machinery, fertilizers and pesticides).
Total energy input	Total direct energy + total indirect energy
Gross energy output	(harvested seed or grain – seed) × energy coefficient
Net energy output	Gross energy output – total energy input
Net energy balance or energy use efficiency indicator	Energy output / energy input ratio, harvested production per unit of energy input, quantity of potato produced per unit of GHG emitted, cost per Mg^{-1} of carbon retained

of carbon g^{-1} of dry matter. Below-ground residue and roots of crops were not included in our study.

Energy efficiencies or intensities of the rotations and management systems were calculated as (1) net energy produced (energy output minus energy input); (2) ratio of energy output to energy input; (3) quantity of potato harvested per unit of energy input; (4) quantity of potato harvested per unit of GHG emitted from inputs; and (5) total production cost per unit of carbon retained (\$ Mg^{-1}), defined as total cost of production ha^{-1} (Khakbazan et al. 2009) divided by total C retained ha^{-1}. This cost per unit of carbon retained provides insight as to which treatment is economically more efficient. The lower the cost, the more efficient the management system is. Production cost was estimated for potato and reported by Khakbazan et al. (2016).

The base results assumed 13% of N and 60% of P contents of compost were utilized by the potato crop when compost was applied and the rest remains in the soil for subsequent crops to use if not lost (Olson et al. 2010). Two scenarios were also developed to check the sensitivity of results if (1) higher percentage of N content in compost is utilized by the potato crop or (2) regardless of N availability, if all N content of compost is utilized by the potato crop when compost was applied. For the base and both scenarios, potato yields remain the same and only different N content in compost was counted in the potato year. In the first scenario we searched for N rate in compost where potato energy efficiency in CONV and CONS was nearly the same, and in the second scenario we assumed 100% of N content in compost was utilized by the potato crop when compost was applied. Not all N content in compost can be utilized by potato in the potato year. This scenario seeks to account for 100% of N contained in applied compost to potato in CONS and compare it with inorganic fertilizer N applied in CONV system. For the base and two additional scenarios we assumed 100% of N applied to potato in CONV rotations was utilized by potato crop and nothing remained in the soil for subsequent crops to use.

The energy performance results are expressed on a per hectare basis for the rotation system and for crop CONV and CONS management practices. The SAS Proc MIXED procedure (SAS/STAT 9.3 User's Guide) was conducted to determine the impact of crop rotation system and CONV and CONS management practices on total energy input, total energy output, net energy, energy output to energy input reatio, crop yield harvested per unit of energy, cost Mg^{-1} of carbon retained, and potato produced per unit of emitted GHG for irrigated potato production. With the MIXED procedure, the management practice was used as the fixed effect variable, while block and replicates were used in the random effect variables. Contrast statements were used in the MIXED procedure to test for impacts of CONV vs CONS practices on EUE indicators over all 12 years (2000–2011), considered significant at $P < 0.05$.

Results And Discussion

Potato Tuber Yield

The 5-yr. and 6-yr. CONS rotations produced significantly higher potato yields than CONV rotations. The 12-yr. (2000–11) average potato yield (Mg ha^{-1}) was highest for the 5-yr. CONS rotation (37.8 Mg ha^{-1}), and significantly lower for the 3-yr. CONV rotation (31.9 Mg ha^{-1}) (Table 3 in Khakbazan et al. 2016). The 5-yr. CONS rotation produced 18% higher potato yields than the 3-yr. CONV rotation. Compost application may have caused significant potato yield improvement, as the 5-yr. CONS system received compost at two entry points, one of which preceded potato. Averaged over 12 years, CONS management practices provided higher average potato yields (36.0 Mg ha^{-1}) than CONV practices (33.5 Mg ha^{-1}) (Table 3 in Khakbazan et al. 2016). Potato yield results indicated that potato crops grown using CONS practices are likely to produce significantly higher yields than those produced through CONV management.

Non-Renewable Energy Input Assuming 13% N Compost Availability

Energy input in potato production varied with the method of input management and with rotational practices (Table 5). The 12-yr. (2000–11) average energy inputs for irrigated potato production among 6 rotations varied from 39.8 GJ ha^{-1} to 42.4 GJ ha^{-1} for 3-yr. CONV and 5-yr. CONS, respectively (Table 5). The intensive management of potato, including more frequent use of inputs (eg. chemicals, fertilizer, compost), tillage, hilling, and specialized harvesting equipment, contributed to increased energy consumption relative to other crops. Averaged over 12 years and averaged over rotations and management practices, the percentage of energy inputs for inorganic fertilizer (15.79%) was lower than irrigation (23.04%), and machinery and fuel (20.35%), due to the application of compost in CONS systems. Other energy uses, including storage buildings, maintenance and climate control, transportation, and fuel related to transportation, was approximated to be 22.07% of total energy input use. Fuel used for farm machinery operation, irrigation, and transportation constituted the highest proportion of total energy inputs in the potato production process. Fertilizer and compost alone accounted for approximately 31% of the energy used in potato production. For non-potato crops, fertilizer energy accounted for 62–70% of the total energy requirements on Thin Black Chernozems (Zentner et al. 2004).

Of the 12 experimental years, statistical differences in energy inputs among rotations were found only in 2005, 2009, and 2011 (Table 5). Energy input for potato tended to be the lowest in 2008 and 2010 for all rotations as compared to other study years because excess moisture and flooding damaged

Table 5 Total energy input and output for potato production from 2000 to 2011 (13% of N and 60% of total P in compost were utilized in the first year potato production)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean 2000-11
	GJ ha^{-1}												
Input													
3-yr CONV	41.3	44.8	31.0	42.6	41.4	32.9c	46.5	48.9	35.4	41.9c	26.2	34.3bc	39.8
3-yr CONS	41.3	48.4	32.7	44.3	42.3	35.0bc	47.8	51.7	36.1	43.0c	29.7	34.4bc	41.4
4-yr CONV	40.2	49.1	32.9	42.7	41.0	36.3ab	48.2	51.4	35.3	44.7b	30.7	33.4c	40.7
4-yr CONS	39.6	47.2	29.6	44.2	41.4	38.2a	47.9	50.5	34.4	45.5ab	29.5	35.8ab	40.7
5-yr CONS	40.3	49.5	31.9	43.5	43.6	35.0bc	47.3	53.8	37.0	46.1a	28.9	36.7a	42.4
6-yr CONS	39.7	49.2	31.2	43.8	43.1	37.6ab	48.6	49.4	36.5	45.7a	28.9	36.8a	40.8
P-value	0.904	0.1257	0.5544	0.9843	0.5858	0.0153	0.8162	0.1696	0.1235	<0.0001	0.761	0.0114	0.1655
Output													
3-yr CONV	134.6	124.6	87.1	143.8	135.3	80.4d	112.6	114.8	62.4b	104.1d	42.3	109.0bc	107.7c
3-yr CONS	126.9	141.8	101.3	157.6	146.6	97.6c	126.2	140.9	71.6ab	116.4c	69.8	109.6bc	119.7b
4-yr CONV	125.3	159.9	101.9	144.8	131.8	113.4ac	126.1	139.9	65.9bc	126.7b	78.6	101.8c	119.2b
4-yr CONS	121.0	134.5	78.6	156.0	135.9	131.8a	127.8	136.7	62.6b	137.0ab	73.2	121.7ab	119.4b
5-yr CONS	126.6	152.6	97.3	150.9	153.4	105.8bc	123.0	163.0	83.8a	142.2a	68.2	129.4a	128.8a
6-yr CONS	121.3	150.5	90.9	153.2	149.9	126.9ab	133.5	127.5	79.9ac	139.1a	68.1	129.5a	120.8ab
P-value	0.9643	0.2022	0.6306	0.9857	0.5194	0.0048	0.7135	0.0992	0.0492	<0.0001	0.7720	0.0087	0.0065

[a] If the *P*-value >0.05, the LSM values are not significant and multiple comparisons are omitted for each section. If *P*-value ≤0.05, multiple comparisons are conducted and the LSM values with same letters in a column for each section are not significantly different ($P > 0.05$). 3-yr. CONV =3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr. CONS =3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr. CONV =4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr. CONS =4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr. CONS =5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr. CONS =6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

crops, and fewer inputs were applied. In normal years with good growing conditions, nearly 41 GJ ha^{-1} of energy was used to meet energy requirements for field activities, such as harvesting, transporting, and storing potato crops. These findings are consistent with those reported in India and Iran (Gulati and Singh 2011; Pishgar-Komleh et al. 2012). Other studies conducted in different parts of the world have reported a range of energy input requirements from 28.4 GJ ha^{-1} to 157.15 GJ ha^{-1} for potato production depending on the soil fertility conditions, agronomic practices, technology used, and the method of potato production (Koga et al. 2013; Zangeneh et al. 2010). The application of chemical fertilizer, diesel and farm machinery, and irrigation were the major sources of energy expended in potato production (Bakhtiari et al. 2015; Mohammadi et al. 2008). Some of the studies (Bakhtiari et al. 2015; Mohammadi et al. 2008; Zangeneh et al. 2010;) conducted in Iran have reported very high energy inputs (81–157 GJ ha^{-1}), due to higher application of chemical fertilizer and perhaps outdated irrigation methods and technologies. New technologies and lower use of chemical fertilizers were found to be the most important factors affecting energy use as compared to other potato production studies conducted elsewhere.

Throughout the study, potato energy input associated with CONV management practices was similar or slightly lower than that of CONS practices, mainly due to the high quantity of compost used in CONS treatments (Table 5). Most of the N requirements for the CONS treatments were met with compost, thereby reducing the overall need for application of N fertilizers. Average potato energy input over the 12 years was highest for the 5-yr. CONS rotation (42.4 GJ ha^{-1}), but was not statistically different from other rotations ($P = 0.17$, Table 5). Compared to CONV management practices, CONS management practices increased total potato energy inputs by 2.6% on average because actual N energy content of compost applied in CONS was higher than N energy of synthetic fertilizer applied in CONV rotations.

Energy Output

Energy output for potato was significantly influenced by crop rotation and varied among CONV and CONS practices. The 12-yr. (2000–11) average energy output was highest for the 5-yr. CONS rotation (128.8 GJ ha^{-1}), as compared to the 3-yr. CONV (107.7 GJ ha^{-1}) or the 3-yr. CONS (119.7 GJ ha^{-1}) rotations, reflecting the higher potato yield produced in the 5-yr. CONS rotation (Table 5). The 5-yr. CONS rotation produced nearly 20% higher potato energy output than the 3-yr. CONV rotation. Compost application caused a significant increase in potato yield (Larney et al. 2015) and therefore energy output, as the 5-yr. CONS system received compost at two entry points, one of which preceded potato.

Average energy outputs were not statistically different among 4-yr. CONV and 3-yr. and 4-yr. CONS rotations; however, the energy output for the 3-yr. CONV rotation was nearly 10% lower than all other rotations.

Energy output for potato also varied greatly among years (Table 5), generally reflecting the growing conditions and weather variability at the test site. When individual years were assessed, statistical differences in energy outputs among rotations were found only in 2005, 2008, 2009, and 2011 (Table 5). The highest energy outputs measured in a specific year were in 2001 and 2003, for 4-yr. CONV (159.9 GJ ha^{-1}) and 3-yr. CONS (157.6 GJ ha^{-1}) rotations respectively, while the lowest energy output were measured in 2010, for 3-yr. CONV (42.3 GJ ha^{-1}) rotation (Table 5). Energy output for potato was lowest in 2010 for all rotations as compared to other study years because of low potato yield due to excess moisture and flooding which significantly affected crop yield (Larney et al. 2015). The potato crop in 2008 also experienced excess moisture and flooding that caused damage to yield. The largest significant difference in potato energy output occurred in 2009, with the 5-yr. CONS rotation yielding 37% more energy output than the 3-yr. CONV rotation. Results suggested that, for the entire 12-yr. period, the highest energy outputs for potato were achieved in the 5-yr. CONS rotation, although it was not statistically different from the potato energy output in the 6-yr. rotation. Overall, compared to CONV management practices, CONS management practices increased total potato energy output by 7.7% due to higher potato yield harvested under the CONS system.

Energy output for potato averaged 119.3 GJ ha^{-1} over the length of the experiment. In studies conducted in Iran and India under different environmental conditions, using different technologies and nutrient management practices, energy output for potato production was reported to range from 102 to 157 GJ ha^{-1} (Bakhtiari et al. 2015; Hamedani et al. 2011; Mohammadi et al. 2008; Yadav et al. 2015; Zangeneh et al. 2010). An earlier study by Pimentel et al. (1983) reported only 84.8 GJ ha^{-1} energy output for conventional potato production in USA while the same potato production required 66.3 GJ ha^{-1} of energy inputs (lower energy output with much higher energy input). Energy output in our study was nearly 41% higher and energy input requirement was 40% less compared to the study by Pimentel et al. (1983), reflecting the improvement in potato technologies and management practices over time.

Net Energy and Energy Use Efficiency Assuming 13% N Compost Availability

Net energy (gross energy output minus energy input) displayed similar trends among rotations as for potato gross energy output. Averaged over all years, crop rotation was found to significantly affect potato net energy ($P = 0.0046$). When 13% of the N in compost and 60% of the P were assumed to be available in years when compost was applied, the study found that the 5-yr. CONS rotation tended to produce higher average potato net energy than those using CONV methods. Over study years, potato in rotations using CONS practices consistently generated higher net energy than potato in rotations using CONV practices due to the higher yields harvested in the CONS system. The average potato net energy difference between CONV and CONS practices over the 2000–2011 period was approximately 10% (80.8 GJ ha^{-1} CONS vs. 73.2 GJ ha^{-1} CONV). The lowest potato net energy occurred in the 3-yr. CONV system (67.9 GJ ha^{-1}). The net energy output for potato in the 5-yr. CONS rotation was 27% higher than that of the 3-yr. CONV rotation. Average potato net energy was higher for the 5-yr. CONS rotation (86.4 GJ ha^{-1}) than all other forms of crop management (Table 6). The 5-yr. CONS rotation was also 13% higher in 12-yr. average net energy of the average of all other potato rotation methods over the 12-yr. period. When individual years were assessed, statistical differences in net energy among rotations were found in 2005, 2008, 2009, and 2011 (Table 6). The highest net energies for specific years were found in 2001 and 2003, for 4-yr. CONV (110.7 GJ ha^{-1}) and 3-yr. CONS (113.3 GJ ha^{-1}) practices, respectively. The lowest net energy was measured in 2010, for the 3-yr. CONV (16.1 GJ ha^{-1}) rotation as most crops that year were severely affected by extremely wet conditions (Table 6).

The average output to input energy ratio over all rotations in 12 years was 2.88. That is, for every unit of energy used, 2.88 units of energy output were harvested. Energy ratios, as affected by rotation, varied from 3.01 for the 5-yr. CONS rotation to 2.68 for the 3-yr. CONV rotation (Table 6). The effects of management on net energy and energy ratio were statistically significant. Of the 12 experimental years, statistical differences in energy ratios among rotations were found in 2005, 2008, 2009, and 2011 (Table 6). Generally, within a given year, a higher ratio were found for rotations with CONS practices, while the lowest ratio was measured in 2010, for 3-yr. CONV (1.62) rotation (Table 6).

In comparison to other studies, Gulati and Singh (2011) reported an energy ratio of 1.4 for potato production in India. Taheri and Shamabadi (2013) studied the effects of planting date and plant density on the yield and energy efficiency of potato tuber production in Iran and reported a low output to input energy ratio of 1.3 due to the relatively lower tuber yields (19.62 Mg ha^{-1}) produced in their experiment. An earlier study by Pimentel et al. (1983) on EUE for conventional potato farming systems in New York State found

Table 6 Net energy output and energy use efficiency (output energy/input energy ratio) for potato production from 2000 to 2011 (13% of N and 60% of total P in compost were utilized in the first year potato production)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean 2000–11
Net													
3-yr. CONV	93.3	79.8	56.0	101.2	93.9	47.5d	66.1	65.9	27.0c	62.2d	16.1	74.7bc	67.9c
3-yr. CONS	85.6	93.4	68.5	113.3	104.3	62.6cd	78.4	89.2	35.5abc	73.4c	40.1	75.2bc	78.3b
4-yr. CONV	85.1	110.7	69.0	102.1	90.8	77.1abc	78.0	88.5	30.6bc	82.0c	47.9	68.3c	78.5b
4-yr. CONS	81.3	87.3	48.9	111.8	94.5	93.6a	79.9	86.2	28.2c	91.5a	43.7	85.9ab	78.6b
5-yr. CONS	86.2	103.1	65.3	107.4	109.9	70.7bc	75.7	109.3	46.8a	96.1a	39.3	92.6a	86.4a
6-yr. CONS	81.7	101.3	59.7	109.4	106.8	89.3ab	84.9	78.1	43.3ab	93.4a	39.2	92.8a	80.0b
P-value	0.9658	0.204	0.6399	0.9859	0.5077	0.0041	0.6935	0.0901	0.0405	<0.0001	0.7695	0.0084	0.0046
Output energy/input energy ratio													
3-yr. CONV	3.26	2.76	2.74	3.36	3.25	2.44c	2.41	2.33	1.75c	2.48c	1.62	3.17c	2.68b
3-yr. CONS	3.06	2.93	3.08	3.53	3.47	2.79b	2.64	2.72	1.98abc	2.70b	2.34	3.18bc	2.87a
4-yr. CONV	3.09	3.25	3.10	3.24	3.20	3.12ab	2.60	2.72	1.86bc	2.83b	2.56	3.04bc	2.90a
4-yr. CONS	3.04	2.83	2.64	3.52	3.28	3.44a	2.66	2.69	1.81c	3.01a	2.45	3.39ac	2.90a
5-yr. CONS	3.11	3.07	3.04	3.42	3.52	3.01b	2.59	3.02	2.26a	3.08a	2.36	3.52a	3.01a
6-yr. CONS	3.04	3.06	2.83	3.47	3.45	3.36a	2.74	2.56	2.17ab	3.04a	2.31	3.52a	2.92a
P-value	0.9458	0.162	0.683	0.968	0.4277	0.0017	0.6408	0.0853	0.0289	<0.0001	0.6741	0.0092	0.0224

[a] If the *P*-value >0.05, the LSM values are not significant and multiple comparisons are omitted for each section. If *P*-value ≤0.05, multiple comparisons are conducted and the LSM values with same letters in a column for each section are not significantly different ($P > 0.05$). 3-yr. CONV =3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr. CONS =3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr. CONV =4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr. CONS =4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr. CONS =5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr. CONS =6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

an energy ratio of only 1.28 compared to a ratio of 3 obtained in our study. This again reflects improvements in technologies and management practices over time including more efficient use of N fertilizer. Energy studies comparing conventional and low-input farming systems for non-potato crops in other parts of Canada (Clements et al. 1995), the USA (Clancy et al. 1993), and Europe (Dalgaard et al. 2001; Haas et al. 2001; Hülsbergen et al. 2001) have also reported higher energy efficiency for crops produced under low-input systems.

Study findings therefore suggest that when 13% of the N and 60% of the P in compost were assumed to be used by potato, the 5-yr. CONS rotation was likely to yield a higher potato net energy and energy ratio than shorter 3-yr. and 4-yr. CONV or CONS rotations. Overall, results of the study indicated that a significantly higher net energy and energy efficiency was obtained in potato crops grown using CONS practices.

Crop Yield Harvested per Unit of Energy Inputs

Potato yield, measured in kg GJ^{-1} of non-renewable energy input varied as a function of rotation and management from 797 (3-yr. CONV) to 885 (5-yr. CONS) (Table 7). The average energy use efficiency was higher for potato in the 5-yr. CONS than the 3-yr. CONV because more potato yield was harvested per unit of energy used. Potato yield produced per GJ of energy input was similar for 4-yr., 5-yr., and 6-yr. CONS rotations. The low potato yield produced per GJ of energy input in year 2008 and 2010 shows the impact of excess moisture and flooding in these two years, reflecting the fact that climate variability could have significant impacts on non-renewable energy efficiency, especially in cropping seasons with more occurrences of extreme events.

The average tuber yield per unit of energy input in this study was 851 kg GJ^{-1}, while Gulati and Singh (2011) and Taheri and Shamabadi (2013) reported only 387 kg and 460 kg GJ^{-1} in India and Iran, respectively, because of lower potato yields in their experiments. Bakhtiari et al. (2015) studied energy, GHG emissions and economics of potato production in the East-Azerbaijan Province of Iran and found only 269 kg of potato tuber harvested GJ^{-1} of energy input, due to a higher application of chemical fertilizer and the outdated irrigation and technologies used, which required more energy inputs. Studies have reported that the energy use efficiency of Canadian agricultural production systems has generally increased over time as a result of technology improvements that have resulted in output outpacing increases (and in some cases decreases) in energy inputs (Swanton et al. 1996; Weseen et al. 1999; Zentner et al. 2004).

Table 7 Yield harvested per gigajoule (GJ) input and cost of carbon retained for potato production from 2000 to 2011 (13% of N and 60% of total P in compost were utilized in the first year potato production)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean 2000-11
Potato yields harvested per GJ input													
	------------------------kg GJ^{-1}------------------------												
3-yr CONV	954	812	828	980	951	739c	713	688	544c	737c	526	940bc	797b
3-yr CONS	898	854	918	1027	1011	832bc	775	794	605ac	798b	717	943bc	847a
4-yr CONV	908	945	922	949	939	923ab	764	795	573bc	832b	777	904c	856a
4-yr CONS	894	828	802	1024	959	1009a	782	788	563c	881a	749	998ab	857a
5-yr CONS	915	893	907	996	1023	894b	763	878	682a	900a	725	1033a	885a
6-yr CONS	896	890	852	1010	1007	987ab	803	753	659ab	888a	711	1033a	863a
P-value	0.9439	0.1602	0.6865	0.9681	0.4212	0.0016	0.6337	0.0829	0.0269	<0.0001	0.6715	0.0091	0.0233
Cost of carbon retained													
	------------------------$ Mg^{-1}------------------------												
3-yr CONV	1369	1627	2189	1306	1369	2092a	1689	1718	2757	1735a	3645	1552ab	1819
3-yr CONS	1495	1443	1809	1228	1261	1781b	1507b	1400	2428	1579b	2447	1560ab	1637
4-yr CONV	1521	1279	1769	1587	1394	1535bc	1537	1390	2624	1458bc	2154	1660a	1646
4-yr CONS	1534	1542	2251	1215	1359	1358c	1492	1447	2711	1367cd	2390	1437bc	1662
5-yr CONS	1490	1366	1850	1305	1223	1658bc	1545	1231	2108	1320d	2447	1348c	1531
6-yr CONS	1535	1360	2274	1261	1265	1416c	1439	1566	2243	1351cd	2627	1350c	1675
P-value	0.9245	0.1333	0.7223	0.8611	0.5214	0.0022	0.6987	0.1709	0.0636	<0.0001	0.4426	0.0218	0.0859

[a] If the *P*-value >0.05, the LSM values are not significant and multiple comparisons are omitted for each section. If *P*-value ≤0.05, multiple comparisons are conducted and the LSM values with same letters in a column for each section are not significantly different ($P > 0.05$). 3-yr. CONV =3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr. CONS =3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr. CONV =4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr. CONS =4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr. CONS =5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr. CONS =6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice

Conservation management contributed significantly to the amount of potato yield per unit of energy input. A comparison of accumulated potato yield harvested GJ^{-1} input indicated that CONS systems were more efficient than CONV systems (data not shown). The difference between CONS and CONV was not significant at the beginning of the study, but as the study progressed there was an approximate 11% difference between these two management systems in terms of potato yield harvested GJ^{-1} input (data not shown). Potato yield, measured in kg GJ^{-1}, of non-renewable energy input was 863 for CONS as compared to 827 under the CONV system (Table 8).

Potato yield harvested per kg of GHG emitted was also calculated for different rotations and for CONV and CONS systems (Table 9). Similar to potato harvested per GJ^{-1}, there were significant effects of rotation and management system on potato harvested per kg of GHG emitted. Assuming 13% N availability from compost, rotation and management system influenced potato harvested per unit of GHG emitted, with CONS was more efficient than CONV. Potato yield harvested per kg of GHG emitted was not significantly different among rotations except in the case of the 3-yr. CONV rotation (Table 9). Potato yield harvested per kg of GHG emitted in 3-yr. CONV rotation was significantly lower than other rotations except for the 3-yr. CONS rotation (Table 9). The CONS system produced 3% higher potato yield per kg of GHG emitted than the CONV system (Table 9). On average, 7.4 kg of potato was produced per kg of GHG emitted. Bakhtiari et al. (2015) reported that 7.79 kg of potato tubers were harvested for every kg of GHG emitted, although, they used a somewhat different method to calculate GHG emission.

Another index developed to measure the GHG efficiency of management systems was cost Mg^{-1} of carbon retained (carbon retained in the system and not emitted). This index indicated that the CONS system was more cost-effective than CONV because the cost Mg^{-1} of carbon retained was lower for CONS than CONV. As the values in Table 8 show, costs were \$1626 Mg^{-1} of carbon retained under CONS versus \$1733 under CONV, over \$100 Mg^{-1} less for CONS than CONV. That is, potato in CONS rotations was 6% more efficient than under CONV management (Table 8). Results indicated that the cost of potato produced Mg^{-1} of carbon retained was the lowest for the 5-yr. CONS rotation (\$1531 Mg^{-1}), while it was highest for potato in the 3-yr. CONV rotation (\$1819 Mg^{-1}) (Table 7). The results, however, showed that there was no statistical difference among rotations and management systems for potato cost Mg^{-1} of carbon retained, although there was a statistical trend. Of the 12 experimental years, statistical differences in potato yield harvested GJ^{-1} input among

Table 8 Effect of crop management practices on net energy output, energy ratio and potato yield harvested per gigajoule (GJ) input under different compost N utilization rates from 2000 to 2011

Crop management practice[a]	Compost *N* = 13%	Compost *N* = 21%	Compost *N* = 100%
Net energy output (GJ ha^{-1})			
CONV	73.2	73.2	73.2
CONS	80.8	77.8	47.5
P-value	0.0034	0.0549	<0.0001
Output energy/input energy ratio			
CONV	2.79	2.79	2.79
CONS	2.93	2.72	1.68
P-value	0.0147	0.1594	<0.0001
Potato yield harvested per GJ input (kg GJ^{-1})			
CONV	827	827	827
CONS	863	803	496
P-value	0.0155	0.0754	<0.0001
Cost per Mg^{-1} carbon retained (\$ Mg^{-1})			
CONV	1733	1733	1733
CONS	1626	1626	1626
P-value	0.0577	0.0577	0.0577

[a] *CONV* Conventional management, *CONS* Conservation management

rotations were found in 2005, 2008, 2009, and 2011 (Table 7). Similarly, potato cost Mg^{-1} of carbon retained was significant in 2005, 2009, and 2011.

Energy Efficiency of Potato Management with Higher Rate of N in Compost

Until now, the results discussed were under the assumption that when compost was applied, only 13% of the N available in compost was utilized or credited to the potato year. Results so far suggested that energy efficiency variables for potato crops were significantly affected by rotation and management, and that CONS was more energy efficient than CONV. The results were also affected when the assumption for the N content in compost, of year applied, changed. If a higher rate of N in compost were utilized or counted in the potato year, the energy balance of management systems would change, and thus the potato energy use efficiency ranking of management systems would change as well. Two scenarios were developed: first, we calculated the N rate in compost where the potato energy use efficiency in CONV and CONS was nearly the same; and second, we assumed that 100% of the N in compost was utilized by the potato crop, which followed in the year after compost was applied. Note that only a portion of N content in compost can be utilized in the first year by potato and the rest remains in the system for subsequent crops to use if not lost. However, the two scenarios hypothesized were situations where more than 13% of N content in compost is utilized by potato, affecting energy input balance. While potato yield and therefore energy output was assumed to be the same, total energy inputs of potato in the CONS rotations significantly increased as a higher proportion of the N in compost was utilized or counted in the potato year. When a greater proportion of the compost N was utilized in the potato year, the result was a higher potato energy input used in CONS and therefore increased energy inputs in the CONS versus CONV potato system. The energy efficiency of CONV and CONS was the same when it was assumed that approximately 21% of the N in compost was used in the potato year (Table 8). If 21% of the N in the compost applied were utilized by the potato year, net energy, output to input energy ratio, and potato yield harvested GJ^{-1} input of CONV and CONS were statistically the same. With the 21% N assumption, net energy of CONS was 77.8 GJ ha^{-1} and net energy of CONV was 73.2 GJ ha^{-1}, and both were statistically the same. In terms of potato produced per unit of energy used, about 803 kg of potato was produced GJ^{-1} of energy versus 827 kg GJ^{-1} under CONV, but both systems were statistically the same, in terms of energy use efficiency (Table 8). Also, at the 21% of N assumption, rotation and management had no significant effect on yield harvested per GHG emitted indicator.

As we assumed that a higher percentage of compost N was utilized as part of the energy input used for potato production, the CONV system became more energy efficient and preferable to the CONS system because the N energy content of the actual compost (28 or

Table 9 Effect of rotation and crop management on potato yield harvested per kg greenhouse gases (GHG) emitted under different compost N energy utilization for potato production from 2000 to 2011

Crop rotation and management practice[a]	Compost N = 13%	Compost N = 21%	Compost N = 100%
Rotation			
3-yr. CONV	6.99b	6.99	6.99b
3-yr. CONS	7.3ab	7.16	6.03c
4-yr. CONV	7.45a	7.45	7.45a
4-yr. CONS	7.41a	7.19	5.6d
5-yr. CONS	7.62a	7.40	5.79cd
6-yr. CONS	7.47a	7.25	5.65d
P-value	0.0457	0.156	<0.0001
Crop management practice			
CONV	7.22	7.22	7.22
CONS	7.45	7.25	5.77
P-value	0.0473	0.771	<0.0001

[a] If the P-value >0.05, the LSM values are not significant and multiple comparisons are omitted for each section. If P-value ≤0.05, multiple comparisons are conducted and the LSM values with same letters in a column for each section are not significantly different ($P > 0.05$). 3-yr. CONV =3-year rotation (potato-bean-wheat) under conventional crop management practice; 3-yr. CONS =3-year rotation (potato-bean-wheat) under conservation crop management practice; 4-yr. CONV =4-year rotation (wheat-sugar beet-bean-potato) under conventional crop management practice; 4-yr. CONS =4-year rotation (wheat-sugar beet-bean-potato) under conservation crop management practice; 5-yr. CONS =5-year rotation (potato-wheat-sugar beet-wheat-bean) under conservation crop management practice; 6-yr. CONS =6-year rotation (oat(timothy)-timothy-timothy-sugar beet-bean-potato) under conservation crop management practice. CONV = Conventional management; CONS = Conservation management

42 Mg ha^{-1}) plus 37 kg ha^{-1} of inorganic fertilizer applied in CONS was higher than the N energy of inorganic fertilizer applied in the CONV rotations. With 100% N content hypothetically utilized in the potato year, potato yield harvested GJ^{-1} input was 827 kg GJ^{-1} in CONV versus only 496 kg GJ^{-1} in CONS. Both the net energy and the output to input energy ratio were significantly higher under CONV than CONS management (Table 8).

As we moved toward the assumption that 100% of the compost N is credited toward potato production energy use, CONV became more efficient than CONS management because, with more N in actual compost applied, energy inputs counted toward the potato year led to higher energy input and more GHG emissions. With the 13% of N assumption, for every unit of GHG emitted, 7.45 kg of potato were harvested under CONS, compared to 7.22 kg of potato under CONV (Table 9). At 100% N utilization, the result was the opposite. Where under CONS only 5.77 kg of potato was harvested per every unit of GHG emitted, 7.22 kg of potato was harvested under CONV. CONS systems with compost application eliminated synthetic fertilizers needs and reduced other external inputs (Pimentel et al. 2005). However, if the entire energy content of the actual compost (28 or 42 Mg ha^{-1}) were counted in the potato year, it does not necessarily improve the environmental and farm economics of CONS systems. This is because the 100% of N energy content of the actual compost plus the 37 kg ha^{-1} of inorganic fertilizer applied to CONS was higher than the N energy in inorganic fertilizer applied to CONV systems. Compost can result in other soil and agronomic benefits, but those were not considered in this study.

Summary And Conclusions

The objective of this paper was to compare net energy differences found among CONV and CONS potato management practices and rotations, to determine the production method with the greatest EUE. Our findings indicated different results under different N availability assumptions for the compost applied to potato. If only 13% of total N and 60% of total P in the compost applied to potato was credited to the potato crop, the study found that the 5-yr. CONS rotation tended to produce higher average potato net energy than those rotations using CONV methods. The net energy output for potato in the 5-yr. CONS rotation was 27.2% higher than that of the 3-yr. CONV rotation. The energy output to input ratio for potato was also higher for the 5-yr. CONS rotation (3.01) than the 3-yr. CONV rotation (2.68), and more potato was harvested per GJ of non-renewable energy input in the 5-yr. CONS (885 kg) than the 3-yr. CONV rotation (797 kg). In 2000–2011, average potato net energy output was 10% higher for CONS than CONV and the cost per Mg of carbon retained was 6.6% lower for CONS than CONV. Overall, results of the study indicated that a significantly higher net energy and energy efficiency was obtained in potato crops grown using CONS practices, particularly for the 5-yr. CONS rotation.

The results of this study were affected when the assumption regarding the crop utilization of N in compost changed for the year that compost was applied. If a higher rate of N utilization is assumed in the potato year with potato yields remaining the same, the energy balance of the management systems change and the energy efficiency ranking of the management systems also change. If it was assumed that 21% of the N in compost was utilized in the potato year (rather than 13%), the EUE of CONV and CONS were the same, meaning both systems were equally energy efficient. As a higher percentage of N from compost application was assigned toward energy input used in potato, the CONV system became more energy efficient and preferable to the CONS because the N energy content of the actual compost applied in CONS surpassed the N energy of inorganic fertilizer applied in the CONV rotations. The CONS systems with compost application eliminated synthetic fertilizers needs and reduced other external inputs; however, if the entire energy content of the compost is counted towards the potato year, it does not necessarily improve the environmental and farm economics of the CONS systems. Although not all of the compost N is used in the first potato year, most of the N applied as compost remains in the soil system and gradually becoming available for crop uptake in subsequent growing seasons. Thus, accounting for a portion of compost N availability in the potato year is a valid assumption, and therefore concluding that CONS is more energy efficient than CONV is not an unrealistic scenario. Provided this is a valid assumption, if the primary focus of producers is to reduce the energy intensity of their potato production, CONS systems are favoured including the use of organic compost, cover crops, and reduced level of tillage where possible. Compost also results in other soil and agronomic benefits that were not discussed in this study. If more than 21% of N in compost is assigned to the energy input used in potato production, then producers should continue with the conventional systems as Khakbazan et al. (2016) showed that the 4-year CONV was the most economical rotation among all of the rotations studied.

Weather and climate variability significantly affected the non-renewable energy balance, especially in growing seasons (2008 and 2010) when wet conditions and extreme events occurred. Our results demonstrated better energy use efficiency for potato production systems than that reported in earlier studies in the USA or current potato studies elsewhere, likely as a result of technology-driven increases in energy output outpacing increases (and in some cases decreases) in energy inputs.

Acknowledgements We thank Dustin Dilay, Nathan Barry, Jim Sukeroff, Dale Reynolds, staff and summer students at the AAFC Vauxhall Sub-station and Brandon Research and Development Centre for field and technical assistance. Ron Gregus assisted with potato management. Jenifer Nitschelem (2000-2006) and Peter Regiting (2007-2011), Rogers Sugar Ltd./Lantic Inc. (Taber, AB) managed sugar beet husbandry. Funding contributions from the Alberta Agriculture Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers; Lantic Inc., Agriculture and Agri-Food Canada, and the Pulse Science Cluster are greatly appreciated.

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Published March 9, 2017

Economics of Conventional and Conservation Practices for Irrigated Dry Bean Rotations in Southern Alberta

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ABSTRACT

Given the tripling of irrigated dry bean (*Phaseolus vulgaris* L.) production in Alberta and interest in conservation (CONS) practices to improve production sustainability, a 12-yr study was conducted to evaluate the economic effects of CONS rotations. Dry bean was grown in 3- to 6-yr CONS and conventional (CONV) rotations, which included potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), soft wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), and timothy (*Phleum pratense* L.). Conservation methods included solid-seeded narrow-row bean, cover crops, reduced tillage, and compost application. The 12-yr results showed that average differences among dry bean yields in CONV and CONS rotations were marginal; however, the net income (NI) of bean in CONV rotations was higher than bean crops in CONS rotations, mainly due to greater seed expenditures for bean in CONS practices. The 12-yr findings showed NI of CONV practices was CAN\$122 ha^{-1} higher than CONS. Risk efficiency analysis showed CONV was preferred over CONS. The 4-yr CONV (potato–wheat–sugar beet–bean) was the preferred rotation. In the last 2 yr of study, bean yield and NI in CONS rotations were significantly higher than bean in CONV due to the undercutting of bean in CONS rotations; therefore, it is possible that the long-term use of undercutting practices may result in a greater adoption preference for CONS management over that of CONV systems.

Core Ideas

- Average differences among bean yields in conventional and conservation rotations were marginal.
- Net income in conventional management was \$122 ha^{-1} higher than net income in conservation practices.
- Risk efficiency analysis shows 4-yr conventional preferred to all other rotations.
- Undercutting narrow-row bean in conservation increased yield and net income than bean in conventional.
- Higher net income of undercutting narrow-row bean may result in a greater adoption of conservation.

Published in Agron. J. 109:576–587 (2017)
doi:10.2134/agronj2016.08.0480
Received 26 Aug. 2016
Accepted 22 Dec. 2016

In recent decades, southern Alberta has played a prominent role in dry bean production in Canada. In Alberta, dry bean production grew substantially from 20,400 t in 1993 to nearly 66,000 in 2014 (Statistics Canada, 2016). This growth was correlated with a doubling in harvested dry bean area, and yield (kg ha^{-1}) increases of >30%, during the same time period (Statistics Canada, 2016). With exports to the United States, the United Kingdom, and South America, dry bean has become Alberta's most profitable pulse crop (Alberta Pulse Growers, 2016). In light of the increased dry bean hectareage, and given the economic importance of the crop to Alberta's pulse industry, it is of interest to investigate potentially beneficial practices in the implementation of dry bean rotations.

Dry bean yields may be influenced by row spacing. Studies found narrow-row (e.g., 20–25 cm) spacing reduced dry bean yield when compared to wide-row (e.g., 60 cm or more) spacing (Alberta Pulse Growers, 2015). However, other findings indicated that narrow-row spacing produced higher dry bean yield (Varner et al., 2010). Narrow-row spacing can also provide a variety of benefits over wide-row spacing including more efficient sunlight uptake per unit area and decreased weed populations, due to denser plant canopies (Malik et al., 1993); reduced erosion from rainfall, providing better soil quality; and decreased intra-row nutrient and water competition, as plants within the same row are dispersed further from one another (OMAFRA, 2016). Larney et al. (2015) reported that when dry bean was seeded into shredded stubble, cases of white mold, a fungal disease of high prevalence in dry bean crops of southern Alberta (Saindon et al., 1993), were lower among narrow-row crops. Narrow-row bean crops may be planted using CONV seeding equipment, eliminating the need for the purchase of wide-row planters, and expanding the opportunity for bean cropping to growers lacking such specialized equipment (Fleury, 2014). These benefits provided improved dry bean yield and economic returns which motivated a large number of Alberta bean growers to shift to utilizing narrow-row cropping systems (Fleury, 2014).

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Abbreviations: ARAC, absolute risk averse coefficient; CDF, cumulative distribution function; CE, certainty equivalents; CONS, conservation; CONV, conventional; NI, net income; PC, preceding crop; SERF, stochastic efficiency with respect to a function.

The use of cover crops can affect the productivity of subsequent crops. Cover crops may provide a multitude of benefits to the underlying soil and crop, including reduced weed incidence, high levels of crop residue, increased soil moisture content, protection from wind and water erosion, and a decrease in the prevalence of diseases (Blackshaw, 2008; Blackshaw and Molnar, 2008). As a result of the benefits associated with cover crops, soil quality is improved and dry bean yields may increase. Furthermore, as dry bean is considered a poor weed competitor, the weed supressing ability of cover crops is important in systems which utilize reduced levels of tillage, such as those in CONS practices (Blackshaw and Molnar, 2008). It was also discovered that the use of fall cover crops of barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), and rye (*Secale cereale* L.) contribute to increases in dry bean yield, while spring seeded crops have no such effect (Blackshaw, 2008). Additionally, it was suggested that cover crops are best utilized where preceding crops leave little residue, as cover crops provide the necessary ground cover for soil protection (Blackshaw, 2008).

Crop rotation, crop sequence, and preceding crops (PCs) have been shown to improve soil properties ((Bezdicek and Granatstein, 1989; Havlin et al., 1990; Campbell and Zentner, 1993; Christenson et al., 1995; Krupinsky et al., 2006) and crop yield and profitability (Hesterman et al., 1986; Zentner et al., 2002; Khakbazan et al., 2014; O'Donovan et al., 2014). Benefits may occur in the form of nutrient returns to the soil, by way of soil protection from wind- and water-based erosion, or by improving yield and net return of subsequent crops. Blackshaw and Molnar (2008) found that dry bean yields benefited from wheat PC when no cover crop was used, as wheat stubble provided soil benefits similar to that of the cover crop. Therefore, PCs such as wheat may compensate for situations where cover crop residue contributions are limited or absent, highlighting the importance of crop rotation in maximizing producer yields. Halloran et al. (2005) noted three benefits of crop rotation including crop yield and income improvement, fewer input requirements, and reduced variability in income and economic risk. Thus, rotation plays an important role in the overall productivity of seeded crops.

The use of compost (e.g., beef feedlot manure) in crop production is viewed as an alternative to that of inorganic fertilizer application. Compost use confers a number of potential advantages over inorganic fertilizer, including an increase in soil organic matter (Li et al., 2015), nutrients (e.g., N, P, K, and Mg) (Edmeades, 2003), and beneficial microorganisms (Tarkalson et al., 1998), while reducing soil-borne diseases (N'Dayegamiye et al., 2013). Ultimately, these soil benefits aid in crop growth, thereby increasing overall yields and profitability (Singer et al., 2010). Alternatively, compost use may result in higher costs for producers who use the CONS practice (Khakbazan et al., 2016).

Reduced tillage has been associated with increased crop yield and economic returns, mainly as a result of the reduced soil degradation commonly found in CONV tillage practices (Li et al., 2015; Williams et al., 2010). Although the use of zero tillage in dry bean production has been slow to develop, the practice has shown promise for dry bean growers (Blackshaw and Molnar, 2008). Blackshaw et al. (2007) found the use of zero-till management resulted in no significant differences in crop disease or pest infestation, had no effect on either dry bean yield or maturity date when compared to CONV tillage practices. In addition to maintaining soil quality, reduced tillage has the added benefit of reducing costs through a decrease in machinery use and fuel consumption normally incurred through tillage practices (Khakbazan et al., 2009).

Studies on stochastic efficiency analyses for crop yield and NI over different crop rotations, tillage systems, and CONV and CONS management practices were reported by Meyer-Aurich et al. (2009), Williams et al. (2010), and Hardaker and Lien (2004). Meyer-Aurich et al. (2009) studied tillage practices in Germany and found that CONV tillage would be preferred by moderate- and higher-risk averse producers. Khakbazan et al. (2016) analyzed the risk premiums of six crop rotations for irrigated potato production in southern Alberta, Canada, and reported that the 4-yr CONV rotation (potato–wheat–sugar beet–dry bean) was the most preferred management for potato NI, as this rotation had the highest probability of achieving a greater profit than the other rotations and potato growers with risk neutral to moderately risk averse preferring would prefer this rotation.

Given the issues described above, a 12-yr study was initiated in southern Alberta to evaluate CONV bean production and to examine the impact of alternative CONS rotations. Dry bean was grown in 3- to 6-yr CONS and CONV rotations, which included potato, sugar beet, soft wheat, oat, and timothy. The CONS practices included narrow-row dry bean seeding, cover cropping, reduced tillage and the addition of compost manure. The objective of this paper was to determine NI differences among CONS and CONV dry bean rotation systems, and the impact of risk preferences on the ranking of these systems.

MATERIALS AND METHODS

Field Experiment

The 12-yr (2000–2011) agronomic study was conducted at the Vauxhall Sub-station of Agriculture and Agri-Food Canada (50°03′ N, 112°09′ W, elevation 781 m) in Alberta, Canada. The study site was an Aridic Cryoll (Soil Survey Staff, 2010) soil, and was cropped uniformly in 1999 to spring barley. Growing-season (1 April–30 September) precipitation averaged 290 mm and air temperature averaged 13.8°C. This section provides only a brief description of the design and implementation of the experiment, as specifics are provided in Larney et al. (2015).

Rotations used either CONS or CONV crop management practices. The CONS management centered on the following four practices: (i) direct seeding or reduced tillage where possible in the rotation, (ii) fall-seeded cover crops where possible, (iii) composted cattle manure as a substitute for inorganic fertilizer, and (iv) straight cutting of solid seeded narrow-row (19–23 cm) dry bean. The CONV management used none of these practices, and hence the CONV rotations had more intensive fall tillage, no cover crops, no organic amendments and dry bean was grown in wide rows (60 cm). Of the four practices, cover cropping and solid-seeded narrow-row planting pertain most to the production of bean crops. Details of CONS management treatments on the CONS rotations were provided by Larney et al. (2015).

Dry bean (bean) was grown in six rotations under CONV or CONS management: two 3-yr (3-yr CONV and 3-yr CONS) rotations, two 4-yr (4-yr CONV and 4-yr CONS) rotations, one 5 yr (5-yr CONS), and one 6 yr (6-yr CONS) (Table 1). The 3-yr CONV and 3-yr CONS rotations had similar crop sequences (dry bean–wheat–potato), as did the 4-yr CONV and 4-yr CONS (dry bean–potato–wheat–sugar beet) rotation. The 5-yr CONS rotation comprised two phases of wheat interspersed with the three row crops (potato–wheat–sugar beet–wheat–dry bean), while oat and timothy were included in the 6-yr CONS (potato–oat–timothy–timothy–sugar beet–dry bean). Each phase of each rotation appeared in each year, resulting in a total of 25 treatments arranged (Table 1) in a randomized complete block design (RCBD). Each treatment was replicated four times, resulting in a total of 100 plots. Individual plots were 10.1 by 18.3 m (185 m^2), with a 2.1 m guard plot between each plot. The number of rotation cycles at the end of the 2011 growing season (12 yr) ranged from 4 (3-yr rotations) to 2 (6-yr rotation) (Table 1). All crops were grown to maturity, except oat in the 6-yr rotation, which was harvested as silage in mid- to late July to allow for timely planting of timothy in late August.

Dry bean seed was not inoculated with *Rhizobia* as McKenzie et al. (2001) found no yield response to inoculation in southern Alberta. All dry bean plots received N fertilizer (as ammonium nitrate, 34–0–0) broadcast prior to seeding (wide row) or banded below the seed (narrow row). The 3-yr CONV and 3- and 5-yr CONS rotations received 90 kg ha^{-1} N, while 4-yr CONV and 4- and 6-yr CONS received 112 kg ha^{-1} N to account for higher N use by the preceding sugar beet crop compared to preceding potato or wheat (Larney et. al., 2015). Only dry bean grown in 2000 to 2002 received P (22 kg ha^{-1}) as soil test levels after that were considered adequate to meet crop P demand. Compost, derived from beef feedlot manure, was fall-applied (except 2003 when it was postponed until spring due to wet conditions) at five entry points (phases of the rotation where compost was applied) in the CONS rotations (Table 1). For the shorter 3-yr CONS rotation, compost was applied at 28 Mg ha^{-1} (fresh wt.) after wheat and before potato. The lower rate was also applied at a second entry point in 5-yr CONS: after sugar beet and before wheat. In the longer 4- 5- and 6-yr CONS rotations, a higher rate (42 Mg ha^{-1} fresh wt.) was used after dry bean and before potato. Compost was sourced from the same feedlot each year and had average concentrations (dry wt., n = 11, fall 2000–2010) of 182 g kg^{-1} total C, 15.4 g kg^{-1} total N, and 5.4 g kg^{-1} total P.

Dry bean was typically seeded in mid- to late May. Conservation rotations were direct drilled in narrow rows at a target rate of 53 plants m^{-2} while wide-row CONV rotations were seeded at a target rate of 29 plants m^{-2}. Dry bean was harvested between 9 September (wide-row, 2006) and 17 October (narrow-row, 2002), with a mean harvest date between 21–22 September (n = 24). At harvest, wide-row dry bean (3-, 4-yr CONV) were undercut and allowed to further mature in swaths before harvesting with a plot combine. Narrow-row dry bean (3-, 4-, 5-, and 6-yr CONS) was direct cut with a plot combine, except in 2003, 2005, 2010, and 2011. Hand-harvesting (6 by 1 m^2 $plot^{-1}$) was performed in 2003 due to high weed populations and in 2005 due to wet soil conditions. In 2010 and 2011, narrow-row dry bean in CONS rotations was undercut prior to combining to reduce harvest losses associated with direct cutting. This change was made in light of observed harvest losses (intact or cracked pods and seed on the ground) in previous years. The high harvest losses underestimated narrow-row dry bean yield potential. Given this change in harvesting practice for the bean in CONS rotations, NI was presented as an average over the entire 12 yr, over the first 10 yr, and over the last 2 yr of study. Pesticide chemical information and prices are shown in Table 2. Irrigation water was applied to the plots using a low pressure pivot system to maintain soil water content at ≥50% field capacity. Amounts of irrigation water varied according to crop demand and prevailing weather conditions. The only cover crop directly impacting dry bean was after potato when fall rye was seeded for 3-yr CONS and dry bean was seeded into fall rye burn-off (Table 1). The 5-yr CONS rotation was direct seeded into wheat stubble shredded with a flail mower.

Economic Analysis

The NI for dry bean and all crops was defined as the income remaining after paying for all cash costs (i.e., seed, fertilizer/compost, pesticides and disease control, irrigation, transportation, fuel and oil, repairs, miscellaneous expenses, land taxes,

Table 1. Outline of rotation treatments over 12 yr (from 2000 to 2011) for dry bean production in Vauxhall, AB, Canada.

Rotation under CONV or CONS practice†	Rotation length	Crop sequence‡	Bean crop row space	Number of crop phases	Number of rotation cycles§	Crop management practice
	yr					
3-yr CONV	3	B–W–P	Wide	3	4	Conventional
3-yr CONS	3	B¶–W#–P¶	Narrow	3	4	Conservation
4-yr CONV	4	B–P–W–SB	Wide	4	3	Conventional
4-yr CONS	4	B#–P¶–W–SB	Narrow	4	3	Conservation
5-yr CONS	5	B#–P¶-W–SB#–W	Narrow	5	2.4	Conservation (cereal break)
6-yr CONS	6	B#–P¶–O/(t)†† –T–T–SB	Narrow	6	2	Conservation (forage-based)

† 3-yr CONV = 3-yr rotation under conventional crop management practice; 3-yr CONS = 3-yr rotation under conservation crop management practice; 4-yr CONV = 4-yr rotation under conventional crop management practice; 4-yr CONS = 4-yr rotation under conservation crop management practice; 5-yr CONS = 5-yr rotation under conservation crop management practice; 6-yr CONS = 6-yr rotation under conservation crop management practice.

‡ W = wheat; P = potato; B = bean; SB = sugar beet; O(t) = oat grown until mid-July followed by timothy seeded in late August; T = timothy.

§ Number of rotation cycles = 12 (yr)/number of crop phases.

¶ Fall-seeded cover crop entry point: fall rye [except oat, 2000–2002, on 3-yr CONS (between dry bean and wheat), 4-yr, 5-yr, and 6-yr CONS].

Feedlot manure compost entry point: 28 Mg ha^{-1} fresh wt. (3-yr CONS, 5-yr CONS after sugar beet) or 42 Mg ha^{-1} fresh wt. (4-yr CONS, 5-yr CONS after dry bean, 6-yr CONS) applied after harvest, except 2003 (postponed to spring 2004 due to wet soil conditions).

†† Oat harvested as silage in July, timothy direct seeded in late August.

and interest costs on variable inputs), land costs and ownership costs on machinery and buildings (depreciation, interest on investment, and insurance and housing), and labor, as described by Zentner et al. (2002). All values including the total cost and NI of irrigated dry bean production were expressed in CAN\$ ha^{-1} for each crop and rotation. Labor cost was assumed to be \$20 h^{-1} to represent labor required for agricultural production. Agronomic data from the field trials, combined with price and cost data for machinery and inputs, were used to develop crop budgets. The economic analysis included all inputs used in field operations from pre-seeding to harvest and post-harvest activities. Input prices from various sources were used to represent more recent costs of crop production at the farm level. The total cost for compost was estimated at \$27 Mg^{-1}, including composting (\$15 Mg^{-1}), truck loading (\$2 Mg^{-1}), handling and hauling (5 km, \$5 Mg^{-1}), and field application (\$5 Mg^{-1}) (E.G. Smith, Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre, Lethbridge, AB, Canada, personal communication, 2015). An average price of \$730 Mg^{-1} (2005–2016) was used for dry bean (Alberta Agriculture and Rural Development, 2014; AFSC, 2016). Table 2 provides a summary of prices of input and output.

Table 2. Prices for seed, fertilizer, herbicides, fungicides, and crops used in dry bean rotations.†

Product name	Active ingredient	Price
Seed		\$ kg^{-1}
Small red dry bean		2.14
Potato		0.47
Sugar beet		55.50
Oat		0.47
Timothy		11.01
Wheat		0.46
Fertilizer		\$ kg^{-1}
N		1.63
P_2O_5		1.20
K_2O		0.78
S		0.75
Compost		0.027
Herbicide		\$ kg^{-1} or \$ L^{-1}
Basagran (bentazon)	480 g L^{-1}	31.33
Edge (ethalfluralin)	5%	25.00
Maverick (glyphosate)	480 g L^{-1}	13.65
Roundup, Roundup Ultra 2, Touchdown, Vantage plus (glyphosate)	540 g L^{-1}	6.30
Poast ultra (sethoxydim)	450 g L^{-1}	44.22
Reglone desiccant (diquat)	240 g L^{-1}	28.95
Solo (imazamox)	70%	1295.41
Fungicide		\$ kg^{-1} or \$ L^{-1}
Parasol (copper hydroxide)	50%	21.83
Ridomil gold (metalaxyl-M)	500 g L^{-1}	10.30
Ronalin (iprodione vinclozolin)	50%	88.07
Tattoo C (propamocarb:chlorothanlonil = 375:375 g L^{-1} SC)	375 g L^{-1}	27.00
Crops		\$ kg^{-1}
Dry bean		0.730
Potato		0.226
Sugar beet		0.049
Oat silage		0.055
Timothy hay		0.172
Wheat		0.217

† Note: Bean did not have insecticide applications. The common name of herbicides and fungicides is listed in parentheses. The average of historical prices from 2005 to 2016 for each product is applied for total income calculation. Source: Wood, 2013; Manitoba Agriculture Food and Rural Development, 2014; and https://www.afsc.ca/Default.aspx?cid=82&lang=1 under risk management/price lists (accessed on 10 Oct. 2016).

Field operation schedules and equipment used were determined for irrigated dry bean production and other crops of each rotation, based on practices followed by producers in western Canada. Farm machinery sizes and work rates were calculated based on an average grain farm size of 907 ha (Alberta Agriculture and Forestry, 2016; Saskatchewan Agriculture, Food and Rural Revitalization, 2014; Manitoba Agriculture Food and Rural Development, 2014). The analysis included the costs and returns for each crop and the entire rotation for each year, but only results for dry bean and the entire rotation are presented in this paper. The results for dry bean provide detailed analyses of the relative returns and risks for bean growers to assess the performance of bean in various crop rotations but the returns to the entire rotation provide an economic perspective in terms of what cropping systems maximize profitability at the farm level.

The Proc MIXED procedure of SAS software (SAS/STAT 9.3 User's Guide, SAS Institute, 2011) was conducted to determine the impact of crop rotation on yearly NIs of (i) dry bean and (ii) the entire crop rotation from 2000 to 2011. With the MIXED procedure, the rotation and year was considered fixed effects, while replicate was considered a random effect. In addition, the MIXED procedure was used to analyze combined average total cost and NI of 2000 to 2011 period for dry bean and the entire crop rotation. In this procedure, the rotation was considered a fixed effect variable, while year and replicate were considered the random effect variables. Contrast statements were used in the MIXED procedure to test CONV and CONS practices on NIs of dry bean and the entire crop rotation for each year and in a separate analysis for combined total cost and NI of the 2000 to 2011 period. The impacts of PC potato (3-yr CONV, 3-yr CONS) vs. PC sugar beet (4-yr CONV, 4-yr CONS) on yearly NI of dry bean over all 12 yr were done with contrasts in the MIXED procedures. If the impacts of PC on dry bean NI were significant, it may be due to residual N from PC, or due to the 1 yr length difference in 3- and 4-yr rotations, or due to effects of fall rye cover crop in 3-yr CONS, or a combination of all. Overall rotation effects and contrast effects between CONV and CONS management practices and between PCs potato and sugar beet were considered significant at $P < 0.05$.

Risk Analysis

Stochastic budgets of NIs were developed for all crops in each rotation to evaluate how the profitability and risky alternatives of these CONS management practices compared with the CONV management practices. Microsoft Excel add-in

Simulation and Econometrics to Analyze Risk (SIMETAR), developed by Richardson et al. (2004), was used to simulate crop yield and price distributions and calculate distributions of NIs to land and management (Richardson et al., 2008). The NI distributions were constructed as defined in the Economic Analysis section. The crop yields and output prices in the model were stochastic, while 2016 input prices were used to estimate cost. A multivariate empirical distribution (Richardson et al., 2000) derived from 12 yr of experimental yield data for each crop in each rotation was multiplied by a simulated price distribution derived from historical crop prices (2005–2016) to calculate gross incomes. Crop production costs based on agronomic management practices of crops in each rotation from 2000 to 2011 and then 2016 input costs were subtracted from gross incomes to obtain the NI. Although 2016 input prices were used to estimate cost, field crop activity requirements varied for each crop in each year. Therefore, an empirical distribution derived from 12 yr of cost was used to simulate cost for each crop. SIMETAR was used to construct a cumulative probability distribution function (CDF) from simulated NI with probability ranging from 0.0 to 1.0.

Stochastic efficiency with respect to a function (SERF) with a constant relative risk-aversion function was used in this study to evaluate risk-efficient alternatives (Hardaker et al., 2004; Hardaker and Lien, 2004; Richardson et al., 2008). SERF identifies the most efficient alternatives for a range of risk preferences by ranking alternatives in terms of certainty equivalents (CE) (Richardson et al., 2008). The CE is a measurement of a payoff that a decision maker would have to receive to be indifferent between the certain payoff and a more risky alternative (Hardaker et al., 2004). For a given level of risk aversion coefficient, the CE is calculated using the negative exponential equation published in Hardaker et al. (2004). The higher CE, with the same level of absolute risk aversion coefficient (ARAC), determines the best management alternatives under different individual risk preferences. The CE values were converted to a risk premium, relative to a base strategy (3-yr CONV). The risk premium is the amount of CE required, or to be given up, for the producer to be indifferent between the two strategies (Hardaker et al., 2004). The risk premium compares the CE values computed in the SERF analysis with the base strategy, and strategies with the highest risk premium would be preferred.

The CE values were calculated for the ARAC for an upper bound of 4/average NI (Hardaker et al., 2004). The ARAC ranged from 0 (risk neutral) to 0.010 (highly risk averse) for bean only and from 0 to 0.007 for entire rotations. There were 500 simulated NI values computed for each crop in each rotation (data not shown). The simulated NI values were then used to determine the risk premium to evaluate the rotation strategies under risk.

RESULTS AND DISCUSSION

Dry Bean Total Cost

The average production cost over the 12 yr for 1 ha of dry bean was \$1345, with CONS costs significantly higher than CONV ($P < 0.0001$) (Table 3). The 3-yr CONS rotation had the highest average total costs (\$1446 ha^{-1}), while the 3- and 4-yr CONV rotations had the lowest (mean \$1271 ha^{-1}). The highest expenditures were for pesticides (22.3%), seed (21.1%), machinery (18.3%), irrigation (14.2%) and chemical fertilizer (12.9%) (Table 3). Of these, the greatest cost difference between CONV and CONS systems was for seed expenditures (\$209 vs. \$322 ha^{-1}). Higher CONS seed costs were due to narrow-row seeding, which had greater plant densities (53 vs. 29 plants m^{-2}) that required almost double the seeding rate. Higher pesticide costs for CONS included the additional herbicide used to kill the cover crop found in CONS. Additional machinery cost in CONV was for tillage to eliminate weeds in wide-row bean. While CONV rotations involved higher average labor expenses, labor costs accounted for only 7.4% of total costs, and hence the impact on overall expenses was limited (Table 3). Overall, differences among rotations showed statistical significance in terms of 12-yr bean annual total costs (Table 3).

Table 3. Costs for dry bean in different rotations and management practices from 2000 to 2011.

Rotations†	Seed	Machinery	Labor	Chemical fertilizer	Herbicide and fungicide	Irrigation	Other	Total cost‡
	\$ ha^{-1}							
3-yr CONV	209	276	108	160	280	191	45	1267d
3-yr CONS	322	285	105	160	313	191	71	1446a
4-yr CONV	209	262	101	187	280	191	45	1275d
4-yr CONS	322	227	94	187	307	191	48	1377b
5-yr CONS	322	199	90	163	313	191	47	1324c
6-yr CONS	322	231	96	187	307	191	48	1382b
Mean of rotation	284	247	99	174	300	191	51	1345
% of total cost	21.1	18.3	7.4	12.9	22.3	14.2	3.8	–
CONV vs. CONS								
CONV	209	269	104	173	280	191	45	1271
CONS	322	236	96	174	310	191	54	1382
P value	<0.0001	<0.0001	<0.0001	–	<0.0001	–	<0.0001	<0.0001

† 3-yr CONV = 3-yr rotation under conventional crop management practice; 3-yr CONS = 3-yr rotation under conservation crop management practice; 4-yr CONV = 4-yr rotation under conventional crop management practice; 4-yr CONS = 4-yr rotation under conservation crop management practice; 5-yr CONS = 5-yr rotation under conservation crop management practice; 6-yr CONS = 6-yr rotation under conservation crop management practice.

‡ Values with same letters in a column are not significantly different ($P > 0.05$).

Dry Bean Net Income

There was a significant rotation effect on dry bean NI in 10 of 12 yr, the exceptions being 2003 (narrow-row hand-harvested due to high weed pressure) and 2004 (Table 4). In 2002, bean in 3-yr CONS (fall rye burnoff) had significant lower NI (–\$700 ha^{-1}) than the low-residue 4- and 6-yr CONS and 4-yr CONV rotations (–\$45 to –\$174 ha^{-1}). More precipitation than normal was experienced in 2002 which caused significant yield loss in all rotations especially 3-yr CONS. Liebman et al. (1995) reported reduced dry bean yield with a fall rye cover crop when early season conditions were cool and wet. In 2005, 3-, 4- and 6-yr CONS had significant higher NI than the two CONV rotations (\$600–\$1104 vs. –\$200 to \$14 ha^{-1}) due, in part, to weather conditions during harvest and harvesting method. During harvest time in 2005, a total of 120 mm of precipitation occurred which may have caused losses of dry bean in the wide-row while in swaths but the narrow-row dry bean were standing throughout the wet period with possibly minimal effects (Larney et al., 2015). Eliminating risks from weather-related losses while wide-row dry bean are in swaths has been highlighted as an advantage of narrow row production (Ablett, 1988). In 2006, NI of dry bean in 3-yr CONV was higher than 3- and 6-yr CONS and NI of dry bean in 4-yr CONV was higher than all other rotations except bean in 3-yr CONV due to higher seed and pesticide costs associated with CONS rotations. In 2008, dry bean in 4-yr CONV (–\$280 ha^{-1}) had less loses compared to all other rotations (–\$740 ha^{-1}). The 2008 crops suffered severe hail damage and bacterial blight causing significant yield losses (Larney et al., 2015). In 2009, there was a clear case of both CONV rotations having higher NI than all four CONS rotations (\$435 vs. \$–181 to \$13 ha^{-1}). In 2010, dry bean in 3- and 4-yr CONS rotations had white mold incidences of 82 to 89% compared to only 4 to 13% in 3- and 4-yr CONV treatments (Larney et al., 2015); dry bean yields and NIs of bean in 3- and 4-yr CONS were the same as bean in 3- and 4-yr CONV (Larney et al., 2015, Table 8). Studies have found that under high white mold pressures, yields were optimized in narrow rows and maximizing distance between plants within rows was more important than maximizing row spacing (Wunsch, 2014; Lee et al., 2005). In 2011, the bean NI of 4-yr CONS was significantly different than 3- and 4-yr CONV (\$1629 vs. \$616–\$1047) and 3-yr CONS was significantly different than 4-yr CONV (\$1453 vs. \$616).

Averaging across all 12 yr, there was significant rotation effect on mean NI ($P = 0.002$) (Table 4). Dry bean in narrow row production under 3-yr CONS rotation resulted in lower NI than wide row production under 3- and 4-yr CONV rotations (\$97 vs. \$293–\$357). Dry bean in the 4-yr CONV (\$357 ha^{-1}) provided the highest 12-yr average NI of all rotations, and was statistically different from 3-, 4-, and 5-yr CONS, while dry bean in the 3-yr CONS (\$97 ha^{-1}) system provided the lowest NI (Table 4).

Average differences (2000–2011) among bean yields in CONV and CONS rotations were marginal, and thus narrow-row dry bean cropping proved to be as effective as wide-row practices (Larney et al., 2015, Table 8; Blackshaw and Molnar 2008). However, comparing the economic benefits of CONV to CONS practices, this study showed that CONV management produced bean crops with significantly higher NI than that of CONS systems ($P = 0.001$) (Table 4). The difference in NI between CONV and CONS can be explained primarily by higher seed costs associated with bean in narrow-row seeding (Table 3). Over 12 yr, both CONV and CONS practices yielded dry bean crops with an average positive NI (Table 4). However, CONV (\$325 ha^{-1}) management provided \$122 ha^{-1} more NI than CONS (\$203 ha^{-1}) systems. Management contrasts (Table 4) revealed that the CONS system in 5 of the 12 yr (2001, and 2006–2009) had significantly lower NI (79–117%) than CONV management. These were also years where CONS management led to significantly higher white mold incidence (Larney et al., 2015, Table 7). Larney et al. (2015) reported that white mold incidence, averaged over 12 yr, was three times greater (19%) in narrow-row than wide-row crops (6%). Ramasubramaniam et al. (2008) reported a significant linear relationship between dry bean yield and white mold incidence in North Dakota, with a yield loss of 14 kg ha^{-1} for every 1% increase in incidence.

The similar yields on CONS and CONV rotations in 2010 and higher yields by CONS rotations in 2011 (Larney et al., 2015, Table 8) were primarily the result of switching from direct combining to undercutting narrow-row bean plants. Seed losses have been estimated at up to 40% of yield in narrow-row production when directly harvested (Saskatchewan Agriculture, 2009; Eckert et al., 2011) due to the cutter bar missing or dissecting pods positioned close to the soil surface (Zyla et al., 2002). Given losses were evident after direct cutting narrow-row dry bean in our experiment, in 2010 and 2011 an attempt was made to reduce harvest losses associated with direct cutting by switching harvest to undercutting and raking into swaths (Larney et al., 2015). Given this change in harvest management, the 12-yr mean rotation NI discussed above may not represent a truly accurate comparison between wide- (CONV) and narrow-row (CONS) production. Hence, average NIs for the first 10 yr (2000–2009) and the last 2 yr (2010–2011) were reported separately (Table 4).

The management effect on dry bean NI for the first 10 yr (2000–09) mean was similar to the mean of 2000–2011 NI, with CONV rotations generating higher NI than CONS in both periods ($P = 0.0001$ and $P < 0.001$). Over the first 10 yr, the bean NI in 4-yr CONV was significantly higher than all other rotations and 3-yr CONV was also higher than 3-(fall rye burnoff) and 5-yr CONS. Blackshaw (2008) reported a 5 to 13% dry bean yield increase due to inclusion of cover crops, an observation that was not seen in this study. However, the implementation of undercutting bean crops in CONS rotations in the final 2 yr of the study greatly increased the yield and NI of these crops (Table 4), indicating that such a practice is highly advantageous in CONS management, and thus beneficial to dry bean producers. The results for the last 2 yr (Table 4) showed that undercutting narrow-row dry bean resulted in higher NI than wide-row 4-yr CONV, and also the management contrast revealed that narrow-row CONS rotations were significantly higher than wide-row CONV rotations. The reversal of the CONV vs. CONS NI trend in the last 2 yr showed that the change in harvesting technique to reduce harvest losses improved the performance of narrow row production. These findings are consistent with those of

Table 4. Effect of rotation, crop management, and preceding crops on net income of dry bean production from year 2000 to 2011.

Rotation/ management	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean 2000–2011	Mean 2000–2009	Mean 2010–2011
	$ ha^{-1}														
Rotation†															
3-yr CONV	220ab	828ab	–398bcd	600	–60	–201c	378ab	487a	–497ab	389a	729abc	1047bc	293ab	175b	888b
3-yr CONS	324a	136c	–700d	266	–26	681ab	–171c	–256b	–682bc	–181b	317c	1453ab	97c	–61d	885b
4-yr CONV	389a	1065a	–99ab	374	212	14c	662a	310a	–280a	481a	538bc	616c	357a	313a	577c
4-yr CONS	337a	427bc	–174abc	292	250	599b	151bc	–120b	–905c	–77b	340c	1629a	229b	78bc	984ab
5-yr CONS	51b	19c	–438cd	818	46	62c	–81bc	423a	–784c	13b	844ab	1448ab	202bc	13cd	1146ab
6-yr CONS	286a	219bc	–45a	384	187	1104a	–140c	–107b	–830c	–43b	1039a	1358ab	284ab	101bc	1199a
P value	0.03	0.02	<0.01	0.43	0.33	<0.01	0.02	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01
Crop management practice															
CONV	304	946	–249	487	76	–93	520	399	–388	435	634	831	325	244	732
CONS	250	200	–339	440	114	612	–60	–15	–800	–72	635	1472	203	33	1053
P value	0.36	<0.01	0.32	0.80	0.71	<0.01	<0.01	<0.01	<0.01	<0.01	0.99	<0.01	<0.01	<0.01	<0.01
Preceding crop‡															
Potato	272	482	–549	433	–43	240	104	116	–589	104	523	1250	195	–	–
Sugar beet	363	746	–136	333	231	307	407	95	–593	202	439	1122	293	–	–
P value	0.19	0.22	<0.01	0.64	0.03	0.68	0.09	0.85	0.97	0.38	0.56	0.49	0.02	–	–

† Multiple comparisons are conducted and the least square mean (LSM) values with same letters in a column for each section are not significantly different ($P > 0.05$). 3-yr CONV = 3-yr rotation (potato–bean–wheat) under conventional crop management practice; 3-yr CONS = 3-yr rotation (potato–bean–wheat) under conservation crop management practice; 4-yr CONV = 4-yr rotation (wheat–sugar beet–bean–potato) under conventional crop management practice; 4-yr CONS = 4-yr rotation (wheat–sugar beet-bean–potato) under conservation crop management practice; 5-yr CONS = 5-yr rotation (potato–wheat–sugar beet–wheat–bean) under conservation crop management practice; 6-yr CONS = 6-yr rotation (oat [timothy]–timothy–timothy–sugar beet–bean–potato) under conservation crop management practice.

‡ The impacts of preceding crop (PC) potato or sugar beet were done for 3-yr rotations (3-CONV, 3-CONS) vs. 4-yr rotations (4-CONV, 4-CONS); therefore, if the impacts of PC on dry bean were significant, it may be due to residual N from PC, or due to 1 yr length difference in 3- and 4-yr rotations, or a combination of both.

Eckert et al. (2011), who found that dry bean yields were significantly higher when using the practice of undercutting than when direct combining, mainly due to a reduction in bean pod damage, which occurs through direct harvesting. In light of the effects of undercutting in 2010 and 2011, it is possible the long-term use of such a practice may result in a greater adoption preference for CONS management over that of CONV systems.

Throughout the study (2000–2011), sugar beet was shown to be a more effective PC than potato in terms of NI produced by the subsequent bean crop. Results, however, showed that the average bean NI was only higher following sugar beet PC than potato PC in 2 of the 12 yr (2002, 2004). Twelve-year NI averages, as affected by cover crop, suggested that the absence of a cover crop yielded bean crops with significantly higher average NI (\$293–\$357 ha^{-1}) than those planted over either 3-yr CONS fall rye (\$97 ha^{-1}) or wheat stubble (\$202 ha^{-1}) (Table 4). Cover crops increased dry bean production costs, but did not benefit crops in terms of dry bean yield or NI increases; therefore, they were not as profitable as dry bean without cover crop treatments.

Overall Economic Performance of Entire Rotations

There was a significant rotation effect on NI of the entire rotation in 7 yr of the 12 yr experiment (Table 5). The 4-yr CONV rotation had a higher NI than all other rotations in 2001 (\$1505 vs. \$652–\$933 ha^{-1}) except 3-yr CONV. The NI of 4-yr CONV was also higher than 3-yr CONV and 6-yr CONS in 2005 and higher than 5- and 6-yr CONS in 2006 (\$831 vs. \$135–\$166 ha^{-1}). In 2008, the loss in 4-CONV was less than 3- and 4-yr CONS and in 2009, NI of 4-CONV was higher than 3-, 5-, and 6-yr rotations (\$807 vs. \$409–\$583 ha^{-1}). In 2010, the 4-yr CONV and 6-yr CONS had positive NI but the rest of rotations had negative NI. In 2011, the 4-yr CONV experienced the lowest NI relative to all other rotations in part due to lower potato yield (15% less than other rotations) and the change in bean harvesting management described earlier in the Dry Bean Net Income section.

Overall economic performance of the entire rotation was summarized in Table 5. Annual NI of the six rotations varied (P = 0.0005) from \$280 to \$627 ha^{-1} (Table 5) when NI was averaged over the period 2000 through 2011. Based on these 12 yr of data, the 4-yr CONV rotation generated the highest annual NI (\$627 ha^{-1}) followed by the 3-yr CONV (\$544 ha^{-1}) and 3-yr CONS (\$483 ha^{-1}) rotations. Potato was the key determinant of NI or profitability of all rotations (Khakbazan et al., 2016). Rotational profitability is a key driver for farmer's decision to adopt it at farm level and that for our rotations studied in this paper the 4-yr CONV was the highest.

Study results showed that CONV management produced higher NI than that of CONS systems (P = 0.0001). The difference in NI between CONV and CONS can be explained by higher compost manure cost in potato CONS (Khakbazan et al., 2016) and seed and pesticide costs associated with bean in narrow-row seeding (Table 3). The overall cost differences for CONV and CONS were shown in Table 5, indicating higher total cost under CONS for most years. There were also significant year to year NI differences between CONV and CONS with NI of CONV being significantly higher than CONS management for all years, except 2011 where CONS produced significantly higher NI than CONV (Table 5).

Table 5. Effect of rotation and crop management on average net income and total cost of entire rotation from year 2000 to 2011.

Rotation/management	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Mean 2000–2011
							\$ ha^{-1}						
Rotation on net income†													
3-yr CONV	1109	1083ab	–286	1353	1169	–126c	762a	626	–448abc	583bc	–329c	1036a	544ab
3-yr CONS	870	933b	–267	1267	923	215ab	525ab	684	–627bc	409c	–293c	1022a	483bc
4-yr CONV	796	1505a	–25	1060	832	359a	831a	917	–305a	807a	97a	585c	627a
4-yr CONS	704	687b	–604	904	643	492a	466ab	569	–721c	631ab	–274c	954ab	378cd
5-yr CONS	624	652b	–603	543	725	–103bc	135b	744	–385ab	513bc	–203bc	718bc	280d
6-yr CONS	680	666b	–152	695	520	375a	166b	214	–279a	436bc	58ab	967ab	349cd
P value	0.33	0.03	0.08	0.24	0.53	<0.01	<0.01	0.13	0.04	0.01	0.02	0.01	<0.01
Crop management practice on net income													
CONV	953	1294	–156	1207	1001	116	796	772	–376	695	–116	810	586
CONS	787	810	–436	1085	783	354	496	626	–674	520	–284	988	431
P value	0.11	<0.01	0.07	0.13	0.18	0.20	<0.01	0.14	0.16	<0.01	0.47	0.19	<0.01
Crop management practice on total cost													
CONV	2804	3094	2832	2829	2831	2687	2890	3089	2831	2875	2490	2627	2827
CONS	2864	3412	3062	3113	3081	3041	3194	3382	3114	3125	2881	2928	3111
P value	0.04	<0.01	0.86	<0.01	0.70	0.03	0.03	<0.01	<0.01	0.10	<0.01	0.02	0.01

† Multiple comparisons are conducted and the LSM values with same letters in a column for each section are not significantly different (P > 0.05).
3-yr CONV = 3-yr rotation (potato–bean–wheat) under conventional crop management practice; 3-yr CONS = 3-yr rotation (potato–bean–wheat) under conservation crop management practice; 4-yr CONV = 4-yr rotation (wheat–sugar beet–bean–potato) under conventional crop management practice; 4-yr CONS = 4-yr rotation (wheat–sugar beet–bean–potato) under conservation crop management practice; 5-yr CONS = 5-yr rotation (potato–wheat–sugar beet–wheat–bean) under conservation crop management practice; 6-yr CONS = 6-yr rotation (oat [timothy]–timothy–timothy–sugar beet–bean–potato) under conservation crop management practice.

MANAGEMENT RANKINGS

Cumulative Density Function and Stochastic Efficiency with Respect to a Function

Dry Bean

Thus far, analysis has been based on point estimates, such as bean mean NI. A risk ranking procedure that does not rely on summary statistics or point estimates, is the CDF of all simulated outcomes of the bean NI for all six rotations. The CDF chart shows that no rotation dominated throughout the distribution range (Fig. 1). Dry bean in the 4-yr CONV rotation appeared to have lower potential for loss (17% probability of a loss) but also a lower maximum NI than other rotations. In contrast, dry bean in the 3-yr CONS had the highest potential loss with NI less than zero 47% of the time. It does have a small probability of a very high NI, however. Based on the CDFs of the six rotations, producers would be unable to make a clear decision as to which rotation is the most preferred strategy for bean production, so alternative methods were required to assess the preferred rotation. Since each individual producer may have different risk preferences, the dry bean system that a producer would choose or adopt cannot be evaluated by the CDF analytical framework alone. Therefore, the concept of SERF is an analytical technique of greater preference (Hardaker et al., 2004; Hardaker and Lien, 2004).

The most risk-efficient dry bean rotation was 4-yr CONV, as the rotation provided a substantially higher risk premium across levels of risk aversion relative to a base strategy (3-yr CONV) (Fig. 2). Therefore, bean growers would be most likely to select the 4-yr CONV rotation. For a risk-neutral bean producer (ARAC = 0.0), the producer would need an additional \$42 ha^{-1} to select 3-yr CONV over 4-yr CONV. The next alternative rotation for a bean grower over ARAC value 0 to 0.0026 is 3-yr CONV rotation, followed by the 6-yr CONS rotation with ARAC value 0.0026 to 0.0086. The 4- and 6-yr CONS are more risky relative to the base strategy, indicated by the declining risk premium as ARAC increased. Alternatively, the 3-yr CONS rotation is the least preferred system (Fig. 2). Thus bean producers would not be expected to use the 3-yr CONS rotation.

Entire Rotations

The CDFs of all 500 simulated outcomes of the NI, for all six rotations, are shown in Fig. 3. Overall, the CDF chart shows that the 4-yr CONV rotation has the lowest potential loss (14%); however, its maximum NI is lower than other rotations. In contrast, the 5-yr CONS rotation (lies furthest to the left, Fig. 3) has the highest potential loss (32%). Of the 500 NI simulated for each rotation, the 4- (75%) and 5-yr CONS (68%) had the lowest probability of positive returns compared to the alternative 4-yr CONV (86%). Whether these positive return distributions can be shifted to more favorable outcomes will depend on lowering compost and seed costs or increasing crop yields. Based on the CDFs of the six rotations, producers would be unable to make a clear decision as to which rotation is the most preferred strategy.

The preferred rotation was the 4-yr CONV when all crops were considered across all possible rotations, as the rotation provided the highest risk premium (Fig. 4). At an ARAC level from 0.0026 and higher, the worst strategy was 4-yr CONS. Overall, the results showed that producers are most likely to

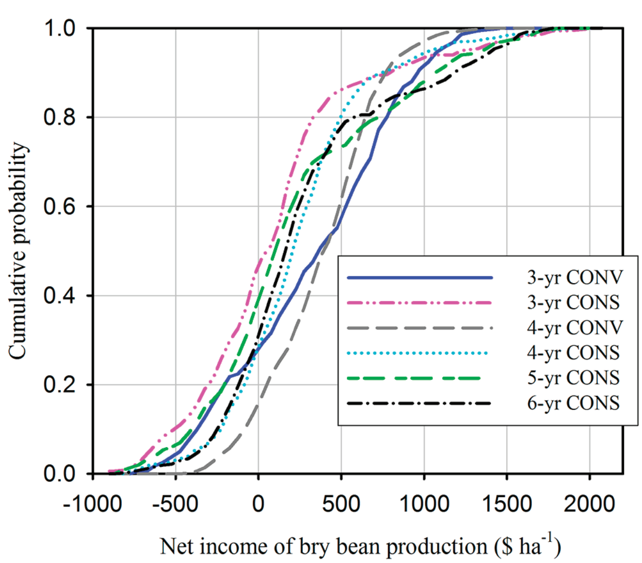

Fig. 1. The cumulative probability of dry bean net income for different rotations. 3-yr CONV = 3-yr rotation (potato–bean–wheat) under conventional crop management practice; 3-yr CONS = 3-yr rotation (potato–bean–wheat) under conservation crop management practice; 4-yr CONV = 4-yr rotation (wheat–sugar beet–bean–potato) under conventional crop management practice; 4-yr CONS = 4-yr rotation (wheat–sugar beet–bean–potato) under conservation crop management practice; 5-yr CONS = 5-yr rotation (potato–wheat–sugar beet–wheat–bean) under conservation crop management practice; 6-yr CONS = 6-yr rotation (oat[timothy] –timothy–timothy–sugar beet–bean–potato) under conservation crop management practice.

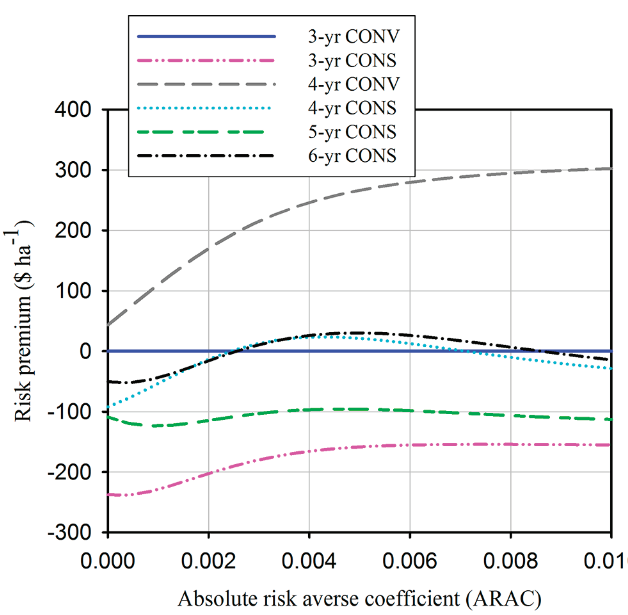

Fig. 2. Risk premiums of net income relative to 3-yr CONV for dry bean production. 3-yr CONV = 3-yr rotation (potato–bean–wheat) under conventional crop management practice; 3-yr CONS = 3-yr rotation (potato–bean–wheat) under conservation crop management practice; 4-yr CONV = 4-yr rotation (wheat–sugar beet–bean–potato) under conventional crop management practice; 4-yr CONS = 4-yr rotation (wheat–sugar beet–bean–potato) under conservation crop management practice; 5-yr CONS = 5-yr rotation (potato–wheat–sugar beet–wheat–bean) under conservation crop management practice; 6-yr CONS = 6-yr rotation (oat [timothy]–timothy–timothy–sugar beet–bean–potato) under conservation crop management practice.

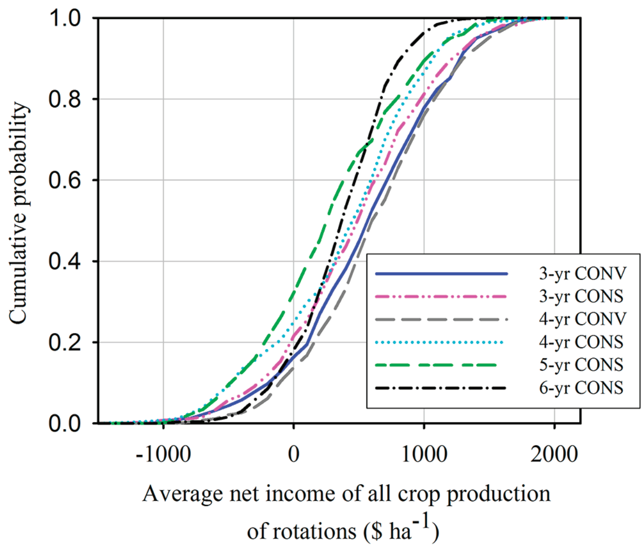

Fig. 3. The cumulative probability of average net income of entire crop rotations. 3-yr CONV = 3-yr rotation (potato–bean–wheat) under conventional crop management practice; 3-yr CONS = 3-yr rotation (potato–bean–wheat) under conservation crop management practice; 4-yr CONV = 4-yr rotation (wheat–sugar beet–bean–potato) under conventional crop management practice; 4-yr CONS = 4-yr rotation (wheat–sugar beet–bean–potato) under conservation crop management practice; 5-yr CONS = 5-yr rotation (potato–wheat–sugar beet–wheat–bean) under conservation crop management practice; 6-yr CONS = 6-yr rotation (oat [timothy] –timothy–timothy–sugar beet–bean–potato) under conservation crop management practice.

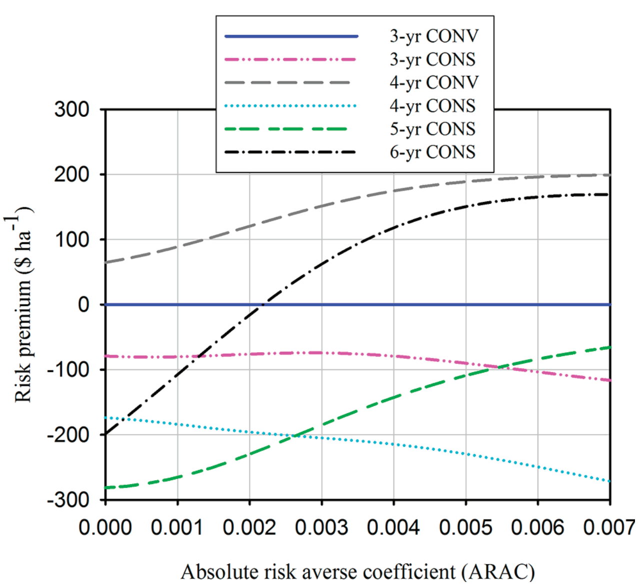

Fig. 4. Risk premiums of net income relative to 3-yr CONV for entire rotations. 3-yr CONV = 3-yr rotation (potato–bean–wheat) under conventional crop management practice; 3-yr CONS = 3-yr rotation (potato–bean–wheat) under conservation crop management practice; 4-yr CONV = 4-yr rotation (wheat–sugar beet–bean–potato) under conventional crop management practice; 4-yr CONS = 4-yr rotation (wheat–sugar beet–bean–potato) under conservation crop management practice; 5-yr CONS = 5-yr rotation (potato–wheat–sugar beet–wheat–bean) under conservation crop management practice; 6-yr CONS = 6-yr rotation (oat [timothy] –timothy–timothy–sugar beet–bean–potato) under conservation crop management practice.

select the 4-yr CONV rotation as the means to grow their crops to maximize profit and to minimize risk.

The CE values mirror findings of rotation-based average NI, as CONV practices showed preference over CONS. The 4-yr CONV rotation was shown to be the most preferred rotation across the range of SERF risk preferences, while the 4- and 5-yr CONS rotations were least preferred, at low-to-moderate and high risk averse levels, respectively (Fig. 4). Accordingly, 12-yr averages showed that the 4-yr CONV rotation produced the highest NI, while the 4- and 5-yr CONS rotation generated the lowest (Table 5). Thus, SERF values are consistent with economic findings, strengthening support for the selection of the 4-yr CONV rotation over all others.

CONCLUSION

Given the recent expansion of irrigated dry bean in Alberta and increasing interest in CONS practices, a 12-yr study was conducted to evaluate the effects of CONS rotations and management practices on the economics of irrigated dry bean production. Some of the highlights of this study are summarized below.

- Average differences among bean yields in CONV and CONS rotations were marginal (Larney et al., 2015).
- Averaged over 12 yr, NI for bean or for all crops in CONV management was \$122 ha^{-1} or \$155 ha^{-1} higher than NI for bean or for all crops in CONS practices.
- Risk efficiency analysis shows 4-yr CONV was preferred over all other rotations.
- Averaged over the first 10 yr, the bean NI in 4-yr CONV was significantly higher than the NI in all other rotations.
- Undercutting narrow-row bean in the final 2 yr of the study significantly increased CONS bean yield and NI compared to bean in CONV.
- In light of the effects of undercutting in 2010 and 2011, it is possible the long-term use of undercutting may result in a greater adoption preference for CONS management over that of CONV systems.

ACKNOWLEDGMENTS

We thank Dustin Dilay, Jim Sukeroff, Dale Reynolds, staff,and summer students at the AAFC Vauxhall Sub-station and Brandon Research and Development Centre for field and technical assistance. Ron Gregus assisted with potato management. Jenifer Nitschelem (2000–2006) and Peter Regiting (2007–2011), Rogers Sugar Ltd./Lantic Inc. (Taber, AB) managed sugar beet husbandry. Funding contributions from the Alberta Agriculture Research Institute, the Potato Growers of Alberta, Alberta Pulse Growers; Lantic Inc., Agriculture and Agri-Food Canada, and the Pulse Science Cluster are greatly appreciated.

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Carabid Assemblages (Coleoptera: Carabidae) in a Rotation of Three Different Crops in Southern Alberta, Canada: A Comparison of Sustainable and Conventional Farming

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Environ. Entomol. 37(5): 1214–1223 (2008)

ABSTRACT Carabids were sampled in 2000 (pretreatment year) and 2003–2005 in experimental plots in southern Alberta, Canada, after a rotation of beans, wheat, and potato under sustainable and conventional farming practices. Each phase of the rotation was present in every year. Crop type had a stronger effect than sustainable treatment on carabid-expected species richness, diversity, and species composition. However, carabid activity density was consistently higher in plots under sustainable treatments than those maintained conventionally. Potato plots, which were sprayed with insecticide for pest control, showed a significantly lower carabid activity density than the other crops. These results support other studies showing the beneficial effect of sustainable farming on activity density of carabid beetles.

KEY WORDS conventional versus sustainable agronomic practices, epigeic predators, ground beetles

Agricultural intensification, especially pesticide use and monoculture cultivation, has been shown repeatedly to negatively affect the structure of faunal and floral landscapes. These effects include soil erosion and contamination, ground water pollution, and biodiversity reduction (Edwards 1987, Pfiffner and Niggli 1996, Hole et al. 2005). In many, if not most, cases, these changes in soil, water, and biodiversity have been linked to conventional farming systems with high chemical input and a predominant focus on high yield production. Not surprisingly, concerns about environmental and food quality have fueled increasing efforts to develop alternative farming practices. Sustainable or low-input farming practices integrate crop rotation, economic injury level (EIL), strip cropping, intercropping, and other practices that can conserve predators of pest arthropods and minimize reliance on synthetic chemicals (Edwards 1987). For example, carabid beetles (Coleoptera: Carabidae) can play an important role in reducing populations of potential insect pests (Menalled et al. 1999, Holland 2002) and weeds (Menalled et al. 2007). The question is how can we maximize the extent and efficiency of this inexpensive, naturally provided pest management force?

Several studies have reported increased diversity and activity density of carabids under organic or sustainable farming (Dritschilo and Wanner 1980, Hokkanen and Holopainen 1986, Kromp 1989, Fan et al. 1993, Pfiffner and Niggli 1996), whereas others have reported no significant effects (Holopainen 1983, Armstrong 1995). Application of manure, a common organic fertilizer used in organic and sustainable farming, has been associated with increases in carabid activity density and diversity (Hance and Gregoire-Wibo 1987, Humphreys and Mowat 1994, Raworth et al. 2004). Moreover, manure application can be the single most important factor influencing farmland carabid community composition and can decrease the negative effects of the use of insecticides (Hance and Gregoire-Wibo 1987). Minimum or zero tillage, as recommended in sustainable agriculture, has been shown to benefit carabid assemblages (House and Stinner 1983, House and Alzugaray 1989, Tonhasca 1993, Andersen 1999). However, some studies have found no significant effects of tillage on the overall carabid abundance (Cárcamo et al. 1995, Hummel et al. 2002, Clark et al. 2006). Responses of some carabid species have also been inconsistent between different tillage intensities (Ferguson and McPherson 1985, Brust et al. 1986, Cárcamo 1995), which may be consequences of carabid life histories and timing of tillage operations.

In this paper, we studied the responses of carabid beetles to three different crops under rotation, wheat (*Triticum aestivus* L.), potato (*Solanum tuberosum* L.), and bean (*Phaseolus vulgaris* L.), and two different levels of agronomic input (conventional and sustainable farming). Our "sustainable" system was not an organic farming system because insecticides were used to manage potato pests; however, this system uses less input in the form of reduced tillage and alternative

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Table 1. Sustainable and conventional treatments and crop types with respective agronomic operations used to study ground beetles near Vauxhall, Alberta, from 2000 and 2003–2005

Rotation	Input	Crop	Variety	Fertilizer	Plant density (plant/m^2)
1	Conventional	Potato	Russet Burbank	134 N, 67 P, 67 K kg/ha, fall	3.6
2	Conventional	Bean	AC Red Bond (2003 UI906)	90 kg/ha, N spring	26
3	Conventional	Wheat	Soft White Spring Wheat AC Reed	90 kg/ha N spring	322
1	Sustainable	Potato	Russet Burbank	62 N, 28 P, 67 K (28 t/ha compost fall)	3.6
2	Sustainable	Bean	AC Red Bond (2003 UI906)	90 kg/ha N spring	43
3	Sustainable	Wheat	Soft White Spring Wheat AC Reed	90 kg/ha N spring	322

nutrient inputs in the form of manure. We analyzed ground beetle responses to these farming systems in terms of diversity, species composition, and activity density.

Materials and Methods

Site Description and Agronomic Treatments. This study was conducted near Vauxhall (50°03′19 N; 112°07′51 W), a region with brown chernozemic soil in the dry grassland of southern Alberta, Canada. The study site was made up of four replicates of 26 plots (10.1 by 18.3 m; interplot distances, 2.0 m) separated by 18-m pathways. Interplots and pathways were seeded with fall cereal that was regularly mowed. Rotations, varying in length for 3–6 yr, were established in 2000, which served as a baseline year where no agronomic inputs were applied. Barley was grown over the whole experimental area in 1999 (the year before project initiation). Each phase of each rotation was present in each year. This study used a subset of these plots to sample carabid assemblages in four replicate plots in wheat, bean, and potato plots of the 3-yr rotation in both sustainable and conventional treatments for a total of 24 plots/yr (in 2000 and 2003–2005; Table 1).

The following practices differentiate the sustainable treatment from the conventional: (1) direct seeding or reduced tillage where possible, (2) fall-seeded cover crops in bean plots, (3) composted cattle manure as a substitute for inorganic fertilizer after potato crop, and (4) straight cutting of solid seeded rather than undercutting of wide-row seeded bean plots. The latter practice may lead to soil erosion risk because it requires subsoil disturbance to uproot the plants in contrast to standard harvesting of straight cutting in one operation with a combine, which leaves some stubble without disturbing the soil. Compost (derived from beef cattle feedlot manure) was applied in the preceding fall to sustainable potato plots. The compost was sourced from the same feedlot each year and had an average (n = 3 yr) total nitrogen content of 12.5 g/kg, total phosphorus content of 4.3 g/kg, and a carbon/nitrogen ratio of 10.9. Fall cultivation involved one pass of a disc and harrow with the exception of the conventional potato treatment that was moldboard plowed. The sustainable bean and wheat plots were preceded by a fall-seeded cover crop cereal (oats or winter-hardy fall rye). Potato and wheat were seeded in late April to early May, and bean plots were seeded in mid-May. Only potato plots, of both treatments, were treated with insecticides (organophosphorous, pyrethroid, or chloronicotinyl) three times a year to control Colorado potato beetles [*Leptinotarsa decemlineata* (Say)] and aphids in this crop. This application was necessary to prevent yield losses from these insect pests that would confound the other "sustainable" treatments such as manure application. Fungicide was applied on beans and potatoes only while herbicides were applied to all crops. Glyphosate was applied once to terminate cover crops before seeding the beans in the sustainable treatment plots. Irrigation was applied to all plots as needed throughout the season. In July 2005, two potato plots (one sustainable and one conventional) were terminated after flooding problems caused by extreme rainfall in June.

Arthropod Sampling. Sampling was done with a 1-liter plastic container buried flush with the soil surface and fitted with another 0.5-liter plastic insert (11 cm diameter) half filled with undiluted plumbing grade propylene glycol (Spence and Niemelä 1994). A rain cover, made of tenplast (standard plastic greenhouse roofing), was suspended, using two 10-cm nails, ≈2 cm above each trap. Pitfall traps were collected every 7–10 d in 2000 (pretreatment year) and 2003–2005. The latter 3 yr constituted the second cycle of the crop rotation; thus, compost had been used at least once on each selected rotation. Sampling periods were as follows: (1) 1 July to 25 August 2000, (2) 12 June to 27 August 2003, (3) 18 May to 1 September 2004, and (4) 3 May to 29 August 2005. Two pitfall traps were placed in opposite corners of each study plot, 2 m from the plot edge and 5 m into the plot. Carabid beetles were stored in 70% ethanol and later identified to species using keys of Lindroth (1961–1969) and the reference collection at the Strickland Entomological Museum of the University of Alberta. Voucher collections were deposited at the Spence Laboratory Insect Collection of the University of Alberta, Edmonton and at the Lethbridge Research Centre.

Weed Survey. Number and frequency of weed species were surveyed using 15 quadrats (0.5 by 0.5 m) placed to form the shape of an inverted "w" on each plot before and after herbicide application (31 May and 24 July 2000; 3 June and 24 July, 2003; 25 May and 9 July 2004; and 4 June and 21 July 2005). Data were expressed in terms of mean plant density (plants/m^2) per plot. Herbicide applications followed the recommendation for chemical and rates as per the crop protection guide of the province of Alberta (Brook

2007). Chemicals used in beans included Ethalfluralin as a seed amendment before planting and sethoxydin and bentazon after emergence. In potatoes, eptam was applied preseeding and metribuzin postemergence. Herbicides used in wheat varied depending on weed presence and included trifluralin preseeding and tralkoxydim-bromoxynil-MCPA and fenoxaprop-p-ethyl, 2–4-D after emergence and glyphosate after harvest.

Analysis. Species that could not be distinguished morphologically were pooled for analysis so that all specimens were retained for at least general analyses. The taxon *Amara carinata* (LeConte, 1848) also included *Amara lacustris* (LeConte, 1855) and *Amara torrida* (Panzer, 1797), and *Harpalus funerarius* (Csiki, 1932) also included *Harpalus fraternus* (LeConte, 1852). Carabid catch from each pitfall trap was standardized for trapping effort (beetle per trap per day) by dividing the number of beetles per trapping days for each trap for each sampling date. Because of the occasional losses of samples of both traps from the same plot for a given period, an average standardized catch was obtained by dividing the standardized catch per sampling date by the number of collection dates.

Rarefaction analysis was applied to the data before standardization using the Vegan package (Jari et al. 2005) available for R software (R Development Core Team 2005). Individual-based rarefaction curves were obtained using 1,000 permutations for each treatment. Rarefaction standardization based on individuals is recommended for standardizing species richness for trapping effort (McCune and Grace 2002). Species diversity was also quantified with the standard Shannon-Wiener function (H') (Krebs 1989). Potential cumulative effects of conventional versus sustainable treatment on H' were tested using repeated-measures analysis of variance (ANOVA) within each of the crop types from 2003 to 2005 (SAS Institute 2005).

Nonmetric multidimensional scaling (NMDS) analysis with Sorensen (Bray-Curtis) distances was performed using PCOrd (McCune and Mefford 1999) to compare the species composition among treatments. NMDS was chosen because it performs well with ecological data that do not meet the assumption of normality (McCune and Grace 2002). A Monte Carlo probability was calculated to evaluate whether the final stress associated with the ordinations differed from random. In NMDS, the stress is a measure of distortion between the positions of real data points from the graphical representation. Thus, low stress represents few distortions from the real position of the data points and is associated with a graph that more accurately represents the dissimilarities in species composition. A preferred number of dimensions is suggested when adding an axis does not reduce stress by more than five.

The number of dimensions of the final ordination was automatically selected when the stress was not lowered by >5 and was near or below 20 with a Monte Carlo test inferior than 0.05. The similarity in species composition among the crop and agronomic input within each crop was tested using multiresponse permutation procedures (MRPP). The procedure uses Sorensen (Bray-Curtis) distances to calculate the variation within (A value) and between groups (T value) and evaluates the probability of these groups to be similar (McCune and Grace 2002). Additionally, species vectors were calculated with a minimum r^2 of 0.3. The angle of the vector indicates the direction of the relationship with the ordination while the length indicates the strength (McCune and Grace 2002).

Beetle catch rates and weed density were log(x + 1) transformed before analysis of variance to reduce heterogeneous variances typical of pitfall data. Weed abundance from both surveys (before and after herbicide use) were summed before transformation. Year-specific sums of carabid catches and weed abundance were analyzed using repeated-measures ANOVA with the catch from each year as the dependent variable and rotation, input, and interaction between these two as model factors. The samples from the year 2000 were used as a model covariate to account for pretreatment heterogeneity. Rotation was used as a model factor instead of crop type, because location of the crop changed every year and consequently the investigation of temporal effects would have been difficult. Although rotation is the model factor, it is feasible to study the effect of crop type every year by determining which crop was present in each rotation in a specific year.

To study the effect of crop type and agronomic input on the catches of the numerically dominant carabid species, we performed a complete factorial multivariate ANOVA (MANOVA) on the catch rate of the five most abundant species each year using crop type and agronomic input as independent factors for each year the treatments were applied (i.e., from 2003 to 2005). Only the five most abundant species were selected, because in certain years, the low catch rate of certain species would have resulted in poor analysis power and unreliable conclusions. In 2005, despite the fact that *Poecilus lucublandus* (Say, 1823) was slightly more abundant than *Bembidion quadrimaculatum* (Linné, 1769), we used the latter in the analysis for the sake of consistency among years. The responses of individual species were tested using ANOVA after significant MANOVA (Wilk's lambda, $P < 0.05$). In each analysis, Tukey's honestly significant difference (HSD) post hoc ($P < 0.05$) test was used to find groupings. We also tested for relationships between each of the five dominant species and weed density through linear regression. Unless otherwise noted, statistical analyses were performed using SPSS 11.0 software (SPSS 1999).

Results

Carabid Fauna. A total of 12,813 carabids, representing 62 species from 22 genera, were collected during the 4 yr of this study (1 pretreatment yr and 3 yr of applied treatments). The highest total catch and number of species were found in 2005 (3,705 individuals) and 2004 (49 species), whereas the lowest were found in 2000 (2,608 individuals and 41 species; Table

Table 2. Count (C) and frequency (F) of carabid species caught near Vauxhall, Alberta, in each study year and pooled total numbers

Carabid species	2000		2003		2004		2005		Total	
	C	F	C	F	C	F	C	F	C	F
Pterostichus melanarius (Illiger, 1798)	1158	44.4	928	30.89	1178	33.7	2257	60.92	5521	43.09
Amara carinata (LeConte, 1848)	30	1.15	655	21.8	267	7.64	271	7.31	1223	9.54
Amara farcta LeConte, 1855	14	0.54	365	12.15	361	10.33		6.15	968	7.55
Poecilus corvus (LeConte, 1873)	230	8.82	27	0.9	288	8.24	246	6.64	791	6.17
Stenolophus comma (F., 1775)	195	7.48	305	10.15	176	5.03	50	1.35	726	5.67
Bembidion quadrimaculatum (Linn 1769)	145	5.56	182	6.06	262	7.49	82	2.21	671	5.24
Poecilus lucublandus (Say, 1823)	293	11.23	22	0.73	122	3.49	97	2.62	534	4.17
Agonum placidum (Say, 1823)	285	10.93	30	1	64	1.83	55	1.48	434	3.39
Harpalus funerarius Mannerheim, 1853	7	0.27	76	2.53	157	4.49	21	0.57	261	2.04
Bembidion timidum (LeConte, 1848)	32	1.23	77	2.56	90	2.57	28	0.76	227	1.77
Harpalus herbivagus Say, 1823	22	0.84	16	0.53	110	3.15	68	1.84	216	1.69
Bembidion obscurellum (Motschulsky, 1845)	9	0.35	52	1.73	68	1.95	54	1.46	183	1.43
Amara apricaria (Paykull, 1790)	5	0.19	47	1.56	23	0.66	37	1.00	112	0.87
Microlestes linearis (LeConte, 1851)	7	0.27	9	0.3	86	2.46	4	0.11	106	0.83
Agonum cupreum Dejean, 1831	51	1.96	1	0.03	21	0.60	17	0.46	90	0.70
Harpalus amputatus Say, 1830	13	0.5	21	0.7	31	0.89	20	0.54	85	0.66
Bembidion rupicola (Kirby, 1837)	17	0.65	24	0.8	22	0.63	19	0.51	82	0.64
Amara torrida (Panzer, 1797)	21	0.81	26	0.87	12	0.34	2	0.05	61	0.48
Bembidion nitidum (Kirby, 1837)	2	0.08	9	0.3	14	0.40	31	0.84	56	0.44
Amara quenseli (Schönherr, 1806)	—	—	29	0.97	15	0.43	10	0.27	54	0.42
Agonum corvus (LeConte, 1860)	1	0.04	17	0.57	16	0.46	12	0.32	46	0.36
Pterostichus femoralis (Kirby, 1837)	35	1.34	5	0.17	3	0.09	1	0.03	44	0.34
Amara latior (Kirby, 1837)	1	0.04	17	0.57	8	0.23	3	0.08	29	0.23
Harpalus fraternus LeConte, 1852	1	0.04	1	0.03	4	0.11	19	0.51	25	0.20
Harpalus paratus Casey, 1924	5	0.19	5	0.17	11	0.31	4	0.11	25	0.20
Calosoma obsoletum Say, 1823	—	—	4	0.13	5	0.14	15	0.40	24	0.19
Pterostichus adstrictus Eschscholtz, 1823	4	0.15	2	0.07	10	0.29	4	0.11	20	0.16
Amara littoralis Mannerheim, 1843	2	0.08	8	0.27	2	0.06	7	0.19	19	0.15
Amara lacustris LeConte, 1855	5	0.19	6	0.2	5	0.14	—	—	16	0.12
Harpalus ventralis LeConte, 1848	1	0.04	—	—	13	0.37	2	0.05	16	0.12
Bembidion bimaculatum (Kirby, 1837)	2	0.08	9	0.3	1	0.03	3	0.08	15	0.12
Bradycellus congener (LeConte, 1848)	2	0.08	5	0.17	5	0.14	2	0.05	14	0.11
Amara obesa (Say, 1823)	1	0.04	2	0.07	5	0.14	6	0.16	14	0.11
Harpalus fuscipalpis Sturm, 1818	—	—	6	0.2	6	0.17	—	—	12	0.09
Poecilus scitulus LeConte, 1848	2	0.08	2	0.07	2	0.06	5	0.13	11	0.09
Bembidion castor Lindroth, 1963	—	—	6	0.2	—	—	3	0.08	9	0.07
Calathus ingratus Dejean, 1828	2	0.08	—	—	6	0.17	1	0.03	9	0.07
Chlaenius sericeus (Forster, 1771)	1	0.04	2	0.07	—	—	4	0.11	7	0.05
Bembidion coloradense Hayward, 1897	—	—	—	—	5	0.14	—	—	5	0.04
Amara confusa LeConte, 1848	—	—	1	0.03	2	0.06	2	0.05	5	0.04
Clivina fossor (Linn, 1758)	—	—	1	0.03	3	0.09	1	0.03	5	0.04
Bembidion rapidum (LeConte, 1848)	—	—	1	0.03	—	—	4	0.11	5	0.04
Harpalus somnulentus Dejean, 1829	—	—	—	—	3	0.09	2	0.05	5	0.04
Amara ellipsis (Casey, 1918)	—	—	1	0.03	3	0.09	—	—	4	0.03
Bembidion scudderi LeConte, 1878	—	—	—	—	1	0.03	3	0.08	4	0.03
Axinopalpus biplagiatus (Dejean, 1825)	—	—	—	—	3	0.09	—	—	3	0.02
Piosoma setosum LeConte, 1848	—	—	—	—	1	0.03	2	0.05	3	0.02
Bembidion acutifrons LeConte, 1879	—	—	1	0.03	1	0.03	—	—	2	0.02
Cymindis cribricollis Dejean, 1831	1	0.04	—	—	—	—	1	0.03	2	0.02
Harpalus nigritarsis Sahlberg, 1827	—	—	—	—	2	0.06	—	—	2	0.02
Cymindis borealis LeConte, 1863	1	0.04	—	—	—	0.00	—	—	1	0.01
Bembidion concolor (Kirby, 1837)	—	—	—	—	1	0.03	—	—	1	0.01
Amara convexa LeConte, 1848	—	—	—	—	—	—	1	0.03	1	0.01
Amara cupreolata Putzeys, 1866	—	—	—	—	—	—	1	0.03	1	0.01
Amara discors Kirby, 1837	1	0.04	—	—	—	—	—	—	1	0.01
Passimachus elongatus LeConte, 1846	—	—	—	—	1	0.03	—	—	1	0.01
Elaphrus lecontei Crotch, 1876	1	0.04	—	—	—	—	—	—	1	0.01
Badister neopulchellus Lindroth, 1954	1	0.04	—	—	—	—	—	—	1	0.01
Bembidion nudipenne Lindroth, 1963	1	0.04	—	—	—	—	—	—	1	0.01
Diplocheila oregona (Hatch, 1951)	—	—	—	—	1	0.03	—	—	1	0.01
Loricera pilicornis (F., 1775)	—	—	1	0.03	—	—	—	—	1	0.01
Lebia vittata (F., 1777)	1	0.04	—	—	—	—	—	—	1	0.01
Total Carabids	2608		3004		3496		3705		12813	

2). The catch frequency varied between years for most species. *Pterostichus melanarius* (Illiger, 1798), a European introduction to North America, was the most abundant species, with 43.1% of the total catch, but in 2005, this species alone represented 60.9% of the total catch (Table 2).

Diversity. Rarefaction curves were prepared for each year of the study and suggested high variability with respect to crops and agronomic inputs from year to year (Fig. 1). In 2000, before the sustainable treatments were applied, beans had the highest expected species richness, although the plots in wheat had the

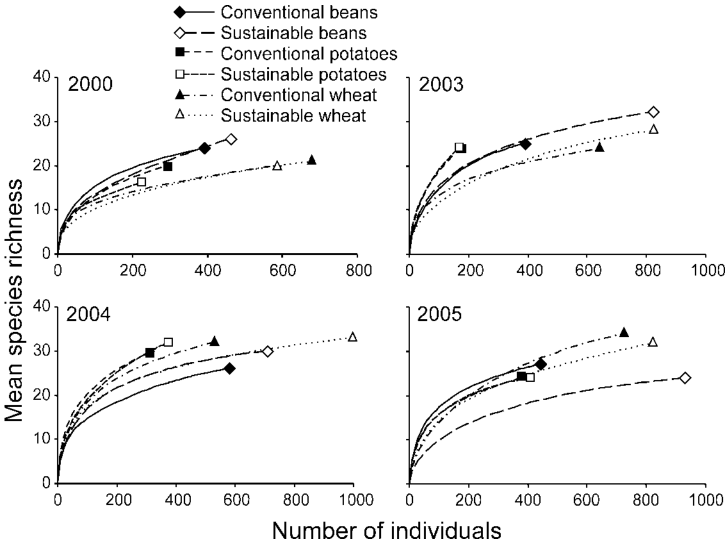

Fig. 1. Individual-based rarefaction curves for each treatment every year. Selection of subsamples of individuals was done randomly and reached the maximum of individuals caught.

highest total number of individuals caught. In general, plots allocated to the conventional or sustainable treatments within crops had similar expected species richness. In most years, and particularly in 2005, one or more of the crops under sustainable management had a higher total number of individuals (longer curves) and often slightly lower expected species richness than those crops under conventional management. The complementary, repeated-measures ANOVA of the Shannon-Wiener diversity index (year 2000 excluded; data not shown) within crops suggested a highly significant effect of year for all crops ($F_{2,12}$ values > 7.30, P < 0.01) but no treatment effects. Bean was the only crop where year interacted significantly with treatment ($F_{2,12}$ = 13.36, P < 0.01); bean plots under the sustainable regimen had lower diversity (0.95 versus 1.88) than those managed conventionally but only in 2005 (least significant difference [LSD], P < 0.05). For the other two crops, the same significant trend of decreasing diversity by 2005 relative to 2003 and 2004 was observed. In 2004 and 2005, sustainable wheat and potatoes also had slightly lower diversity (LSD, P > 0.05) than their conventional counterparts.

Species Composition. Crop type consistently influenced species composition each year (Fig. 2). The carabid assemblages in bean and wheat plots differed from those in potato each year, whereas the carabid assemblages in wheat significantly differed from those in bean plots only in 2000 and again in 2003 (MRPP, P < 0.05). Species composition of sustainable and conventional potato plots was similar every year. However, sustainable bean plots harbored a different carabid assemblage than plots under conventional bean in 2003 and in 2005, whereas the species assemblages of plots under sustainable and conventional wheat differed from each other in 2004 (MRPP, P < 0.05). Species vectors associated with the ordination varied from year to year (Fig. 2; Table 3), except for *P. melanarius*, which was present each year and consistently pointed in the opposite direction of the potato plots. Vectors of *Agonum placidum* and *Harpalus amputatus* were associated mostly with wheat. The only species vector that showed strong association with potato plots was *Bembidion timidum* in 2003. No other species vectors were associated with that crop in any other year.

Activity Density. Because two plots were not operational for more than one half of the collecting season in 2005, they were excluded from this analysis. There was an overall effect of agronomic input on the total carabid catch when all the years were analyzed using a repeated-measures design (F = 5.53; df = 1,15; P = 0.03) but no significant effects were found when years were analyzed separately despite a constant higher carabid catch rate mean in the sustainable treatments each year. Overall, the sustainable input plots had a higher carabid activity density than conventionally managed plots (Table 4). Additionally, potato plots accumulated lower catches than bean or wheat plots each year (2003: F = 7.63, df = 2,15, P = 0.005; 2004: F = 7.21, df = 2,15, P = 0.006; 2005: F = 4.65, df = 2,15, P = 0.027; Table 4). From 2003 to 2005, input and crop type interacted to influence the activity density of the five most abundant species (2003: F = 2.439, df = 10,30, P = 0.031; 2004: F = 2.935, df = 10,30, P = 0.012; 2005: F = 4.431, df = 10,30, P = 0.001; Table 4; Fig. 3). For 2 yr, the activity density of *Amara farcta* was enhanced by the sustainable wheat (2003: F = 8.27, df = 2,18, P = 0.003; 2004: F = 5.78, df = 2,18, P = 0.011), whereas treatments in other crops had no influence on its activity density. In 2004, the activity density of *Bembidion quadrimaculatum* was increased by conventional beans and wheat as well as by sustainable potatoes (F = 7.82, df = 2,18, P = 0.004). However, in 2005, only conventional beans increased

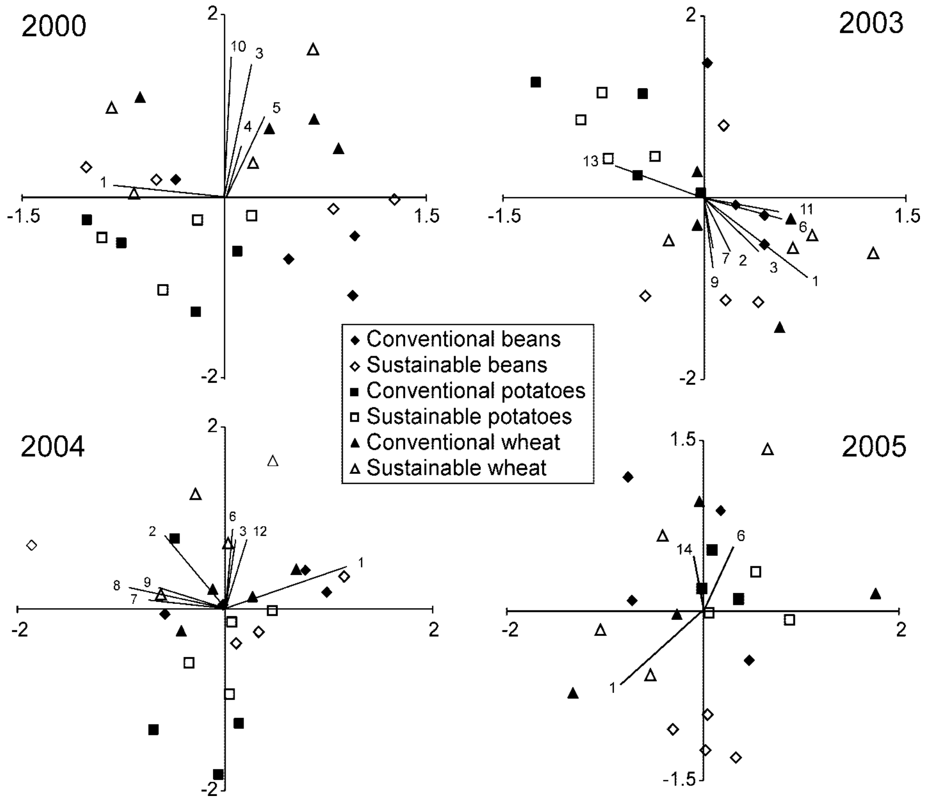

Fig. 2. Nonmetric multidimensional scaling (NMDS) ordination calculated with Sorensen distances done separately for each year to show systematic variations in the species composition of carabids among treatments. Each symbol represents the position of the carabid species composition of an experimental plot relative to the others. Note that input treatments were not applied in 2000. Vectors (minimum r^2 of 0.3) show the NMDS scores for different species as follows: 1, *Pt. melanarius*; 2, *H. amputatus*; 3, *A. placidum*; 4, *A. cupreum*; 5, *P. corvus*; 6, *Am. farcta*; 7, *Am. quenseli*; 8, *H. funerarius*; 9, *Am. carinata*; 10, *P. lucublandus*; 11, *S. comma*; 12, *Am. littoralis*; 13, *B. timidum*; 14, *B. quadrimaculatum*.

it activity density (F = 10.93, df = 2,16, P = 0.001). Other species such as *Stenolophus comma* and *Poecilus corvus* were also affected by the interaction between crop and input treatment (Fig. 3).

Weed Density and Carabid Activity Density. There was an overall treatment (F = 22.77, df = 1,15, $P <$ 0.001) and rotation effect (F = 5.085, df = 2,15, P = 0.021) on weed density (Fig. 4). Sustainable agronomic practices significantly increased weed density every year (2003: F = 22.16, df = 1,15, P = 0.001; 2004: F = 9. 58, df = 1,15, $P <$ 0.001; and 2005: F = 4.57, df = 1,15, P = 0.050), whereas wheat and potatoes had higher weed density than beans in 2003 (F = 12.01, df = 2,15, P = 0.001) and 2004 ($F_{2,15}$ = 18.81, $P <$ 0.001; Fig. 4). No significant differences in weed density between crops were found in 2005. There was no significant relationship between the total activity density of carabid beetles and the total weed density for any year. However, in 2003, *A. farcta* and *S. comma* showed a positive significant relationship with weed density ($F_{1,22}$, $R^2 >$ 0.89, both $P <$ 0.001).

Discussion

This study provides a synthesis of carabid responses to an alternative cropping system that includes less tillage and replacement of synthetic fertilizers with manure, as is characteristic of sustainable regimens. Relative to normal farm scales, the size of the experimental plots were small, but

Table 3. Parameters associated with NMDS ordination for the carabid community for each year at the study site near Vauxhall, Alberta

Year	Iterations	Stress	Monte Carlo P	Axis 1 R^2	Axis 2 R^2	R^2 cumulative
2000	33	18.174	0.0392	0.306	0.409	0.735
2003	71	10.517	0.0196	0.304	0.463	0.767
2004	146	12.526	0.0392	0.258	0.624	0.882
2005	68	20.002	0.0196	0.240	0.462	0.702

Refer to text for methodological details.

Table 4. Mean activity density (specimens/trap days) of the five most abundant carabid species and total carabid abundance in three crops (n = 8, ±1 SE, except potato in 2005 where n = 6) and two input levels (n = 12, ±1 SE, except in sustainable in 2005 where n = 10)

Carabid species	Crop			Input	
	Bean	Potato	Wheat	Conventional	Sustainable
2003					
Amara carinata	0.359 ± 0.138	0.021 ± 0.006	0.200 ± 0.152	0.152 ± 0.102	0.234 ± 0.103
Stenolophus comma	0.007 ± 0.003	0.003 ± 0.002	0.194 ± 0.072	0.017 ± 0.012	0.120 ± 0.055
Amara farcta	0.049 ± 0.014	0.016 ± 0.004	0.230 ± 0.082	0.033 ± 0.010	0.164 ± 0.061
Pterostichus melanarius	0.360 ± 0.114	0.075 ± 0.030	0.372 ± 0.074	0.299 ± 0.074	0.239 ± 0.077
Bembidion quadrimaculatum	0.054 ± 0.011	0.048 ± 0.010	0.032 ± 0.006	0.039 ± 0.007	0.051 ± 0.007
Total carabids	1.025 ± 0.265a	0.288 ± 0.053b	1.188 ± 0.272a	0.683 ± 0.199	0.985 ± 0.215
2004					
Amara carinata	0.090 ± 0.055	0.032 ± 0.007	0.041 ± 0.012	0.025 ± 0.006	0.083 ± 0.036
Poecilus corvus	0.039 ± 0.008	0.031 ± 0.010	0.126 ± 0.040	0.056 ± 0.013	0.076 ± 0.030
Amara farcta	0.044 ± 0.017	0.029 ± 0.009	0.199 ± 0.094	0.049 ± 0.012	0.132 ± 0.067
Pterostichus melanarius	0.320 ± 0.084	0.122 ± 0.031	0.257 ± 0.046	0.221 ± 0.048	0.245 ± 0.056
Bembidion quadrimaculatum	0.071 ± 0.014	0.041 ± 0.009	0.083 ± 0.012	0.077 ± 0.013	0.054 ± 0.006
Total carabids	0.817 ± 0.116ab	0.466 ± 0.103b	1.018 ± 0.183a	0.640 ± 0.082	0.895 ± 0.156
2005					
Amara carinata	0.045 ± 0.008	0.037 ± 0.009	0.089 ± 0.038	0.044 ± 0.008	0.070 ± 0.026
Poecilus corvus	0.094 ± 0.019	0.059 ± 0.012	0.050 ± 0.011	0.064 ± 0.009	0.070 ± 0.015
Amara farcta	0.026 ± 0.011	0.070 ± 0.027	0.100 ± 0.035	0.073 ± 0.023	0.057 ± 0.023
Pterostichus melanarius	0.660 ± 0.127	0.206 ± 0.045	0.671 ± 0.228	0.430 ± 0.149	0.595 ± 0.122
Bembidion quadrimaculatum	0.037 ± 0.014	0.026 ± 0.009	0.018 ± 0.004	0.040 ± 0.010	0.015 ± 0.003
Total carabids	1.046 ± 0.106a	0.531 ± 0.048b	1.099 ± 0.196a	0.835 ± 0.141	0.949 ± 0.116

Letters indicate results from pairwise comparisons (Tukey's $P < 0.05$) after a significant result in ANOVA.

relative to most published experiments (Butts et al. 2003) of this nature, our plots are above average in size. Although pitfall catches in small plots (<10 m wide) may partly reflect interplot carabid movement, many studies have used relatively small plots to study successfully the effects of farming practices on carabids (Clark et al. 1993, 2006, Honek 1997, Raworth et al. 2004). We thus believe that despite this possible effect, the catches reliably reflect carabid habitat association.

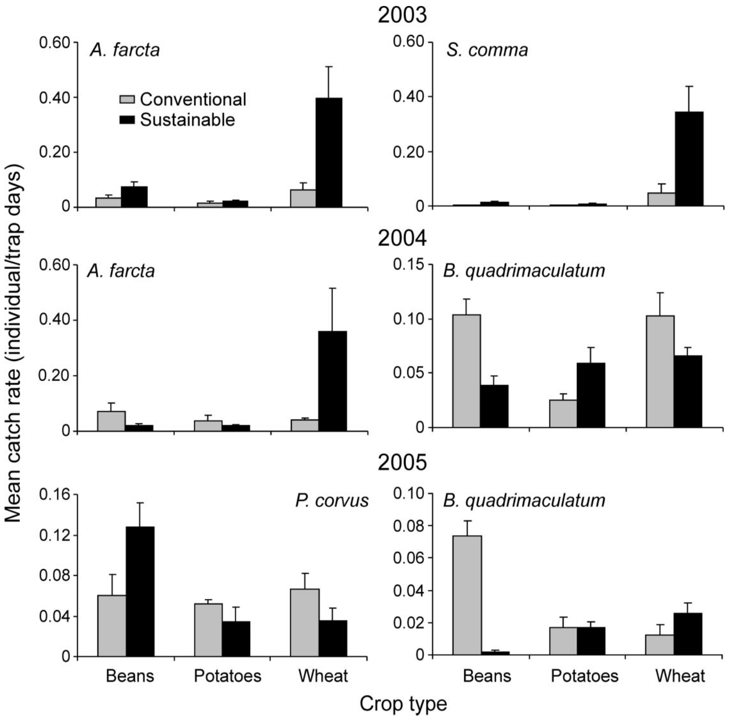

Fig. 3. Mean activity density of carabid species showing a significant response to the interaction between crop and input after a significant MANOVA (n = 4; ±1 SE except potatoes in 2005 where n = 3).

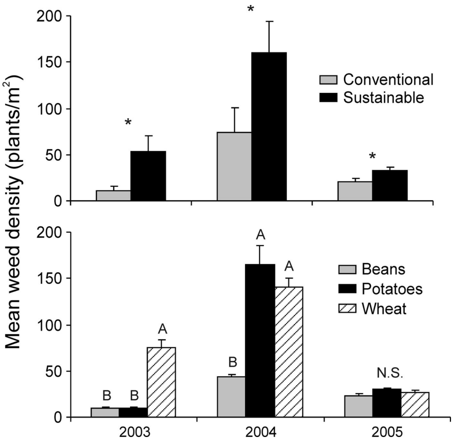

Fig. 4. Average weed density in plots with different inputs ($n = 12$; ± 1 SE) and crop types ($n = 8$; ± 1 SE) for the 3 posttreatment yr obtained by combining two surveys per year. *Significant difference ($P < 0.05$) was detected each year between sustainable and conventional inputs (left). Letters represent differences among the crop species, within respective years, after a significant ANOVA result (Tukey's test, $P < 0.05$).

Sustainable Versus Conventional Inputs. Contrary to our hypothesis and some past results (Dritschilo and Erwin 1982, Cárcamo et al. 1995, Pfiffner and Niggli 1996, Bengtsson et al. 2005), the sustainable agronomic input treatment did not consistently increase carabid diversity and had a minor role in producing a distinctive species composition. Thus, our results are more similar with those of Holopainen (1983), Clark (1999), and Melnychuk et al. (2003). The higher activity density of common carabids in sustainable wheat plots found in this study changed the structure of the community by reducing its evenness compared with conventional wheat. However, the expected or observed average number of species did not differ markedly between the two treatments. Thus, sustainably or conventionally grown crops such as wheat may not differ in ability to support different carabid species, but sustainable wheat increases the activity density of more common species such as *A. farcta.* Similarity in carabid diversity between sustainably and conventionally grown potato has also been reported by Armstrong (1995), whereas Kromp (1990) reported higher diversity in potato plots managed biologically than in those managed conventionally. Despite the use of the mold board plow in the conventional potatoes, we did not detect a difference in the activity density of carabid beetles in these two types of plots. This suggests that at this site, in contrast to others (Dubrovskaya 1970), the local community is resilient to this type of disturbance; effect of tillage was highly variable and results were site dependent. For example, recent work by Clark et al. (2006) in Maryland suggested little differences between no till and chisel-tilled plots. Menalled et al. (2007) found significantly higher overall carabid diversity and higher activity density of seed predators in plots that were managed under no tillage compared with those managed conventionally. More detailed population studies, in addition to community description, are needed to get a grip of the mechanisms at work in a given site.

In beans, the presence of cover crop and narrower planting rows may have provided different microhabitat structure throughout the season in the sustainable plots, which may have favored some species over others. For example, the absence of cover crop in conventional beans at the beginning of the year likely enhanced the activity density of *B. quadrimaculatum* (in 2004 and 2005), whereas later in the season, *A. carinata* was higher in plots under sustainable bean cultivation (in 2003 and 2004).

Consistently higher carabid catch in plots subjected to various sustainable practices has been reported in earlier studies (Dritschilo and Wanner 1980, Cárcamo et al. 1995, Clark 1999, Clark et al. 2006). A possible explanation for this finding may be the augmentation of potential prey items after manure application, which may also be responsible in the observed increased weed density. Vegetation structure under organic or sustainable agriculture, as observed in our study because of the greater weediness, is more complex than under conventional agriculture, and this, in turn, may support richer carabid assemblages (Andersen and Eltun 2000, Menalled et al. 2007). Hence, sustainable inputs may provide more prey items—arthropods or weeds, depending on species—to carabids. Also, soils in plots under tillage are often characterized by lower moisture and higher temperature. Humidity and temperature are important factors explaining distribution and abundance of carabids (Rivard 1966, Honek 1997).

Some numerically dominant carabid species showed a response to the interaction between crop type and input, which shows their sensitivity to variation in environmental conditions. Many species were also consistently most abundant in plots of a particular crop. The higher abundance of *A. farcta* in sustainable wheat for 2 consecutive yr (2003 and 2004) is probably because of higher weed abundance in both the sustainable treatment and wheat. Indeed, *A. farcta* is often found among weeds (Lindroth 1961–1969). Menalled et al. (2007) showed experimentally through the use of vertebrate exclosures that weed seed removal was correlated with carabid activity density. For some species, however, the combination of lower crop and weed density may enhance their activity density; in our study, *B. quadrimaculatum* was more abundant in conventional bean plots. Because crops were rotated each year on the study site, the location of a specific crop varied among the study years. Thus, in many of these fields, carabids probably recolonized the more suitable habitats that better explains variation in carabid catches than the possible effect of overwintering of individuals within the experimental plots.

Effect of Crop Type. Plots with potato had consistently fewer carabids but not lower diversity than plots with wheat or bean plots. For example, the catches of

P. melanarius, an introduced species, were lower in potato plots than in those planted to beans or wheat. These results can be explained mostly by the heavy application of insecticides, which likely lowered both the abundance of carabids and their available prey. Insecticide application has been shown to reduce carabid activity density (Sekulic et al. 1987; Floate et al. 1989).

Although bean and wheat plots generally had a similar overall carabid abundance, species composition differed between these two crops in 2 of the 4 yr. Differences in microhabitat structure may explain most of this separation. Mature broadleaf plants, such as bean and potato, produce a dense canopy compared with the canopy of wheat that remains more open throughout the season. Canopy structure can be important for thermoregulation of many species. Generally, open canopy provides a drier and warmer environment that may favor xerophilous species. However, wheat and beans are also grown at different plant densities. Plant density was lower in bean than wheat plots, which potentially facilitated carabid movements among plants. It is possible that species associated with open habitat would be enhanced under low plant density. In fact, only small open-habitat species (such as *B. quadrimaculatum* and *B. timidum*) seemed to associate with potato and bean plots.

We conclude that, after 6 yr of subjecting our plots to conventional and sustainable management, the carabid activity density was higher under the regimen that incorporated alternative, more environmentally friendly practices such as the use of manure in combination with reduce soil disturbance before seeding or during bean harvest. Expected species richness, diversity, and community structure were not impacted significantly by cropping systems and seemed to respond more to the type of crop planted. Future studies focusing on populations of carabid beetles are needed to elucidate the mechanisms responsible for the patterns observed.

Acknowledgments

We thank M. Koivula and T. Cobb for improvement of this manuscript and D. Pearson, C. Herle, J. Sukeroff, and C. Lyke for technical assistance. This work was funded primarily from Agriculture and Agri-Food Canada's Matching Investment Initiative program awarded to F.L.

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Received 7 August 2007; accepted 10 April 2008.

Populations, diversity and identities of bacterial endophytes in potato (*Solanum tuberosum* L.) cropping systems

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Received 21 May 2013, accepted 16 July 2013. Published on the web 31 July 2013.

Pageni, B. B., Lupwayi, N. Z., Larney, F. J., Kawchuk, L. M. and Gan, Y. 2013. **Populations, diversity and identities of bacterial endophytes in potato (*Solanum tuberosum* L.) cropping systems**. Can. J. Plant Sci. **93**: 1125–1142. Most plants host endophytic bacteria, but their identities and functions are usually unknown. Bacterial endophytes associated with potato grown after dry bean (*Phaseolus vulgaris* L.) or wheat (*Triticum aestivum* L.) were isolated, quantified and identified in a field study that compared crop rotations (3 to 6 yr in length) and soil management (CONV, conventional; CONS, conservation) for dry bean, potato, sugar beet (*Beta vulgaris* L.) and spring wheat. Populations of culturable endophytes ranged from 2.83×10^3 to 7.65×10^3 colony-forming units g^{-1} of root dry matter. The populations and diversity of the endophytes were greater with CONS than CONV soil management, and tended to be greater in longer than shorter rotations. The community structures of the endophytes were different between CONV and CONS soil management. A terminal-restriction fragment length polymorphism assay targeting the 16S rRNA gene, and its sequencing, showed that CONS management systems contained more *Proteobacteria* than CONV management systems, and vice-versa for *Acidobacteria*. *Bacteriodetes* were found only in long CONS rotations. This phylogenetic characterization of potato endophytes is important for further studies on their effects on the host plants.

Key words: Crop rotations, endophytic bacteria, soil management, terminal-restriction fragment length polymorphism

Pageni, B. B., Lupwayi, N. Z., Larney, F. J., Kawchuk, L. M. et Gan, Y. 2013. **Populations, diversité et identité des bactéries endophytes dans les cultures de pomme de terre (*Solanum tuberosum* L.)**. Can. J. Plant Sci. **93**: 1125–1142. La majorité des plantes hébergent des bactéries endophytes dont on ignore souvent l'identité et le rôle. Les auteurs ont isolé, quantifié puis identifié les bactéries endophytes présentes chez la pomme de terre cultivée après le haricot (*Phaseolus vulgaris* L.) ou le blé (*Triticum aestivum* L.) dans le cadre d'une étude sur le terrain qui devait servir à comparer les méthodes d'assolement (rotation de 3 à 6 ans) et de gestion du sol (CONV, travail classique; CONS, conservation) pour le haricot, la pomme de terre, la betterave sucrière (*Beta vulgaris* L.) et le blé de printemps. Les populations de bactéries endophytes cultivables varient de $2,83 \times 10^3$ à $7,65 \times 10^3$ colonies par gramme de matière sèche de racine. Les populations et la diversité des bactéries endophytes sont plus grandes avec des pratiques CONV que CONS de gestion du sol et ont tendance à être plus importantes avec les assolements longs qu'avec les assolements courts. La population d'endophytes n'a pas la même structure selon que le sol est travaillé CONV ou CONS. Un essai de polymorphisme de longueur des fragments de restriction terminaux (T-RFLP) sur le gène 16S de l'ARNr et le séquençage subséquent de ce dernier indiquent que le sol CONS renferme plus de *Proteobacteria* que le sol CONV, l'inverse étant vrai pour les *Acidobacteria*. *Bacteriodetes* n'a été identifié que dans les longs assolements sur sol CONS. Cette caractérisation phylogénétique des endophytes de la pomme de terre facilitera les études qui approfondiront les effets des endophytes sur la plante hôte.

Mots clés: Assolement, bactéries endophytes, gestion du sol, T-RFLP

Endohphytes are microorganisms that live within a plant in a mutualistic relationship (Wilson 1995; Schulz and Boyle 2006). They are believed to support plant processes that include growth promotion, nutrient uptake, tolerance to abiotic stresses, and inhibition of infection by pathogens (Ryan et al. 2008). Culturable bacterial endophytes can be isolated after surface sterilization of plant material. Endophytes are found in roots, stems and leaves of plants and are ubiquitous in a range of different plant species (Garbeva et al. 2001). Bacterial endophytes have been isolated from sweet potato (*Ipomoea batatas*) (Khan and Doty 2009), cottonwood (*Populus deltoids*) (Xin et al. 2009),

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Abbreviations: **CFU**, colony-forming units; **CONS**, conservation soil management; **CONV**, conventional soil management; **PCR**, polymerase chain reaction; **T-RFLP**, terminal-restriction fragment length polymorphism; **TRF**, terminal-restriction fragments grapevine (*Vitis vinifera*) (West et al. 2010), poplar (*Populus alba*) (Doty et al. 2005), soybean (*Glycine max*) (Hung et al. 2007), tomato (*Solanum lycopersicum*) (Marquez-Santacruz et al. 2010) and potato (Garbeva et al. 2001; Sessitsch et al. 2002; Andreote et al. 2009; Manter et al. 2010). Greater soil microbial counts, biomass and diversity have been observed in legume-based crop rotations (Lupwayi et al. 1998; Biederbeck et al. 2005). Some of the soil bacteria develop endophytic associations with non-legumes (Lupwayi et al. 2004), probably resulting in nutritional, crop protection and stress tolerance benefits to the host plants. Therefore, endophytic microorganisms can play important roles and offer environmentally friendly methods to increase productivity while reducing chemical inputs.

While culturable endophytes have been isolated in the studies cited above, endophytic populations in potato monitored by denaturing gradient gel electrophoresis (Garbeva et al. 2001) revealed the presence of several distinct phylogenetic groups of organisms, suggesting that non-culturable endophytes are also present in potato. Despite the difficulty of obtaining taxonomic information on the organisms from particular terminal-restriction fragments (TRFs), the terminal-restriction fragment length polymorphism (T-RFLP), a semiquantitative fingerprinting method, is extensively used for comparative community analysis. In the method, fluorescent end-labelled polymerase chain reaction (PCR)-amplified markers (commonly the small-subunit rRNA gene) are digested with one or more restriction enzymes, resulting in the production of fluorescent labelled TRFs of different lengths. The TRFs can be separated and detected as peaks on an automated sequence analyser. The T-RFLP technique has the advantage of using an internal size marker with each sample, which greatly facilitates automatic sizing of peaks as compared with other molecular fingerprinting methods like denaturing gradient gel electrophoresis. This method has been widely used to investigate bacterial community structures in various environments (Liu et al. 1997; Dunbar et al. 2000; Osborn et al. 2000; Conn and Franco 2004; Luna et al. 2006) including plant interiors.

The objective of this study was to isolate, quantify and identify endophytic bacteria from the roots of potatoes grown in various crop rotations under irrigation, as a first step towards understanding their effects on potato growth. The rotation study had been running for 12 yr (2000–2011) when sampled. The diversity and identities of the endophytes were determined using T-RFLP analysis, and the identities were confirmed using 16S rRNA gene sequencing. To our knowledge, this is the first report of microbial analysis by T-RFLP of 16S rRNA genes to characterize endophytic bacterial communities of potatoes grown in irrigated cropping systems.

MATERIALS AND METHODS

Treatments

An irrigated cropping study was initiated in 2000 at Vauxhall, Alberta (lat. 50°06′N, long. 112°13′W) to compare the effects of 3- and 4-yr rotations under conventional soil management (CONV) or conservation soil management (CONS), and 5- and 6-yr rotations under CONS soil management on yields of dry bean, potato, sugar beet and spring wheat. The CONS rotations represented a package built around five specific soil conservation practices: (1) Direct seeding/reduced tillage where possible to maintain surface residue and reduce wind and water erosion risk; (2) Fall-seeded cover crop (fall rye, *Secale cereale* L.) to reduce wind erosion risk in fall and early spring; (3) Feedlot cattle manure compost application (28 or 42 t ha^{-1} every third year) to replace inorganic fertilizer inputs and improve soil organic matter; (4) Solid-seeded narrow-row (20 cm) beans direct-cut at harvest vs. conventional wide-row (60 cm) beans, which are under-cut at harvest leaving loose soil and non-anchored stubble; (5) Longer rotations of 5- and 6-yr under CONS soil management. The CONV rotations had none of the above management practices. There were a total of six rotations with all 26 phases appearing every year, arranged in a randomized complete block design (RCBD) and replicated four times (104 plots, each 10.1×18.3 m) (Table 1). Rotations varied in length from 3 to 6 yr with 2 yr of timothy (*Phleum pratense* L.) included in the longest rotation. Soil management systems (CONV, CONS) and length of crop rotations were considered the different treatments.

Isolation of Endophytes

Potato roots and adhering rhizosphere soil were sampled in all 24 potato plots (6 rotations × 4 replicates, Table 1) at the flowering stage in August, 2011 and kept at −20°C until required. Roots were washed with distilled water and surface-sterilized using 10% (vol vol^{-1}) sodium hypochlorite for 8 min, followed by 1% iodophor for 5 min, and then washed 10 times with sterile water. About 0.5 g of surface-sterilized roots was macerated to fine powder using liquid nitrogen in a sterilized and precooled mortar. The powder was

Table 1. Irrigated rotation treatments at Vauxhall, Alberta

Treatment	Length (yr)	Rotation[z]	Management
1	3	P–B–W	CONV
2	3	P–B–W	CONS
3	4	W–SB–B–P	CONV
4	4	W–SB–B–P	CONS
5	5	P–W–SB–W–B	CONS
6	6	O(t)–T–T–SB–B–P	CONS

[z]W, wheat; B, beans; P, potato; SB, sugar beet; O (t), silage oats harvested July, timothy seeded August; T, timothy. CONV, conventional soil management; CONS, conservation soil management.

suspended and serially diluted with sterile water to isolate bacterial endophytes. Aliquots of 100 μL were plated in tryptic soy agar medium plates containing 100 μg mL^{-1} cycloheximide (antifungal chemical), and the plates were incubated at 28°C for 48 h (Garbeva et al. 2001; Khan and Doty 2009). Samples of root tissue from the surface-sterilization process were also plated into the same medium to check the success of the sterilization. Bacterial colonies were counted after 48 h, and these colonies were further screened in tryptic soy agar medium. Different morphological characteristics (number, colour and size of colonies) of endophytes were observed, counted, and different colonies were chosen for further analysis. Endophyte populations were estimated as colony-forming units per gram of potato root tissue. Culture broths of screened endophytes were kept at −80°C with 30% glycerol solution as stock solution.

Nucleic Acid Extraction and 16S rRNA Gene Amplification

Some of the distinct colonies were grown in tryptic soy broth liquid media and chromosomal DNA isolated using the QIAamp DNA Mini kit (Qiagen, Gaithersburg, MD). The concentration and purity of chromosomal DNA were checked with Nano Drop 2000 spectrophotometer (Thermo Scientific, Wilmington, DE). Eubacterial 16S rRNA gene sequences were amplified by universal bacterial primers (8F: 5′- AGAGTTTGATCC TGGCTCAG-3′ and 1492R: 5′-GGTTACCTTGTTAC GACTT-3′) using the chromosomal DNA as template for identification of 16S rRNA, while 341F: 5′-CCTACGG GAGGCAGCAG-3′ and 1492R were used for amplification of 16S rRNA gene for T-RFLP analysis (Liu et al. 1997; Khan and Doty 2009). PCR was carried out with a thermocycler (Eppendorf, Hamburg, Germany) using an initial denaturation step of 7 min at 95°C followed by 40 cycles of 30 s at 95°C, 1 min annealing at 56°C and 1 min extension at 72°C, followed by final extension at 72°C for 7 min. The PCR products of 16S rRNA genes were visualised with ethidium bromide in 1% agarose gel.

Endophyte Community Analysis by 16S rRNA-Based T-RFLP

Genomic DNA from potato root tissue was used for T-RFLP analysis. Eubacterial universal forward primer 341F (Liu et al. 1997) was labelled at the 5′ primer end with 6-carboxyfluorescein (6-FAM) (Integrated DNA Technologies, Coralville, IA) and reverse primer 1492R (Khan and Doty 2009) were used to amplify the 16S rRNA gene. Reactions were carried out in a thermocycler (Eppendorf, Hamburg, Germany) as described above. The PCR reactions (50 μL) contained 5 U HotStarTaq DNA polymerase (Qiagen, Hilden, Germany), PCR Buffer (with 3 mM $MgCl_2$), and 400 μM of each dNTP (Qiagen, Hilden, Germany), 800 μM of each primer and 15–25 ng template DNA. The PCR products were purified using QuickA PCR Purification Kit following the manufacturer‘s protocol from Qiagen. About 1200 ng of purified-16S rRNA PCR products were individually digested for 4 h at 37°C with 4-bp recognition sites *Hinf*I, *Rsa*I, *Mbo*I and a combination of *Hae*III and *Mbo*I (New England Biolabs Inc., Ipswich, MA). Restriction enzymes that generated unique TRFs were determined using Restriction Endonuclease Picker (REPK v1.3) (Collins and Rocap 2007). Preliminary experiments showed that *Hinf*I was the best endonuclease because it produced more TRFs than the other enzymes, and results presented here are for this endonuclease.

Enzyme reactions were quenched at 65°C for 10 min to inactivate enzyme activity, purified and 0.5 μL aliquots were mixed with 1 μL of loading buffer (5 deionised formamide:1 loading dye) and 0.3 μl of DNA fragment length standard (Genescan 500 Rox; Perkin-Elmer). Reaction mixtures were denatured at 92°C for 2 min and chilled on ice prior to electrophoresis. Samples (1.75 μL) were applied on 6% denaturing polyacrylamide gels and fluorescently labelled terminal restriction sizes were analysed using an ABI 3730x 1 genetic analyser automated DNA sequencer (University of Calgary, Calgary, AB). The TRFs were only scored as positive when they had more than 50 fluorescence units. Fragments were sized using Peak Scanner software v1.0 (Applied Biosystems) and the resulting data was imported into T-REX software (Culman et al. 2009) for further processing. Data were subjected to quality control procedures including TRF alignment (clustering threshold = 2 bp), noise filtering (peak area, standard deviation multiplier = 1), and elimination of TRFs < 50 bp. The total fluorescence within each T-RFLP profile was calculated by summing the heights of peaks detected. Additive Main Effects and Multiplicative Interaction Model (AMMI) analysis was carried using T-REX software (Culman et al. 2009). The TRFs obtained from each electropherogram after running in T-REX software were used in PAT+ program from Microbial Community Analysis (MiCA3) software server application (Shyu et al. 2007) to assign putative taxonomic identities. Operational taxonomic units of each type of endophyte were derived from the number of TRFs obtained from each treatment.

The online server Chang BioScience (2004) was used to calculate indices of diversity: Shannon-Wiener index (H’), species richness (S) and evenness (E). Average TRFs were taken from three analyses for each sample, and the TRFs from all four field experimental replicates were included in the statistical analysis of H’, S and E.

Construction of 16S rRNA Gene Library

Amplified PCR products of 16S rRNA genes from the isolates were purified using QuickA PCR purification kit (Qiagen, Gaithursburg, MD) according to the manufacturer’s instructions and were cloned into pGEM-T-easy vector (Promega, Madison, WI), and then transformed into competent cells of *Escherichia coli* DH5α. Positive colonies were selected using the white-blue-colony method on Luria–Bertani (LB) medium containing

X-Gal (5-bromo-4-chloro-3-indolyl-β-D-galactopyrano side), IPTG (isopropyl- β-D-thiogalactopyranoside), and 50 μg mL^{-1} ampicillin and cultured in liquid LB culture medium. Cloned DNA was extracted from the culture broth of positive colonies. Cloned products were sequenced at Génome Québec Innovation Centre (McGill University, Montreal, QC) using T7 and SP6 promoter's primers. Purified PCR products of 16S rRNA gene were also sequenced using 8F and 1492R primers. The 16S rRNA gene sequences were compared and identified by homology comparison to entries in the GenBank nucleotide database using BLASTN (Altschul et al. 1997). All cultured endophytes from various treatments are listed in Supplementary Table 1. Phylogenetic molecular evolutionary analyses were conducted using ClustalW2 online software (Larkin et al. 2007) and the aligned sequences were exported to MEGA 5.05 version (Tamura et al. 2011). All sequences were screened for potential chimeric sequences using database-enabled code for ideal probe hybridization employing R (DECIPHER) online software (Wright et al. 2012).

Nucleotide Sequence Numbers

All the nucleotide sequences of 16S rRNA gene from potato endophytes have been deposited in the NCBI GenBank database under accession numbers JX912365 to JX912472.

Statistical Analysis

All data [CFU, Shannon-Wiener index (H'), species richness (S) and evenness (E)] were subjected to analysis of variance (ANOVA) according the RCBD of the field experiment, using SAS software (Ver. 9.1, SAS institute, Inc., Cary, NC). Unless otherwise specified, statistical analyses were based on peak height used in T-REX software. Statistical significance was established at $P = 0.05$ and means were separated by the least significant difference (LSD) test. Principal component analysis (PCA), a multivariate procedure, was used to classify the TRFs of the endophyte communities using PAST 2.02 software (Hammer et al. 2001).

RESULTS

Endophyte Populations

The lowest endophyte population, i.e., 2.83×10^3 CFU g^{-1} of potato root tissue, was found in 3-yr potato–bean–wheat rotation under CONV soil management, whereas the highest endophyte population, i.e., 7.65×10^3 CFU g^{-1} of root, was found in 5-yr potato–wheat–sugar beet–wheat–bean rotation under CONS soil management (Fig. 1). The endophytic populations in the 5-yr and 6-yr CONS rotations were significantly greater than those in the 3-yr and 4-yr CONV rotations. Between the two 3-yr rotations, the populations were significantly greater under CONS management than CONV management, and the same result was observed between the two 4-yr rotations.

Endophyte Diversity, Community Structures and Phylogenetic Identities: T-RFLP Analysis

Table 2 shows that differences in H' between treatments were similar to differences in endophyte populations described above (Fig. 1). Thus, between the two 3-yr or 4-yr rotations, the endophytes in rotations under CONS management were more diverse (greater H') than those under CONV management, and the 5- and 6-yr CONS rotations tended to have more diverse endophytes than 3- and 4-yr CONV rotations. Both S and E contributed to these differences in H' (H' is a composite of S and E).

Ordination of TRFs by PCA revealed differences in community structures of the endophytes in the different treatments (Fig. 2). This analysis indicated that most (77%) of the variance in endophyte community structures was explained by PC1 (x-axis, left to right in Figure 2). Therefore the endophyte communities in treatment T5 (5-yr CONS) and, to a lesser extent, T6 (6-yr CONS) were very different from those in T1 (3-yr CONV) and, to a lesser extent, T3 (3-yr CONV) and T2 (3-yr CONS). Figure 2 also shows that α- and γ-*Proteobacteria* (see below) were more associated with T5, and the *Firmicutes* with T6, than with other treatments.

The endophytes were identified and assigned to distinct putative phylogenetic groups. Many TRFs shared more than one phylogenetic group and the identified TRFs revealed differences in the relative population structures in various treatments. The TRFs were affiliated to *Proteobacteria* (α, β, γ and δ), *Firmicutes*, *Cyanobacteria*, *Actinobacteria*, *Bacteriodetes*, *Acidobacteria* and some unidentified bacteria (Fig. 3). Within 3-yr or 4-yr rotations, β-*Proteobacteria* were more abundant in CONS management than in CONV management, but the reverse was observed for *Acidobacteria*. A side-by-side comparison of the average distribution for all CONV vs. CONS management shows that the sum of all *Proteobacteria* was greater under CONS management than under CONV management, and so were *Bacteriodetes*, but the reverse was true for *Acidobacteria* (Fig. 4).

Taxonomic Identities: 16S rRNA Gene Sequencing

A total of 108 endophytes from various treatments were selected for sequencing (Supplementary Table 1). All of these 16S rRNA encoding gene sequences were identified by sequence homology using NCBI BLAST followed by Ribosomal Database Project (RDP) (Larkin et al. 2007). Based on this sequencing, the dominant phyla in all treatments were *Proteobacteria*, *Firmicutes*, *Cyanobacteria* and *Actinobacteria*, but their relative distribution in each treatment was different (Fig. 5). Due to culturing difficulty (Jones et al. 2009), no *Acidobacteria* were detected based on 16S rRNA gene sequencing. Within 3-yr or 4-yr rotations, *Proteobacteria* were more abundant in CONS practices than CONV practices, whereas *Actinobacteria* were more abundant in CONV practices than in CONS practices. Furthermore, *Bacteriodetes* were only found in the

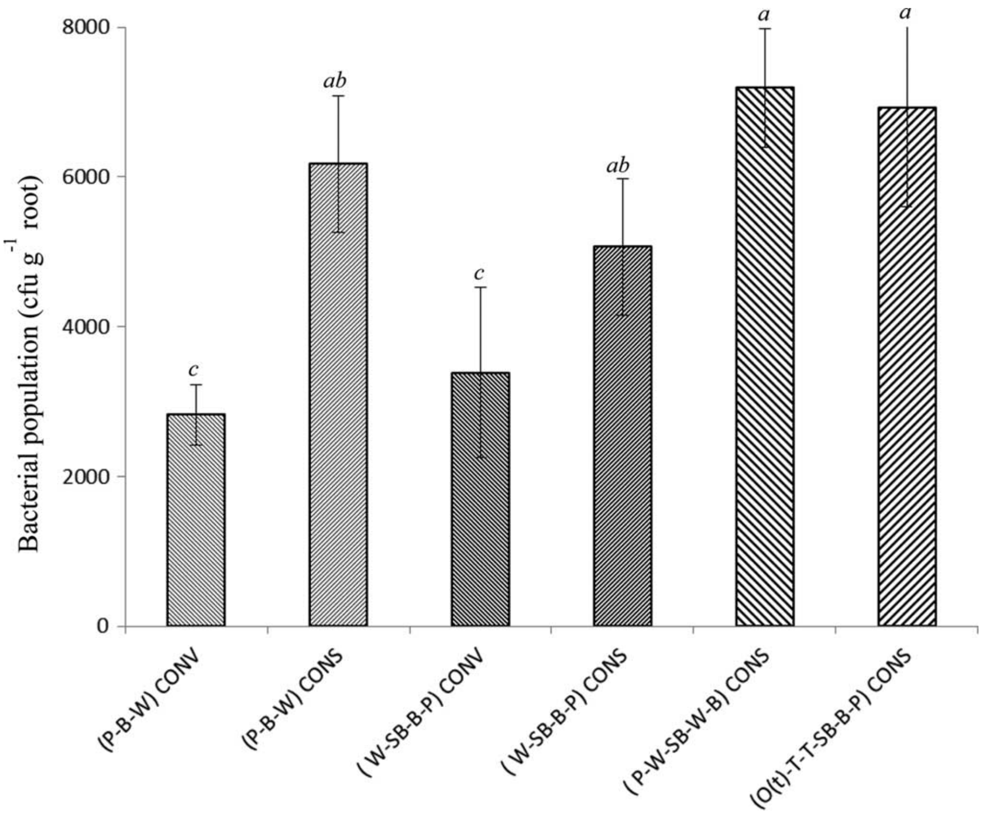

Fig. 1. Effect of crop rotation length (3 to 6 yr) and soil management (CONV or CONS) on bacterial endophyte populations of potato roots. Each bar is an average of four field replications, and the standard error is indicated. Treatment means with the same letter are not significantly different at the 5% significance level. W, wheat; B, beans; P, potato; SB, sugar beet; O (t), silage oats harvested July, timothy seeded August; T, timothy. CONV, conventional soil management; CONS, conservation soil management.

longer rotations under CONS soil management. Relatively equal percentages of *Firmicutes* were found in all treatments and the distribution of *Cyanobacteria* was variable. Results of phylogenetic analysis of the 16S rRNA gene of endophytes from each treatment are shown in Supplementary Figs. 1–6. The *Firmicutes* were mostly the genera *Bacillus*, *Paenibacillus, Lysinibacillus, Solibacillus* and *Staphyloccocus*. Some of the genera belonging to *Proteobacteria* were *Pseudomonas*, *Cedibacter*, *Agrobacterium*, *Rhizobium*, *Ralstonia* and *Cupriavidus*. The *Cyanobacteria* were represented by *Halospirulina* and *Planktothricoides* spp. Bacteria belonging to *Actinobacteria* included the genera *Kribbia, Brevibacterium, Microbacterium* and *Arthrobacter*.

DISCUSSION

Bacterial endophytes in agricultural systems are subject to a wide range of management practices. Characterizing these endophyte communities is important considering their potential significance in plant growth promotion, nitrogen fixation, protection against disease, biotic and abiotic stress tolerance, or sources of novel

Table 2. Diversity of bacterial endophytes isolated from potato in various treatments. Average values (± standard error) of shannon index, species richness and evenness are from four field replicates

Treatment[z]	Management	Shannon index (H')	Species richness (S)	Evenness (E)
P–B–W	CONV	1.99 ± 0.20*bc*	8.75 ± 1.5*ab*	0.92 ± 0.03*ab*
P–B–W	CONS	2.11 ± 0.09*a*	9.75 ± 0.5*a*	0.93 ± 0.02*ab*
W–SB–B–P	CONV	1.92 ± 0.21*c*	8.50 ± 1.9*b*	0.91 ± 0.01*b*
W–SB–B–P	CONS	2.11 ± 0.07*a*	9.50 ± 0.6*ab*	0.94 ± 0.02*a*
P–W–SB–W–B	CONS	2.07 ± 0.16*ab*	9.25 ± 1.5*ab*	0.94 ± 0.01*a*
O(t)–T–T–SB–B–P	CONS	2.09 ± 0.12*a*	9.50 ± 1.0*ab*	0.93 ± 0.01*ab*

[z]W, wheat; B, beans; P, potato; SB, sugar beet; O (t), silage oats harvested July, timothy seeded August; T, timothy. CONV, conventional soil management; CONS, conservation soil management.
a–c Means with the same letter in a column are not significantly different 5% significance level.

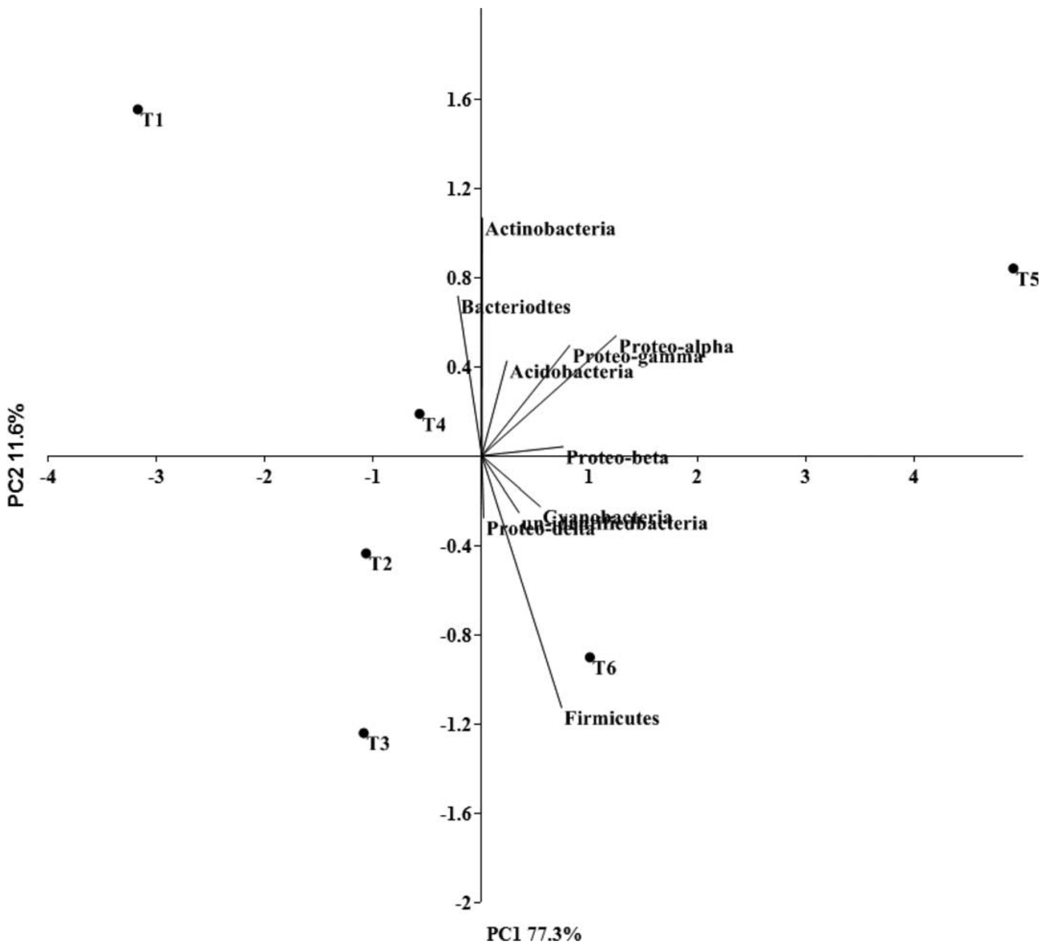

Fig. 2. Ordination of endophyte TRFs (from T-RFLP analysis) of endophyte communities from different treatments (T1 to T6) by principal component analysis (PCA). Each treatment point is a mean of four replicates. The percentage of variance explained by each axis is indicated. T1, (potato–bean–wheat) and T3 (wheat–sugar beet–bean–potato) under CONV soil management while T2 (potato–bean–wheat), T4 (wheat–sugar beet–bean–potato), T5 (potato–wheat–sugar beet) and T6 (oat–timothy–timothy–sugar beet–bean–potato) under CONS soil management.

biomolecules for bioremediation (Trivedi et al. 2011). As endophytes occur in intercellular spaces of plant tissues, their role in supporting plant growth is matter of discussion (Sessitsch et al. 2002). It is assumed that endophytic bacteria play an important role in plant growth and its adaptation to the environment. Their presence indicates that they are critical for plant health, growth and other ecologically relevant functions of plants. The rhizosphere is an important source of root endophytes, and most of the root endophytes are also present in the rhizopshere. Root endophytes enter the plant by local cellulose degradation or fractures in the root system (Gough et al. 1997). In this study, conservation practices increased soil microbial diversity and biomass (F. J. Larney, unpublished data). We also found that changing the soil management practices and lengthening crop rotations influenced bacterial endophyte populations and altered their community structures.

Endophyte populations under CONS soil management were higher, probably due to the improved soil quality (Larkin et al. 2011), in this case resulting from direct seeding (zero or reduced tillage), addition of composted manure, and cover-cropping. Many reports show that residue retention with direct seeding increase the abundance of bacteria in no-till systems (Hammesfahr et al. 2008; Ceja-Navarro et al. 2010). Agronomic practices that include reduced tillage and crop residue retention can be adopted as sustainable agricultural practices that preserve and improve the diversity of soil microbial communities (Ceja-Navarro et al. 2010). Tillage reduces microbial populations because it accelerates the breakdown of soil organic C, a key substrate for microorganisms. Tillage also reduces microbial diversity (Lupwayi et al. 1998), presumably because it homogenizes the soil and the C substrates within it. Addition of organic amendments like compost to agricultural soil increases the population of soil

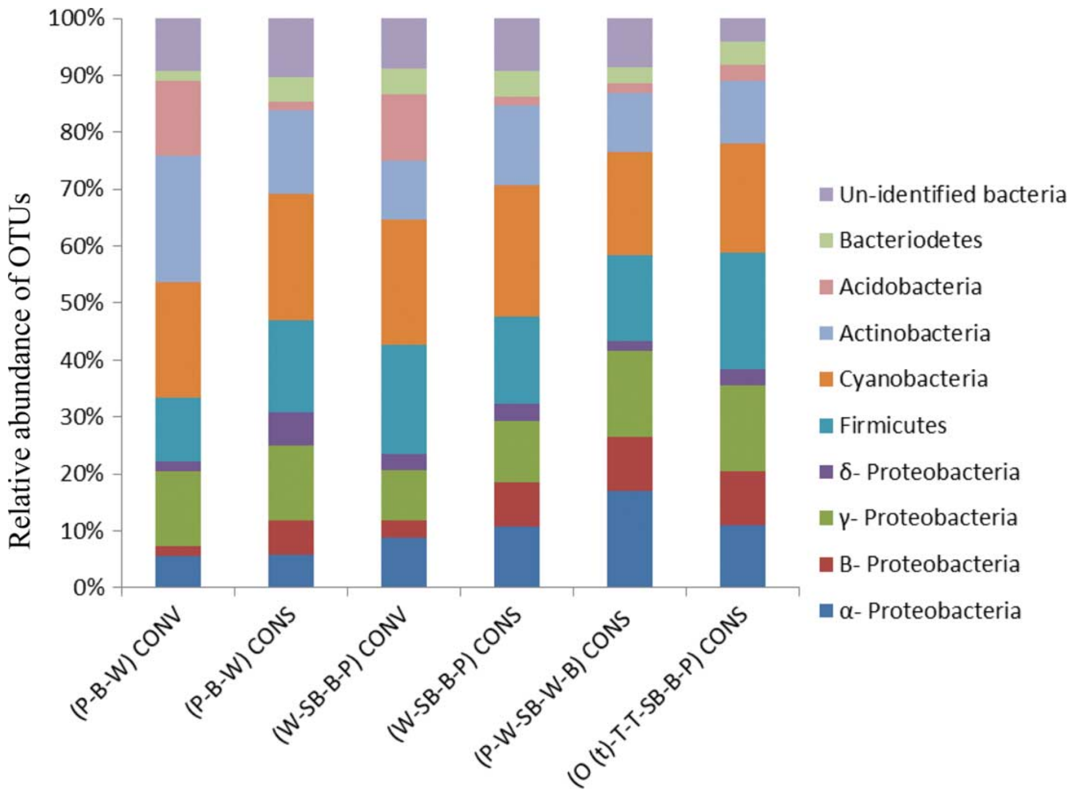

Fig. 3. Relative abundance of different bacterial phylogenetic groups (from T-RFLP analysis) in various treatments. Each data point was calculated from the average operational taxonomic units (OTUs) from four field replicates.

micro-organisms and recycling of nutrients, resulting in improvement of both soil biological and chemical properties (Goyal et al. 1999). Composting not only concentrates nutrients but also kills pathogens (Larney et al. 2003) and weed seeds (Larney and Blackshaw 2003). Composted manure is used to substitute for inorganic fertilizers and is widely used in organic farming systems (Lynch et al. 2011). Compost applied to agricultural fields improves soil structure and increases microbial activities due to the organic C inputs (Steger et al. 2007). Cover cropping, another practice employed in the CONS rotations, increases soil microbial populations because it increases soil organic C. Carrera et al. (2007) reported a significant effect of cover cropping on soil microbial community structure.

A consistent observation in both T-RFLP analysis for culture independent bacteria and 16S rRNA gene sequencing analysis for cultivated bacteria with regard to community structures of the endophytes was that CONS management systems contained more *Proteobacteria* than CONV management systems, and vice-versa for *Acidobacteria* (in T-RFLP). *Bacteriodetes* were found only in long rotations. The phylum *Proteobacteria* is the most heterogeneous of all bacterial phyla both morphologically and metabolically, and most bacteria of medical, industrial, and agricultural importance belong to this phylum (Oren 2010). In this study, the N_2-fixing *Rhizobium* was one of the genera found. Other endophytes found in rotations under CONS soil management also have potentially beneficial characteristics. For example, *Paenibacillus polymyxa* (in 5-yr rotation) is a nitrogen-fixing bacterium (Anand 2010) and *Kribbia dieselivorans* (in 6-yr rotation) has diesel-oil degradation activity (Jung et al. 2006). On the other hand, the phylum *Acidobacteria* is composed of a small group of acidophilic organotrophs and iron reducers (Oren 2010).

Sequencing of the 16S rRNA gene directly from potato root tissue (without culturing the endophytes) was not possible in constructing the gene library since the eubacterial primers used to amplify 16S rRNA are also homologous to chloroplast 16S and mitochondrial 18S rRNA of plants (Reiter et al. 2002; Sessitsch et al. 2002). The majority of clones contained mainly mitochondrial and, to a lesser extent, chloroplast small-subunit rRNA sequences. This limited our ability to compare the 16s rDNA clone library with a number of community members found by T-RFLP analysis. Hence, putative taxonomic analysis of TRFs was assigned based on PAT+ analysis from MiCA3 software (Shyu et al. 2007). Our phylogenetic and molecular evolutionary analyses (Supplementary Figs. 1–6) were based on cultured endophytes. The relative distribution of the most abundant phyla (from 16S rRNA gene

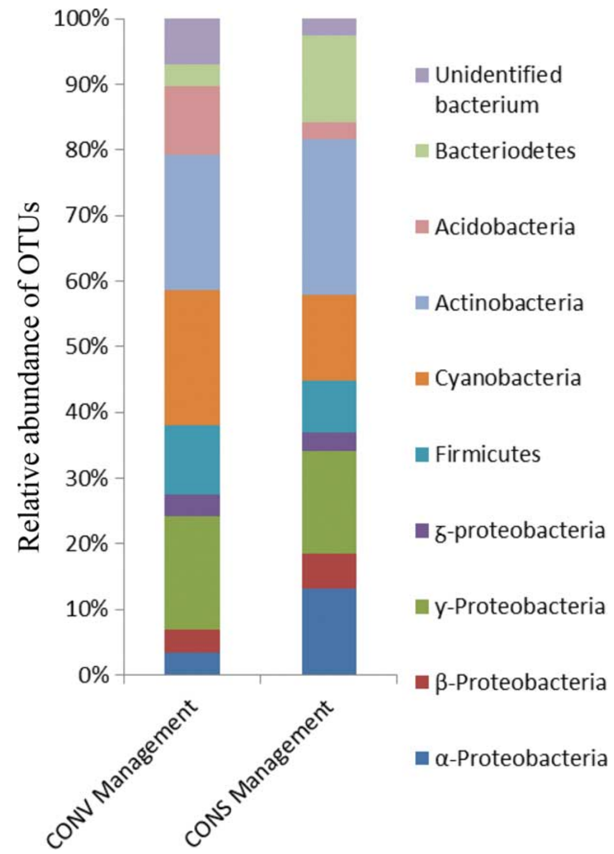

Fig. 4. Relative distribution of the different bacterial phylogenetic groups (from T-RFLP analysis) in conventional (CONV) and conservation (CONS) soil management treatments.

sequencing) of the cultured endophytes in different treatments are shown in Fig. 5. In previous studies of potato endophytes, α, β, and γ sub-divisions of *Proteobacteria*, *Actinobacteria*, *Flexibacter*, *Cytophaga*, and *Bacteriodetes* genera were identified (Reiter et al. 2002; Sessitsch et al. 2002). Pyrosequencing analysis of potato root endophytes also revealed α-*Proteobacteria*, β-*Proteobacteria,* γ-*Proteobacteria,* δ-*Proteobacteria*, *Cyanobacteria*, *Firmicutes*, *Acidobacteria*, *Actinobacteria*, *Bacteriodetes*, *Chloflexi*, *Plancomycetes*, *Fusobacteria*, *Verrucomicrobia*, *Gemmatimonadetes* and other unidentified bacteria families (Manter et al. 2010). More than 20 species of *Pseudomonas*, *Bacillus*, *Enterobacter* and *Agrobacterium* genera appear to be the most common culturable bacterial endophytes found in potato (Manter et al. 2010). Our results are in agreement with these observations.

In this study, we isolated, quantified and identified bacterial endophytes from potato grown in conventional and conservation soil management systems of different crop rotation lengths, and demonstrated that the endophyte communities are complex. Conservation soil management practices and long crop rotations increased the populations and diversity on the endophytic bacteria compared with conventional soil management and short rotations. The community structures of the endophytes were also different in these treatments. This phylogenetic characterization of the endophytes needs to be followed by functional characterization to understand how these bacteria affect their host plants. Novel endophytes and their bioactive secondary metabolites could also be

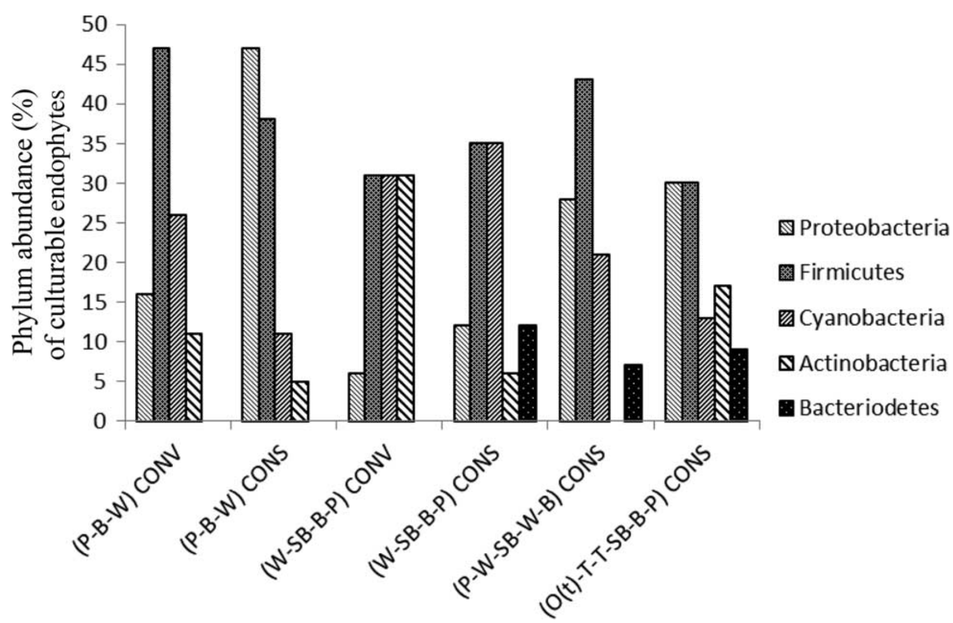

Fig. 5. Relative distribution of the most abundant phylogenetic groups (from 16S rRNA gene sequencing) of cultured endophytes in various treatments. W, wheat; B, beans; P, potato; SB, sugar beet; O (t), silage oats harvested July, timothy seeded August; T, timothy. CONV, conventional soil management; CONS, conservation soil management.

identified to develop technologies that increase crop growth and yields.

ACKNOWLEDGMENTS

We thank Lisa Kalischuk-Tymensen for assistance with T-RFLP analysis and Derrick Kanashiro and Drusilla Pearson for valuable technical assistance. Jim Sukeroff and Dale Reynolds at Agriculture and Agri-Food Canada (AAFC) Vauxhall substation provided field help. The Potato Growers of Alberta, Alberta Pulse Growers, Alberta Agricultural Research Institute, AAFC-Matching Investment Initiative and the Pulse Science Cluster provided funding.

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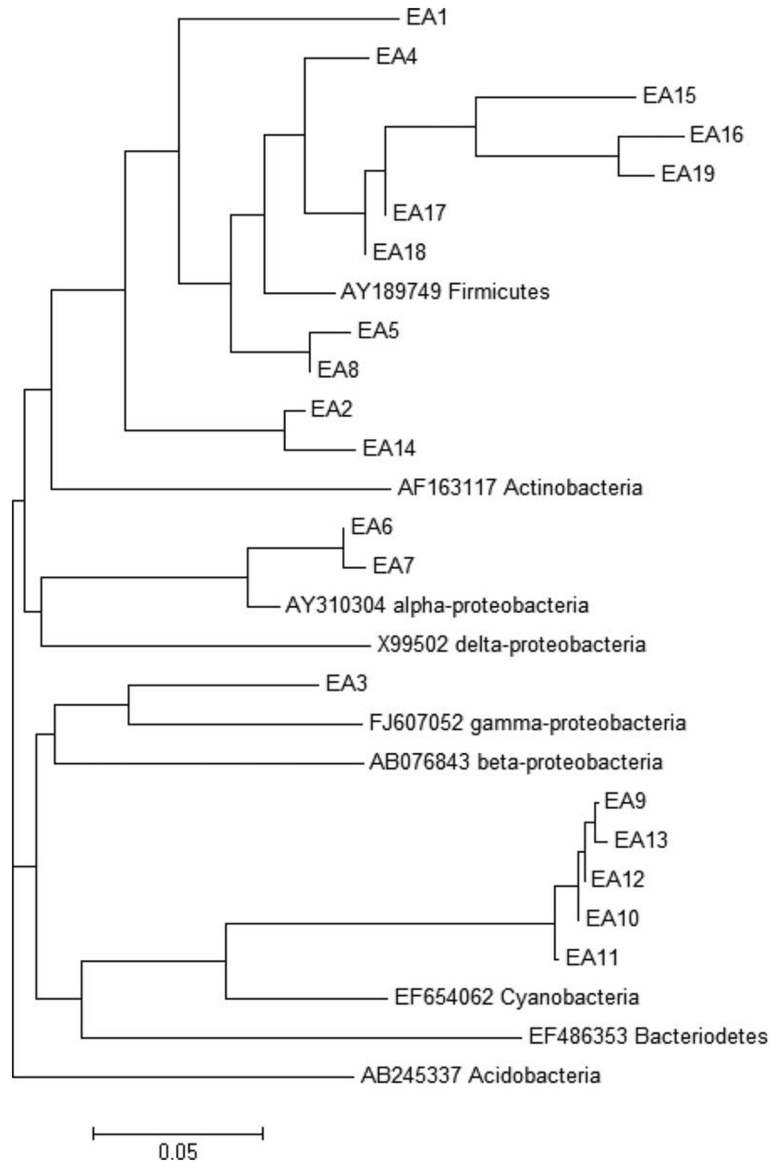
Supplementary Table 1. Endophytic bacteria cultured and identified based on 16S rRNA gene sequencing

Endophyte	TMT[z]	Closest NCBI database match	% similarity	NCBI accession number
EA1	T1	*Staphylococcus warneri* strain AW 25 (NR_025922)	99	JX912365
EA2	T1	*Paenibacillus tundrae* strain Ab10b (NR_044525)	99	JX912366
EA3	T1	*Pseudomonas brassicacearum* strain NFM421 (NR_074734)	99	JX912367
EA4	T1	*Bacillus marisflavi* strain TF-11 (NR_025240)	99	JX912368
EA5	T1	*Brevibacterium frigoritolerans* strain: DSM 8801 (NR_042639)	99	JX912369
EA6	T1	*Agrobacterium tumefaciens* strain IAM 12048 (NR_041396)	99	JX912370
EA7	T1	*Rhizobium selenitireducens* strain B1 (NR_044216)	99	JX912371
EA8	T1	*Bacillus sp.* LMG 20238 (NR_042083)	98	JX912372
EA9	T1	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	84	JX912373
EA10	T1	*Planktothricoides raciborskii* NIES-207 strain (NR_040858)	84	JX912374
EA11	T1	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	85	JX912375
EA12	T1	*Planktothricoides raciborskii* NIES-207 strain (NR_040858)	84	JX912376
EA13	T1	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	84	JX912377
EA14	T1	*Paenibacillus tundrae* strain Ab10b (NR_044525)	99	JX912378
EA15	T1	*Bacillus megaterium* QM B1551 strain (NR_074290)	99	JX912379
EA16	T1	*Staphylococcus pasteuri* strain ATCC51129 (NR_024669)	99	JX912380
EA17	T1	*Bacillus thuringiensis* strain IAM 12077 (NR_043403)	99	JX912381
EA18	T1	*Bacillus thuringiensis* strain IAM 12077 (NR_043403)	99	JX912382
EA19	T1	*Staphylococcus warneri* strain AW 25 (NR_025922)	99	JX912383
EB1	T2	*Cupriavidus metallidurans* strain CH34 (NR_074704)	99	JX912384
EB2	T2	*Bacillus weihenstephanensis* strain DSM11821 (NR_024697)	99	JX912385
EB3	T2	*Bacillus weihenstephanensis* strain DSM11821 (NR_024697)	99	JX912386
EB4	T2	*Bacillus megaterium* strain IAM 13418 (NR_043401)	99	JX912387
EB5	T2	*Paenibacillus tundrae* strain Ab10b (NR_044525)	98	JX912388
EB6	T2	*Bacillus megaterium* strain IAM 13418 (NR_043401)	99	JX912389
EB7	T2	*Brevibacterium frigoritolerans* strain: DSM 8801 (NR_042639)	99	JX912390
EB8	T2	*Pseudomonas brassicacearum* strain NFM421(NR_074834)	99	JX912391
EB9	T2	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	83	JX912392
EB10	T2	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	84	JX912393
EB11	T2	*Bacillus pumilus* SAFR-032 (NR_074977)	100	JX912394
EB12	T2	*Bacillus pumilus* SAFR-032 (NR_074977)	99	JX912395
EB13	T2	*Bacillus thuringiensis* strain IAM 12077 (NR_043403)	99	JX912396
EB14	T2	*Agrobacterium tumefaciens* strain IAM 12048 (NR_041396)	99	JX912397
EB15	T2	*Bacillus simplex* strain DSM 1321 (NR_042136)	99	JX912398
EB16	T2	*Bacillus megaterium* QM B1551 (NR_074290)	99	JX912399
EB17	T2	*Bacillus thuringiensis* strain IAM 12077 (NR_043403)	99	JX912400
EB18	T2	*Arhrobacter globiformis* strain DSM 20124 (NR_026187)	97	JX912401
EB19	T2	*Bacillus simplex* strain DSM 1321(NR_042136)	99	JX912402
EC1	T3	*Bacillus megaterium* QM B1551 (NR_074290)	99	JX912403
EC2	T3	*Brevibacterium frigoritolerans* strain: DSM 8801(NR_042639)	99	JX912404
EC3	T3	*Pseudomonas kilonensis* strain 520-20 (NR_028929)	100	JX912405
EC4	T3	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	83	JX912406
EC5	T3	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	83	JX912407
EC6	T3	*Serratia ficaria* strain DSM 4569 (NR_041979)	99	JX912408
EC7	T3	*Pseudomonas veronii* strain CIP 104663 (NR_028706)	99	JX912409
EC8	T3	*Arthrobacter sulfonivorans* strain ALL (NR_025084)	99	JX912410
EC9	T3	*Bacillus cereus* ATCC 14579 (NR_074540)	99	JX912411
EC10	T3	*Bacillus anthracis* str. Ames strain (NR_0074453)	99	JX912412
EC11	T3	*Bacillus marisflavi* strain TF-11 (NR_025240)	100	JX912413
EC12	T3	*Rhizobium huautlense* strain SO2 (NR_024863)	97	JX912414
EC13	T3	*Rhizobium selenitireducens* strain B1 (NR_044216)	99	JX912415
EC14	T3	*Rhizobium selenitireducens* strain B1 (NR_044216)	98	JX912416
EC15	T3	*Arthrobacter sulfureus* strain DSM 20167 (NR_026237)	99	JX912417
EC16	T3	*Bacillus megaterium* strain IAM 13418 (NR_04341)	99	JX912418
ED1	T4	*Bacillus clausii* strain DSM 8716 (NR_026140)	99	JX912419
ED2	T4	*Bacillus clausii* KSM-K16 (NR_074988)	99	JX912420
ED3	T4	*Bacillus licheniformis* DSM 13 (NR074923)	99	JX912421
ED4	T4	*Staphylococcus warneri* strain AW (NR_025922)	99	JX912422
ED5	T4	*Pseudomonas kilonensis* strain 520-20 (NR_028929)	100	JX912423
ED6	T4	*Bacillus pumilus* ATCC 7061 (NR_043242)	98	JX912424
ED7	T4	*Bacillus marisflavi* strain TF-11 (NR_025240)	99	JX912425
ED8	T4	*Bacillus marisflavi* strain TF-11 (NR_025240)	99	JX912426
ED9	T4	*Brevibacterium frigoritolerans* strain: DSM 8801 (NR_042639)	99	JX912427
ED10	T4	*Pseudomonas lurida* strain: DSM 15835 (NR_042199)	99	JX912428
ED11	T4	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	83	JX912429
ED12	T4	*Brevibacterium frigoritolerans* strain: DSM 8801 (NR_042639)	100	JX912430

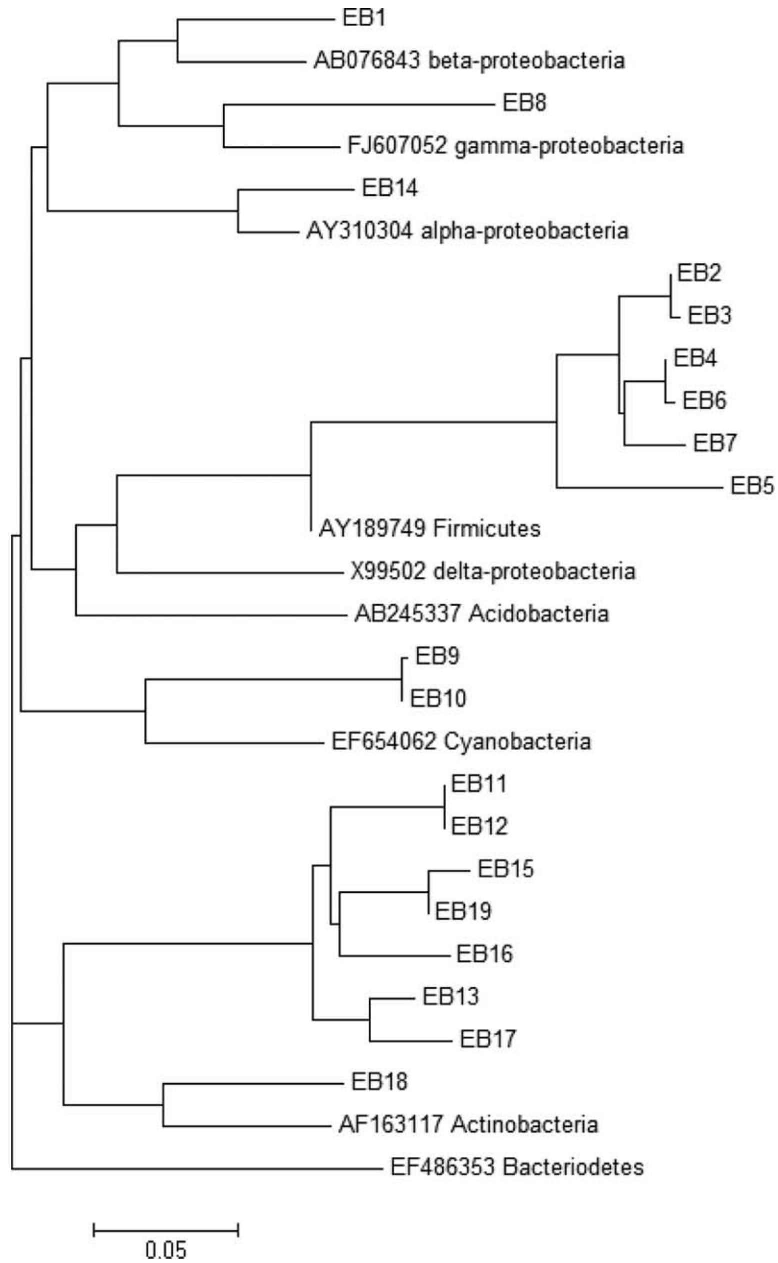
Supplementary Table 1 (*Continued*)

Endophyte	TMT[z]	Closest NCBI database match	% similarity	NCBI accession number
ED13	T4	*Lysinibacillus fusiformis* strain DSM 2898 (NR_042072)	99	JX912431
ED14	T4	*Bacillus vietnamensis* strain 15-1 (NR_024808)	97	JX912432
ED15	T4	*Agrobacterium tumefaciens* strain IAM 12048 (NR041396)	99	JX912433
ED16	T4	*Bacillus horikoshii* strain DSM8719 (NR_040852)	100	JX912434
ED17	T4	*Bacillus odysseyi* strain 34hs1 (NR_025258)	99	JX912435
EE1	T5	*Bacillus circulans* (NR_042726)	98	JX912436
EE2	T5	*Bacillus thuringiensis* strain IAM 12077 (NR_43403)	99	JX912437
EE3	T5	*Staphylococcus warneri* strain AW 25 (NR_025922)	99	JX912438
EE4	T5	*Pseudomonas brassicacearum* NFM421 (NR_074834)	99	JX912439
EE5	T5	*Pseudomonas asplenii* strain ATCC 23835 (NR_040802)	98	JX912440
EE6	T5	*Microbacterium saperdae* strain IFO 15038 (NR_024637)	99	JX912441
EE7	T5	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	84	JX912442
EE8	T5	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	84	JX912443
EE9	T5	*Anabaena variabilis* ATCC 29413 (NR_074300)	86	JX912444
EE10	T5	*Bacillus marisflavi* strain TF-11 (NR_025240)	99	JX912445
EE11	T5	*Rhizobium daejeonense* strain L61 (NR_042851)	97	JX912446
EE12	T5	*Rhizobium selenitireducens* strain B1 (NR_044216)	99	JX912447
EE13	T5	*Bacillus farraginis* strain R-6540 (NR_025785)	98	JX912448
EE14	T5	*Bacillus cereus* ATCC 14579 (NR_074540)	99	JX912449
EF1	T6	*Kribbia dieselivorans* strain N113 (NR_043763)	96	JX912450
EF2	T6	*Kribbia dieselivorans* strain N113 (NR_043763)	96	JX912451
EF3	T6	*Serinicoccus marinus* strain JC1078 (NR_025774)	96	JX912452
EF4	T6	*Bacillus atrophaeus* 1942 (NR_075016)	99	JX912453
EF5	T6	*Bacillus ginsengi* strain ge14 (NR_044193)	99	JX912454
EF6	T6	*Bacillus ginsengi* strain ge14 (NR_044193)	99	JX912455
EF7	T6	*Paenibacillus tundrae* strain Ab10b (NR_044525)	99	JX912456
EF8	T6	*Bacillus pumilus* SAFR-032 (NR_074977)	99	JX912457
EF9	T6	*Bacillus stratosphericus* strain: 41KF2a (NR_042336)	99	JX912458
EF10	T6	*Ralstonia insidiosa* strain AU2944 (NR_025242)	100	JX912459
EF11	T6	*Cupriavidus metallidurans* CH34 (NR_074704)	99	JX912460
EF12	T6	*Solibacillus silvestris* strain HR3-23 (NR_028865)	99	JX912461
EF13	T6	*Arthrobacter polychromogenes* strain DSM 20136 (NR_026192)	99	JX912462
EF14	T6	*Agrobacterium tumefaciens* strain IAM 12048 (NR_041396)	99	JX912463
EF15	T6	*Rhizobium selenitireducens* strain B1(NR_044216)	98	JX912464
EF16	T6	*Anabaena variabilis* ATCC 29413 (NR_074300)	86	JX912465
EF17	T6	*Halospirulina tapeticola* strain CCC Baja-95 Cl.2 (NR_026510)	84	JX912466
EF18	T6	*Bacillus horikoshii* strain DSM8719 (NR_040852)	99	JX912467
EF19	T6	*Rhizobium daejeonense* strain L61 (NR_042851)	98	JX912468
EF20	T6	*Bacillus foraminis* strain: CV53 (NR_042274)	98	JX912469
EF21	T6	*Cupriavidus metallidurans* CH34 (NR_074704)	99	JX912470
EF22	T6	*Ornithinimicrobium kibberense* strain K22-20 (NR_043056)	96	JX912471
EF23	T6	*Rhizobium selenitireducens* strain B1 (NR_044216)	99	JX912472

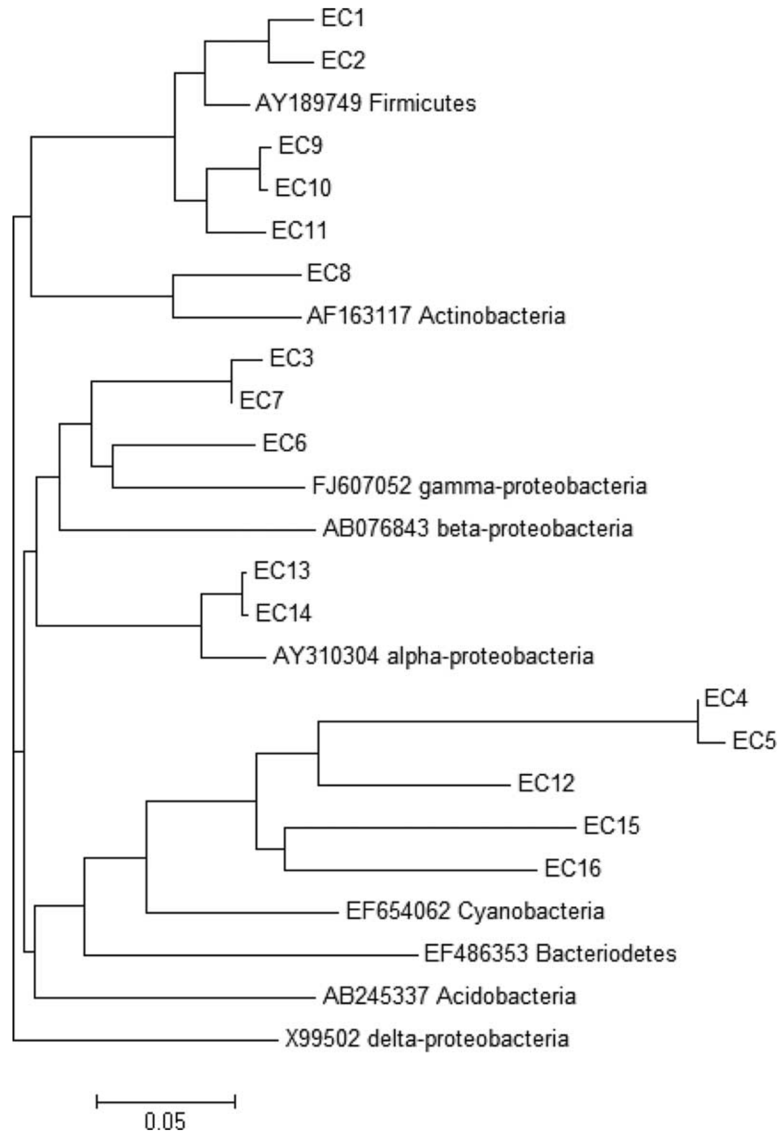
[z]TMT, treatment; T1, (P–B–W) and T3 (W–SB–B–P) under CONV soil management; T2 (P–B–W), T4 (W–SB–B–P), T5 (P–W–SB–W–B) and T6 O(t)–T–T–SB–B–P under CONS soil management.



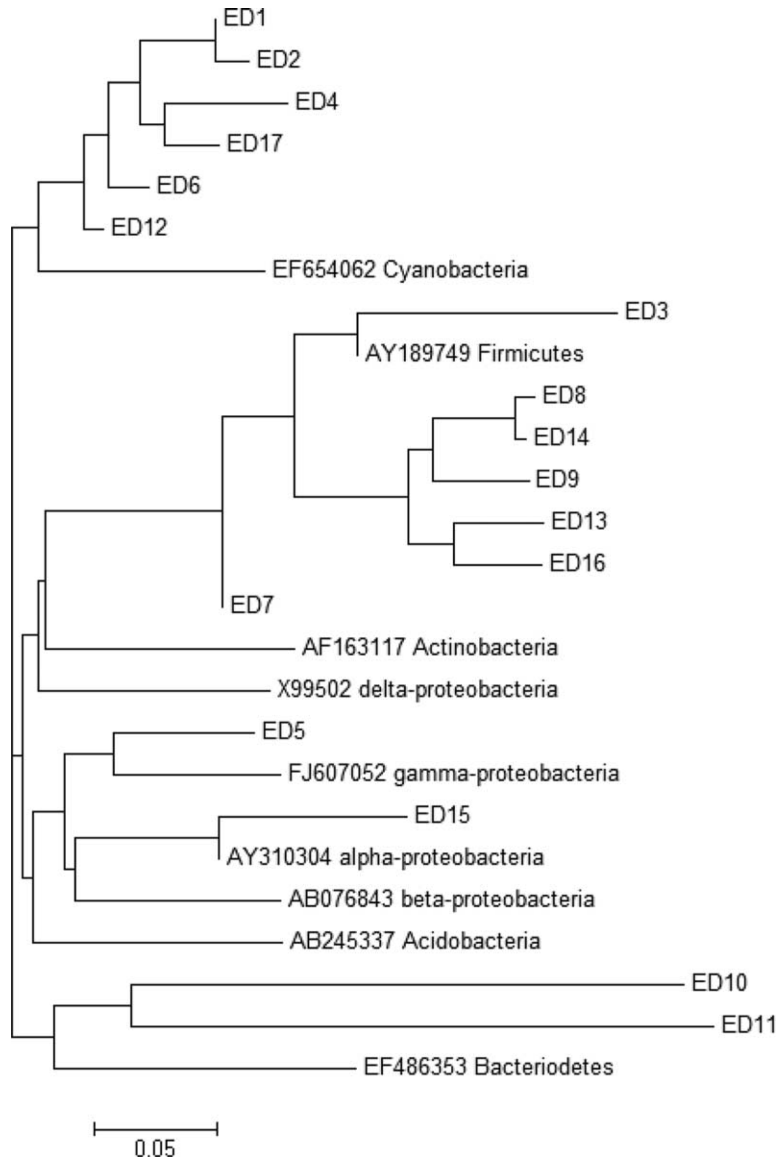
Supplementary Fig. 1. Phylogenetic tree based on 16S rRNA gene sequences of endophytes of potato from T1 treatment (3-yr potato–bean–wheat rotation) under conventional soil management using neighbour-joining method in ClustalW2 program. EA1 to EA19, are the endophytes identified from treatment T1.



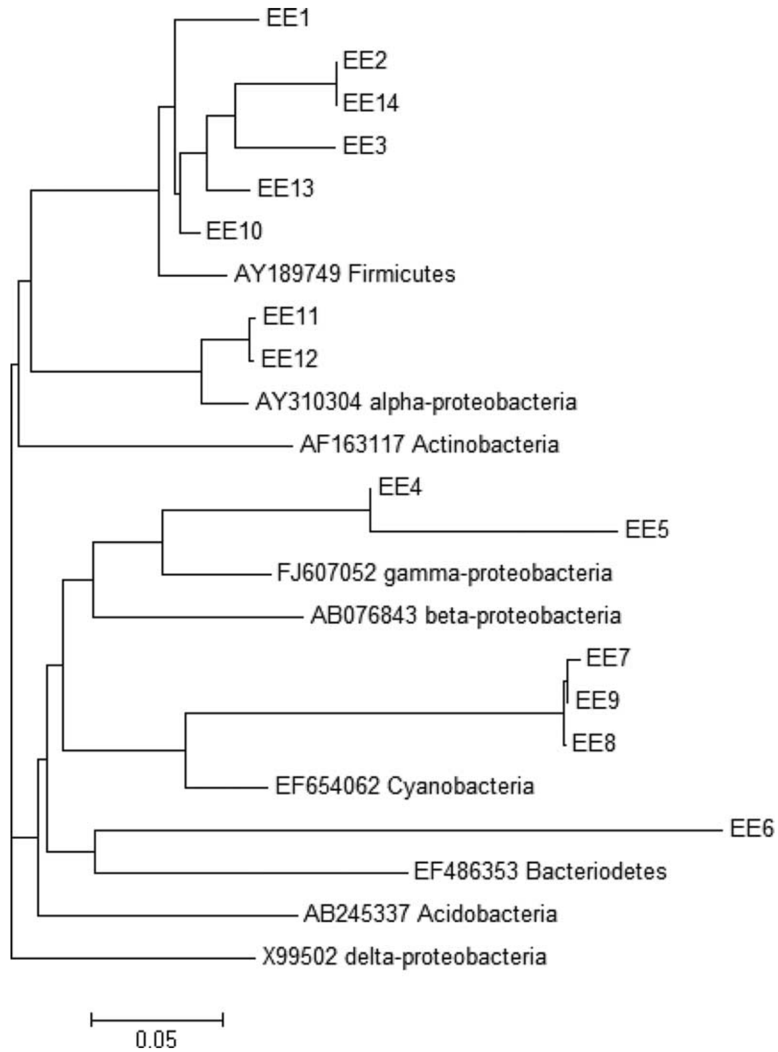
Supplementary Fig. 2. Phylogenetic tree based on 16S rRNA gene sequences of endophytes of potato from T2 treatment (3-yr potato–bean–wheat rotation) under conservation soil management using neighbour-joining method ClustalW2 program. EB1 to EB19 are the endophytes identified from treatment T2.



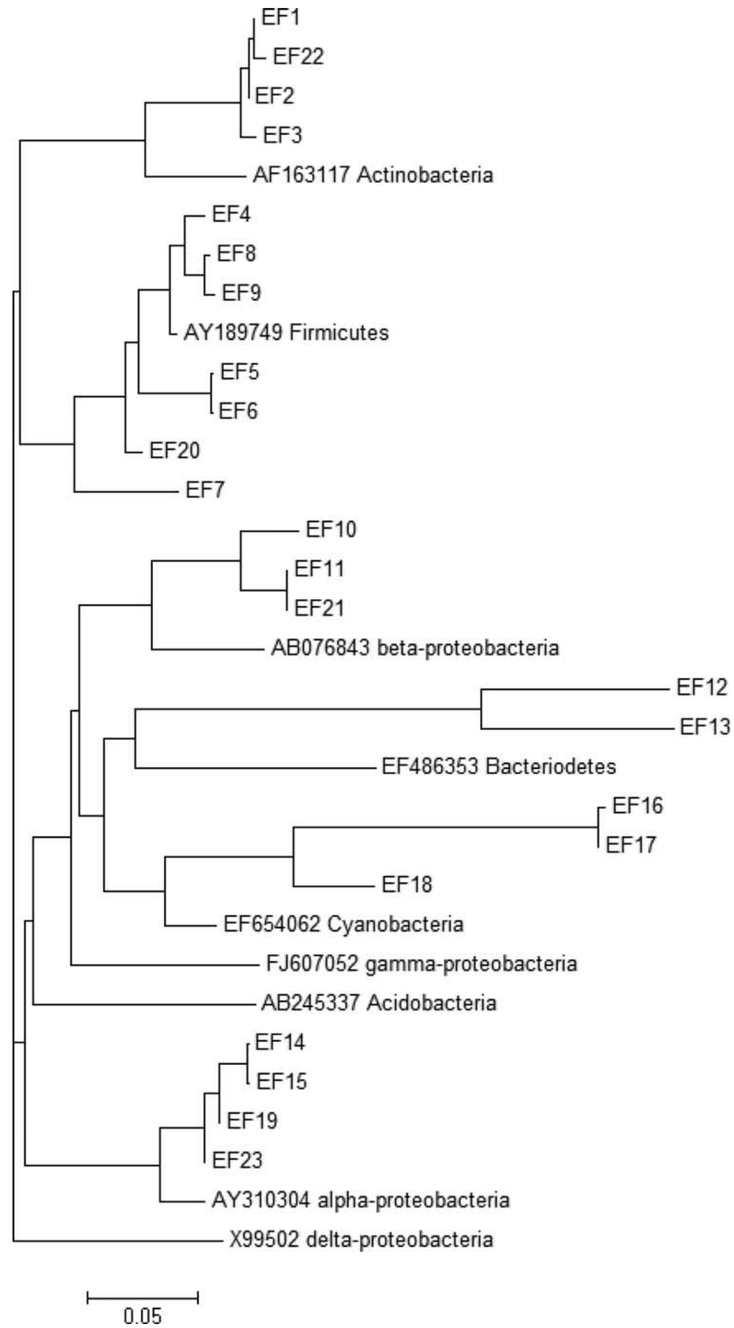
Supplementary Fig. 3. Phylogenetic tree based on 16S rRNA gene sequences of endophytes of potato from T3 treatment (4-yr wheat–sugar beet–bean–potato rotation) under conventional soil management using neighbour-joining method ClustalW2 program. EC1-EC16 are the endophytes identified from treatment T3.



Supplementary Fig. 4. Phylogenetic tree based on 16S rRNA gene sequences of endophytes of potato from T4 treatment (4-yr wheat–sugar beet–bean–potato rotation) under conservation soil management using neighbour-joining method ClustalW2 program. ED1 to ED17 are the endophytes identified from treatment T4.



Supplementary Fig. 5. Phylogenetic tree based on 16S rRNA gene sequences of endophytes of potato from T5 treatment (5-yr potato–wheat–sugar beet–wheat-bean rotation) under conservation soil management using neighbour-joining method ClustalW2 program. EE1 to EE14 are the endophytes identified from treatment T5.



Supplementary Fig. 6. Phylogenetic tree based on 16S rRNA gene sequences of endophytes of potato from T6 treatment (6-yr oat–timothy–timothy–sugar beet–bean–potato rotation) under conservation soil management using neighbour-joining method ClustalW2 program. EF1 to EF23 are the endophytes identified from treatment T6.

Plant growth-promoting and phytopathogen-antagonistic properties of bacterial endophytes from potato (*Solanum tuberosum* L.) cropping systems

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[1]Agriculture and Agri-Food Canada, Lethbridge Research Centre, P. O. Box 3000, Lethbridge, Alberta, Canada T1J 4B1; and [2]Agriculture and Agri-Food Canada, Semiarid Prairie Agricultural Research Centre, Gate #3 Airport Road East, Swift Current, Saskatchewan, Canada S9H 3X2.
Received 4 November 2013, accepted 6 March 2014. Published on the web 11 March 2014.

Pageni, B. B., Lupwayi, N. Z., Akter, Z., Larney, F. J., Kawchuk, L. M. and Gan, Y. 2014. **Plant growth-promoting and phytopathogen-antagonistic properties of bacterial endophytes from potato (*Solanum tuberosum* L.) cropping systems**. Can. J. Plant Sci. **94**: 835–844. Endophytes are microorganisms that live within a plant without harming it. Bacterial endophytes were isolated from roots of potatoes (*Solanum tuberosum* L.) grown under different rotations (3 to 6 yr in length) and soil management (CONV, conventional; CONS, conservation) in irrigated cropping systems with dry bean (*Phaseolus vulgaris* L.), sugar beet (*Beta vulgaris* L.) spring wheat (*Triticum aestivum* L.) and timothy (*Phleum pratense* L.). The endophytes were characterized for nitrogen fixation potential, phytohormone production and phytopathogen-antagonistic properties. The nitrogen-fixing nitrogenase (*nif*H) gene was detected in potato grown in all rotations, presumably partly because the soil in all rotations contained *Rhizobium leguminosarum* bv. *phaseoli* from the dry bean phase. Sequence analysis revealed that it was homologous to the genes found in *Burkholderia*, *Azospirillum*, *Ideonella*, *Pseudacidovorax* and *Bradyrhizobium* species. Indole acetic acid (IAA) hormone production by endophytes isolated from potato grown under CONS management was 66% greater than that those isolated from potato grown under CONV management, and tended to be greater in longer than shorter rotations. When 12 endophytes were inoculated to dry bean, four increased shoot biomass by 27–34%, and six increased total (shoot + root) biomass by 25% on average. Endophytes from the longer CONS rotations (4–6 yr) resulted in significantly higher (by 9%) shoot biomass than the shortest CONS (3 yr) rotation. Six of 108 endophyte isolates exhibited antagonistic properties (reduced pathogen biomass by 12 to 58% in dual culture assays in liquid media) against potato pathogens *Pectobacterium atrosepticum*, *Fusarium sambucinum* and *Clavibacter michiganensis* subsp. *epedonicus*. All the six isolates were from CONS soil management. Therefore, the benefits of long rotations, with their associated CONS soil management, to crop productivity in these irrigated cropping systems probably include nutritional (biological nitrogen fixation and IAA hormone production) and disease-control benefits imparted by endophytic bacteria.

Key words: Endophytic bacteria, biological disease control, crop rotation, *nif*H, indole acetic acid

Pageni, B. B., Lupwayi, N. Z., Akter, Z., Larney, F. J., Kawchuk, L. M. et Gan, Y. 2014. **Propriétés d'accélérateur de croissance et d'antagoniste des phytopathogènes des bactéries endophytes de la pomme de terre (*Solanum tuberosum* L.) dans divers systèmes culturaux**. Can. J. Plant Sci. **94**: 835–844. Un endophyte est un microorganisme qui vit dans une plante sans lui causer de tort. Des bactéries endophytes ont été isolées des racines de pommes de terre (*Solanum tuberosum* L.) cultivées sous divers régimes d'assolement (de 3 à 6 ans) et de gestion du sol (CONV, classique; CONS, conservation). Les pommes de terre étaient cultivées sur des terres irriguées, en rotation avec le haricot (*Phaseolus vulgaris* L.), la betterave sucrière (*Beta vulgaris* L.), le blé de printemps (*Triticum aestivum* L.) et la fléole (*Phleum pratense* L.). Les endophytes se caractérisaient par leur capacité à fixer l'azote, la synthèse de phytohormones et leur pouvoir antagoniste contre les phytopathogènes. Le gène de la nitrogénase fixatrice d'azote (*nif*H) a été décelé chez les pommes de terre venant de tous les assolements, sans doute parce que le sol renfermait *Rhizobium leguminosarum* bv. *phaseoli* consécutivement à la culture du haricot. L'analyse séquentielle révèle que ce gène est homologue à ceux découverts chez les espèces des genres *Burkholderia, Azospirillum*, *Ideonella*, *Pseudacidovorax* et *Bradyrhizobium*. Les endophytes isolés chez les pommes de terre cultivées selon le régime CONS produisent 66 % plus d'acide indole-acétique (AIA) que ceux isolés chez les tubercules du régime CONV, et ont tendance à être plus nombreux dans les assolements longs que dans les assolements courts. Sur les douze endophytes inoculés au haricot, quatre ont accru la biomasse des pousses de 27 à 34 %, et six ont augmenté la biomasse totale (pousses + racines) de 25 % en moyenne. Les endophytes des assolements CONS plus longs (4–6 ans) donnent une biomasse de pousses sensiblement plus élevée (de 9 %) que ceux des assolements CONS plus courts (3 ans). Six des 108 isolats d'endophytes présentaient des propriétés d'antagoniste (diminution de la biomasse des pathogènes de 12 à 58 % lors

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Abbreviations: **CONS**, conservation (soil management); **CONV**, conventional (soil management); **IAA**, indole acetic acid; **PCR**, polymerase chain reaction; **PDA**, potato dextrose agar; **TSB**, tryptic soy broth

des essais de culture double en milieu liquide) contre les pathogènes de la pomme de terre *Pectobacterium atrosepticum, Fusarium sambucinum* et *Clavibacter michiganensis* subsp. *epedonicus*. Les six venaient tous de régimes de gestion du sol CONS. Parmi les avantages pour la productivité des cultures irriguées découlant d'un assolement long, et du régime de gestion du sol CONS connexe, figurent donc sans doute des propriétés nutritionnelles (fixation biologique de l'azote et production d'AIA) et la lutte contre les maladies par les bactéries endophytes.

Mots clés: Bactéries endophytes, lutte biologique contre la maladie, assolement, *nif*H, acide indole-acétique

Microorganisms that live within a plant without harming it are called endophytes. Soils in legume-based crop rotations usually have greater total microbial counts, biomass and diversity than soils monocropped with non-legumes (Lupwayi et al. 1998, 1999; Biederbeck et al. 2005). Some of these microorganisms develop endophytic associations with non-legumes (Lupwayi et al. 2004a, b) and confer nutritional, disease control and stress tolerance benefits to them (Marquez-Santacruz et al. 2010; Mehnaz et al. 2010; Mei and Flinn 2010). Endophytic diazotrophs such as *Acetobacter*, *Azoarcus* and *Herbaspirillum* fix nitrogen that benefit rice (*Oryza sativa*), sugarcane (*Saccharum officinarum* L.), oat (*Avena sativa*), sweet potato (*Ipomoea batatas*) and Cameroon grass (*Pennisetum purpureum*) (Elbeltagy et al. 2001; Soares et al. 2006). Endophytic bacteria have also been shown to enhance the growth and disease resistance of potato (Diallo et al. 2011; Pavlo et al. 2011). The study of plant bacterial endophytes is increasingly important in understanding ecological interactions and developing biotechnological applications (Ryan et al. 2008). Synthesis of novel chemicals, resistance to heavy metals and xenobiotic degradation are often attributed to endophytes (Siciliano et al. 2001; Ryan et al. 2007).

Alberta is ranked third in Canada for potato production, after Prince Edward Island and Manitoba, with 21 626 ha grown in 2011 (Statistics Canada 2012). Because of semiarid conditions, potatoes are grown under irrigation, which presents a dual challenge of producing high value crops while maintaining soil quality. In 2000, we established an irrigated crop rotation study with potatoes, dry beans, sugar beet, wheat and timothy grown under conventional (CONV) and conservation (CONS) soil management. Bacterial endophytes from the potato phases of these rotations were quantified and phylogenetically characterized by terminal-restriction fragment length polymorphism (T-RFLP) analysis and 16S rRNA gene sequencing (Pageni et al. 2013). Results showed that endophytes were more abundant and diverse in potato grown under CONS than CONV soil management, and tended to be greater in longer than shorter rotations. The community structures of the potato endophytes were also different between CONS and CONV soil management practices. The objective of this follow-up study was to examine the functional attributes of the endophytes in the various rotations. Specifically, we evaluated their potential for nitrogen fixation (*nif*H gene presence), phytohormone [indole acetic acid (IAA)] production and disease control (antagonism to phytopathogens). Furthermore, the growth-promoting effects of endophytes were tested by inoculating them to dry bean, one of the crops in the rotations.

MATERIALS AND METHODS

Treatments

An irrigated cropping study was initiated in 2000 at Vauxhall, Alberta (lat. 50°06′N, long. 112°13′W) to compare the effects of rotation length (3, 4 yr) rotations under CONV or CONS soil management, and 5- and 6-yr CONS management rotations on yields of potato, dry bean, sugar beet and spring wheat (Table 1). Two years of timothy were included in the longest rotation. CONS soil management included reduced tillage, fall-seeded cover crops, composted cattle manure application and narrow-row (20 cm) solid-seeded beans, whereas CONV management used conventional tillage, no cover crops, fertilizer nitrogen and phosphorus, and wide-row (60 cm) beans. There was a total of six rotations with each of 26 phases appearing every year and replicated four times (104 plots, each 10.1×18.3 m) (Table 1). Soil management systems (CONV, CONS) and length of crop rotations were considered the different treatments. Potato roots in the potato phases of the rotations were sampled at the flowering stage in August, 2011 and kept at -20°C until bacterial endophytes were isolated from them.

Isolation of Bacterial Endophytes

Bacterial endophytes from potato roots were isolated as described by Pageni et al. (2013). Briefly, the roots were surface sterilized by immersing them in 10% (vol/vol) sodium hypochlorite for 8 min, followed by 1% iodophor for 5 min, and then washed 10 times with

Table 1. Irrigated rotation treatments at Vauxhall, Alberta

Treatment	Length (yr)	Rotation	Management
1	3	P–B–W	CONV
2	3	P–B–W	CONS
3	4	W–SB–B–P	CONV
4	4	W–SB–B–P	CONS
5	5	P–W–SB–W–B	CONS
6	6	O(t)–T–T–SB–B–P	CONS

W, wheat; B, beans; P, potato; SB, sugar beet; O (t), silage oats harvested July, timothy seeded August; T, timothy. CONV, conventional soil management; CONS, conservation soil management.

sterile water. About 0.5 g of surface-sterilized roots was macerated to fine powder using liquid nitrogen in a sterilized and precooled mortar and pestle. Aliquots were serially diluted with sterile water and plated on tryptic soy agar (TSA) in the presence of cycloheximide fungicide (100 μg mL^{-1}), and incubated at 28°C for 48 h (Garbeva et al. 2001; Khan and Doty 2009). The isolates (10 from each potato phase of the six rotations for a total of 240, i.e., 10 isolates × 6 rotations × 4 replicates) were grown in broths of the same medium and kept at −80°C with 30% glycerol as stock solution. Polymerase chain reaction (PCR) of 16S rRNA gene sequences of 108 isolates were amplified using universal primers (8F: 5′- AGAGTTTGATCCTGGCTCAG-3′ and 1492R: 5′-GGTTACCTTGTTACGACTT-3′) using the endophytes' chromosomal DNA. All 16S rRNA gene sequences were identified and deposited at NCBI GenBank database under accession numbers JX912365 to JX912472.

Evaluation of Nitrogen Fixation Potential

To evaluate the potential of the endophytes to fix nitrogen, we assayed for the presence of the nitrogen fixation (*nif*H) gene. Chromosomal DNA from potato root tissue was isolated using a QIAamp DNA mini kit (Qiagen, Gaithursburg, MD) following the manufacturer's instructions. The DNA sequence of the PCR products was used to predict the *Nif*H protein sequences for H1, H2, H3, H4, and H5 obtained from the rotation treatments 3YrCONS, 4YrCONV, 4YrCONS, 5YrCONS and 6YrCONS, respectively. The *nif*H gene from 3YrCONV rotation treatment was not sequenced. *Nif*H primers (HF2.F:5′-GGCTGCGATCCCAAGG CTGA-3, HF2.R:5′-CGTACATGGCCATCATCTC-3′) (Integrated DNA technologies, Coralville, IA) were used for PCR of *nif*H gene fragments (Bürgmann et al. 2004). PCR of *nif*H gene was carried out using both primers at 0.8 μM of final concentration, and 20 to 50 ng μL^{-1} concentration of chromosomal DNA from root tissue as templates. The following cycling conditions were used: initial denaturation at 95°C for 7 min, denaturation at 95°C for 45 s, annealing at 57°C for 45 s, polymerization at 72°C for 1 min in 40 cycles, and final extension at 72°C for 7 min. The PCR products (371 bp) were subjected to electrophoresis in 2% agarose gel in the presence of ethidium bromide and purified with a gel extraction kit (Qiagen, Gaithursburg, MD). Purified PCR products of the *nif*H gene were cloned in pGEM-T-easy kit (Promega, Madison, WI) and transformed in *E. coli* DH5α for plasmid extraction. Plasmid DNA of cloned samples was isolated with a Qiagen kit (Qiagen, Gaithursburg, MD). The purity and concentration of the plasmid DNA was checked using a NanoDrop-2000 spectrophotometer (Thermo Scientific, Wilmington, DE) before sequencing. Sequencing of plasmid DNA was performed at the Génome Québec Innovation Center (McGill University, Montreal, QC) using T7 and SP6 promoter's primers. The partial sequence of the *nif*H gene was determined using NCBI nucleotide BLAST to compare with identified nitrogenases. *Nif*H gene sequences were trimmed to active open reading frames (ORF) by NCBI ORF finder. Multiple alignments of potato *nif*H protein sequences with previously identified diazotroph's nitrogenases from NCBI were performed using ClustalW2 software (Larkin et al. 2007). Phylogenetic molecular evolutionary analyses were conducted using ClustalW2 software (Larkin et al. 2007), based on the neighbour joining clustering method. The output file for phylogenetic tree analysis obtained from ClustalW2 was used to observe maximum likelihood in MEGA5.05 software (Tamura et al. 2011).

Phytohormone Production

To quantify IAA production, four endophytes from each rotation treatment were grown in tryptic soy broth (TSB) medium (17 g tryptone, 3 g soytone, 2.5 g glucose, 5 g sodium chloride, 2.5 g dipotassium hydrogen phosphate in one litre, pH = 7.3) at 28°C for 4 d individually. One milliliter of cell suspension was centrifuged at 13 000 rpm for 10 min at room temperature and 200 μL of supernatant was mixed with 800 μL of Salkowski's reagent (Gordon and Weber 1951). The intensity of the pink color developed in the mixture was measured after 15 min by Evolution 60S UV-Visible Spectrophotometer (Thermo-Scientific, Madison, WI) at 530 nm wavelength. Indole acetic acid was quantified using Beer-Lambert law (Ingle and Crouch 1988), using standard curves set up for the standard solution of IAA in TSB medium (Sarwar and Cremer 1995).

Plant Growth Promotion

The ability of the endophytes to promote plant growth was evaluated in a growth chamber experiment by inoculating dry bean with suspensions of two endophytes from each rotation treatment. Dry bean was used because some of the endophytes isolated from potato roots were rhizobia, suggesting a possible rotational benefit of potato to dry bean. Seeds of two bean cultivars, AC Island (pinto bean) and AC Resolute (great northern bean), were surface sterilized with 3% (vol/vol) NaOCl for 3 min and 95% ethanol for 1 min, followed by five washings with sterile water. Seeds were then germinated in petri plates containing anhydrous calcium sulphate (2 g L^{-1}) at 22°C for 3 d in dark conditions. The germinated seeds were transferred aseptically to seed germination pouches (Mega International, Minneapolis, MN) filled with 10 mL of modified nitrogen-free Hoagland's solution (Hershey 1994) and maintained at 23°C under a 16-h photoperiod in the growth chamber. The photon flux density emitted by fluorescent lamps in the growth chamber was 620 mol m^{-2} s^{-1}.

Two endophytes, one *Bacillus* strain and one *Rhizobium* strain, were selected from each of the six rotation treatments to compare the effects of a plant growth-promoting rhizobacterium with a putative root-nodulating rhizobium. Pure cultures of all 12 endophytes (6 rotations $\times$ 2 strains) were grown to the mid-log phase in TSB medium at 28°C and diluted to a final concentration of 1.82 to 2.89×10^7 colony-formation units mL^{-1}, of which 2 mL was used for inoculation of each dry bean cultivar in four replicates. Uninoculated plants received sterile water as negative controls (−N) and positive control treatment (+N) plants received 5 mL of 2.5 mM $Ca(NO_3)_2$ resulting in 1.25 mM final concentrations of $Ca(NO_3)_2$. This resulted in 14 inoculation treatments (12 endophytes, −N, +N). The bean plants were harvested after 14 d and shoot, root and total (shoot+root) biomass determined after drying at 60°C for 3 d (Montanez et al. 2012).

Antagonism to Phytopathogens

The plant disease biocontrol capabilities of 108 endophytes from all treatments were evaluated by screening them for antagonism to potato bacterial and fungal pathogens. The endophytes and test pathogenic strains were streaked on the edge of petri dish containing potato dextrose agar (PDA). The ability of the endophytes to suppress the mycelial growth of *Pectobacterium atrosepticum* (causal agent of potato blackleg disease) *Fusarium sambucinum* (causal agent of potato dry rot disease) and *Clavibacter michiganensis* subsp. *sepedonicus* (causal agent of potato ring rot disease) was evaluated by in vitro dual culture assays on Luria-Bertani (LB) agar and PDA media (Lahlali et al. 2007). Each combination of pathogen/endophyte was replicated four times and plates were randomly placed in the dark and incubated at 28°C until the PDA medium plate was completely covered with pathogen growth. As negative controls, four petri dishes were inoculated only with pathogens. The radial mycelial growths of pathogenic microorganism towards the antagonistic endophyte and that on a control plate were determined.

Quantitative antagonism evaluation of endophytes was measured in potato dextrose broth growth medium. A volume of 500 μL of endophyte culture grown in TSB broth for 24 h (containing 10^7 colony-forming units mL^{-1}) and a disc of test fungus (5 mm) from a well-grown fungal colony on PDA plates were inoculated in 50 mL of potato dextrose broth in 250 mL conical flasks and grown together at 28°C on a rotary shaker for 5 d. Broth inoculated only with pathogenic fungi/bacteria served as a control. The differences in dry weights between test fungus or bacterium and control cultures (without endophyte) were recorded after 5 d (Trivedi et al. 2008). The percentage reduction in weight of the test fungus/bacterium was calculated using the formula: $(w_1 - w_2/w_1) \times 100$, where w_1 represents the weight of the test fungus/bacterium in control flasks without endophyte and w_2 represents the weight of the test fungus/bacterium with endophyte. Besides dual culture assay, secondary metabolites of potential endophytes were extracted in methanol and their crude products were also used to perform bioassays using filter paper disc method (Qadrie et al. 2009).

Statistical Analysis

Data from all experiments were analyzed using mixed models (SAS Ver. 9.1, SAS Institute Institute, Inc., Cary, NC), and effects were considered significant if $P \leq 0.05$. Growth hormone (IAA) was analyzed with rotation treatment as the main effect, and means were separated by an LSD test ($P \leq 0.05$). Root, shoot and total dry weights of dry bean cultivars from endophyte inoculation experiments were analyzed with inoculation treatment as the main-treatment effect, and cultivar (AC Island, AC Resolute) as the sub-treatment effect. Variables were also tested for an inoculation treatment $\times$ cultivar interaction. Where the main effect (inoculation treatment) was significant (Tukey–Kramer test, $P \leq 0.05$), orthogonal contrasts were constructed and tested to compare various groups of treatments as follows: CONV vs. CONS rotations; short (3–4 yr) vs. long (5–6 yr) rotations (CONS and CONV pooled); short (3 yr) vs. longer (4–6 yr) CONS rotations; and *Bacillus* vs. *Rhizobium* strains. In the biocontrol screening experiment, endophyte, pathogen and endophyte $\times$ pathogen interaction effects on pathogen growth reduction were analyzed.

RESULTS

Nitrogen Fixation Potential

The presence of the *nif*H gene in potato from various treatments was detected with a non-quantitative PCR in potato roots grown under all treatments under both CONV and CONS soil management systems (Fig. 1). The sequence of the predicted protein from the PCR sequence showed that there was more than 98% similarity in *nif*H amino acid sequences present in H1, H2, H3, H4 and H5 (data not shown), and so there were no significant predicted protein sequence differences

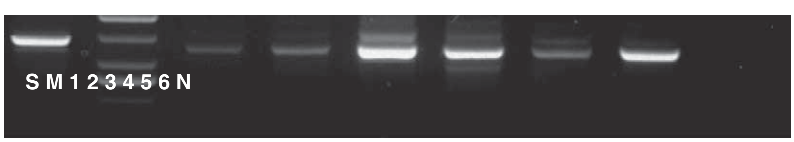

Fig. 1. *Nif*H gene presence in potato roots from various treatments. S: *nif*H gene PCR product from dry bean as standard; M: 50 bp DNA ladder; 1: Treatment 3YrCONV; 2: Treatment 3YrCONS; 3: Treatment 4YrCONV; 4: Treatment 4YrCONS; 5: Treatment 5YrCONS; 6: Treatment 6YrCONS; and N: negative control using distilled water as template.

between treatments. Sequence homology of the predicted *nif*H protein showed similarity with *Burkholderia* sp. PTK47 (protein ID AAU85620), *Burkholderia* sp. Ms116 (protein ID ACK76288), *Bradyrhizobium japonicum* (protein ID ACT67985), *Cupriavidus taiwanensis* (protein ID CAD4395), *Azospirillum brasilense* strain AWB12 (Protein ID ACS45076), *Ideonella* sp. Long 7 (protein ID AAQ01723), *Azospirillum doebereinerae* strain DSM 13131 (protein ID ACO35353), *Pseudacidovorax* sp. ptl-2 (protein ID ACV49864), and *Methylocystis parvus* (protein ID AAO49391) by 99, 99, 97, 98, 90, 93, 92, 91 and 92%, in that order (Fig. 2). The active domain of the nitrogenase gene belonging to the P-loop_NTPase superfamily having multiple domains, a distinguishing characteristic for the nitrogenase family, was found to be well conserved.

Phytohormone Production

The rotation effect on IAA growth hormone production by the endophytes was significant ($P = 0.09$) if a 0.10 level of significance is used (Fig. 3). The 6YrCONS rotation had significantly higher production (6.7 mg L^{-1} IAA equivalent) than the 3Yr and 4YrCONV rotations (3.1 and 3.8 mg L^{-1} IAA equivalents, respectively). Using orthogonal contrasts, production on the CONS rotations averaged 5.8 mg L^{-1} IAA equivalent which was 66% higher ($P = 0.007$) than 3.5 mg L^{-1} IAA equivalent for the CONV rotations.

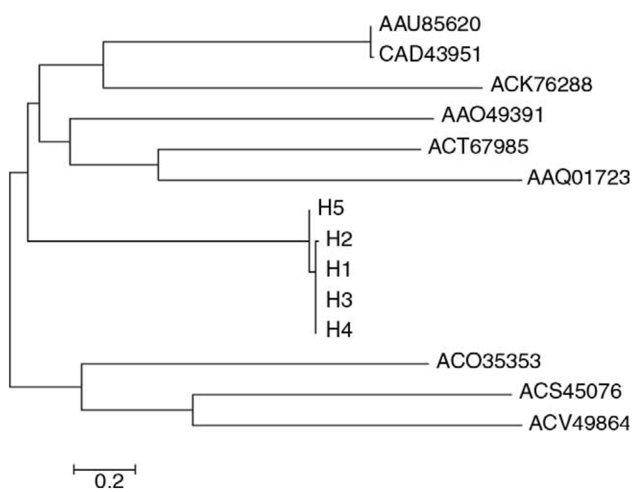

Fig. 2. Phylogenetic tree of nitrogenase protein of potato in relation to known nitrogenase protein sequences from NCBI database. H1, H2, H3, H4 and H5 are the potato root *nif*H protein sequences from our study. Protein IDs AAU85620, ACK76288, ACT67985, CAD4395, ACS45076, AAQ01723, ACO35353, ACV49864 and AAO49391 are the *nif*H proteins from *Burkholderia* sp. PTK47, *Burkholderia* sp. Ms116, *Bradyrhizobium japonicum*, *Cupriavidus taiwanensis*, *Azospirillum brasilense* strain AWB12, *Ideonella* sp. Long 7, *Azospirillum doebereinerae* strain DSM 13131, *Pseudacidovorax* sp. ptl-2 and *Methylocystis parvus*, respectively.

Plant Growth Promotion

There were no significant inoculation × cultivar interactions for root, shoot or total (root + shoot) biomass, which showed that each cultivar (AC Island, AC Resolute) responded similarly to endophyte inoculation. Therefore, biomass data from the two bean cultivars were pooled (Table 2). Inoculation with the *Bacillus* strain from the 4YrCONV rotation and the *Rhizobium* strains from the 4Yr, 5Yr and 6YrCONS rotations led to 27–34% increase in shoot biomass (212–224 mg $plant^{-1}$) over the –N control treatment (167 mg $plant^{-1}$) but not the +N control (185 mg $plant^{-1}$). None of the inoculation treatments had a significant effect on average root biomass (Table 2) whereas six endophytes (*Bacillus* from the 3YrCONV, 4YrCONV and 5YrCONS and *Rhizobium* from the 4YrCONS, 5YrCONS and 6YrCONS) led to significantly higher (341–355 mg $plant^{-1}$) total biomass than the –N Control (278 mg $plant^{-1}$), an average increase of 25%. However, compared with the +N Control treatment, the 11% increase in total biomass of bean cultivars by the above six endophytes was non-significant.

Orthogonal contrast tests between various groups of endophytes showed that, overall, there was no significant difference ($P \geq 0.90$) in shoot or total biomass production between endophytes isolated from CONV vs. CONS rotations (Table 2). Also, the strain of endophyte (*Bacillus* vs. *Rhizobium*) was non-significant for both shoot and total biomass. Short (3-4YrCONV and CONS) rotations vs. long (5-6YrCONS) rotations were also non-significant for both parameters. However, endophytes (both strains pooled) from the longer CONS rotations (4–6 yr) resulted in significantly higher ($P = 0.02$) shoot biomass (average 213 mg $plant^{-1}$) than the shortest CONS (3Yr) rotation (average 196 mg $plant^{-1}$), a difference of 9%. Additionally, the longest 6YrCONS rotation resulted in a significant ($P = 0.03$) shoot biomass increase of 10% compared with the shortest 3YrCONS rotation (216 vs. 196 mg $plant^{-1}$). The latter two contrasts were non-significant for total biomass (Table 2). The effects of increased biomass production from endophytes isolated from longer rotations is borne out by regression analysis of average root, shoot and total biomass (average of both varieties and all endophytes) against rotation length (Fig. 4). The relationship with rotation length was significantly linear for total biomass ($P = 0.03$), and showed a strong linear tendency ($P = 0.09$) for shoot biomass. The relationship between root biomass and rotation length was non-significant.

Antagonism to Phytopathogens

All 108 endophytes from various treatments were screened against three pathogens and six of them, all under CONS soil management, showed antagonistic effects. Endophytes 3YrCONS1, 3YrCONS2, 4YrCONS1, 4YrCONS2, 5YrCONS and 6YrCONS reduced pathogen biomass by 12 to 58% in dual culture assay in liquid media (Fig. 5). There was a significant

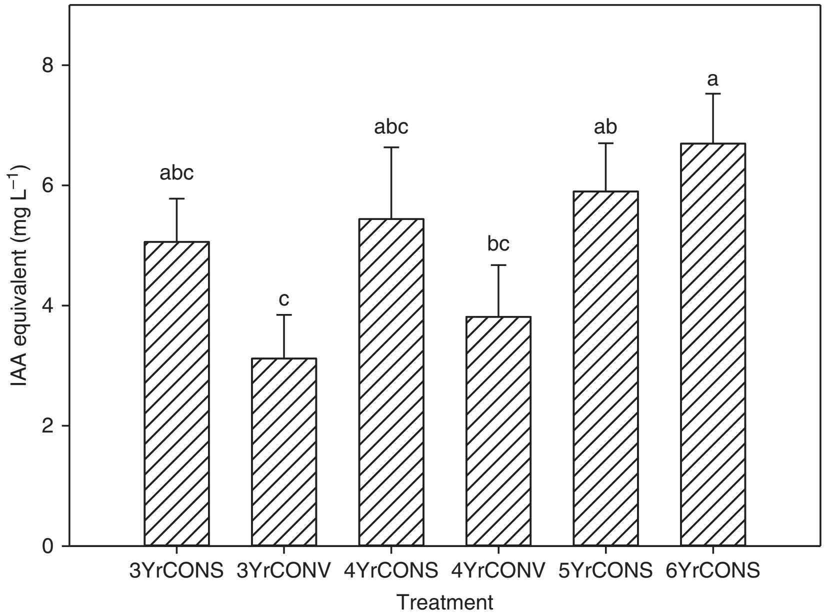

Fig. 3. IAA production by bacterial endophytes from various treatments. Each bar is an average of four replicates. Bars with identical letters within a tryptophan treatment are not significantly different ($P > 0.05$).

endophyte × pathogen interaction on pathogen growth reduction, which showed that endophytes behaved differently depending on the target pathogen (Fig. 5).

Table 2. Response of dry bean biomass to inoculation with endophytic bacteria

		Shoot	Root	Total
Treatment[z]	Strain	(mg plant^{-1})		
−N	Control	167*b*	111*a*	278*b*
+N	Control	185*ab*	127*a*	312*ab*
3YrCONV	*Bacillus*	210*ab*	131*a*	341*a*
3YrCONV	*Rhizobium*	209*ab*	114*a*	333*ab*
3YrCONS	*Bacillus*	194*ab*	111*a*	330*ab*
3YrCONS	*Rhizobium*	198*ab*	119*a*	328*ab*
4YrCONV	*Bacillus*	218*a*	124*a*	354*a*
4YrCONV	*Rhizobium*	201*ab*	127*a*	328*ab*
4YrCONS	*Bacillus*	210*ab*	130*a*	340*ab*
4YrCONS	*Rhizobium*	212*a*	131*a*	343*a*
5YrCONS	*Bacillus*	209*ab*	136*a*	345*a*
5YrCONS	*Rhizobium*	217*a*	126*a*	343*a*
6YrCONS	*Bacillus*	207*ab*	130*a*	337*ab*
6YrCONS	*Rhizobium*	224*a*	131*a*	355*a*
Orthogonal contrast P *values*				
CONV vs. CONS		0.94	NA[y]	0.90
Bacillus vs. *Rhizobium*		0.67	NA	0.70
Short (3-4Yr) vs. Long (5-6Yr)		0.16	NA	0.32
Shortest (3Yr) CONS vs. Longer (4-6Yr) CONS		0.02	NA	0.16
Shortest (3Yr) CONS vs. Longest (6Yr) CONS		0.03	NA	0.19

[z]–N control un-inoculated; +N control fertilized with 2.5 mM of $Ca(NO_3)_2$.
[y]NA, not applicable. Because treatment effect was non-significant, orthogonal contrasts were not tested.
a, *b* Means followed by same letter are not significantly different at $P = 0.05$.

For *Pectobacterium,* endophytes isolated from the 5Yr and 6YrCONS rotations led to significantly higher (45–47%) pathogen reduction than all other rotation endophytes (13–34%). For *Fusarium*, the 3YrCONS1 rotation endophyte led to significantly higher reduction (40%) than all others (18–37%), whereas for *Clavibacter*, the 6YrCONS isolate resulted in significantly higher reduction (57%) than all other rotations (16–24%). Secondary metabolites from endophytes (3YrCONS1 and 6YrCONS) also showed positive results with the bioassay using filter disc method (data not shown).

DISCUSSION

Endophytes have been reported to contribute to the growth and health of a variety of plants through mechanisms including nitrogen fixation, production of phytohormones, enhanced availability of nutrients, competition with pathogens, production of antibiotics, and induced systematic resistance (Sturz et al. 2000; Lodewyckx et al. 2002). These mechanisms are similar to those exhibited by rhizosphere microorganisms (Sessitsch et al. 2004). Our results on endophytes isolated from potato plants corroborated some of these mechanisms and that they can be manipulated by soil management.

Chromosomal DNA from various treatments was used to detect nitrogen-fixing potential by the presence of *nif*H gene, which encodes for nitrogen reductase, a key component of nitrogenase enzyme involved in nitrogen fixation. The gene was detected in potato grown in all rotations, possibly because all rotations included dry bean, which can be nodulated by *Rhizobium leguminosarum* bv. *phaseoli*. However, rhizobial

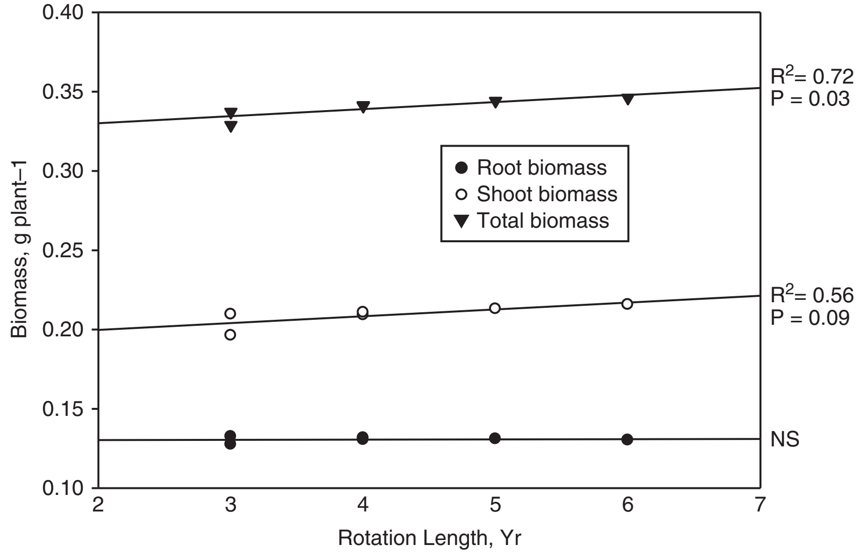

Fig. 4. Regression analysis of root, shoot and total biomass (average of both bean varieties and all endophytes) against rotation length.

endophytes are known to exist in many non-leguminous plants, like barley, wheat, canola (Lupwayi et al. 2004a), rice (Chi et al. 2005), maize (Gutiérrez-Zamora and Martínez-Romero 2001), sweet potato (Tonooka et al. 2008) and cucumber (Juraeva et al. 2006). Nitrogen-fixing endophytic bacteria provide more nitrogen to the plant than rhizospheric bacteria because the plant interior is a more suitable niche for nitrogen fixation due to its low oxygen partial pressure, and the fixed nitrogen is directly accessible to the plant without losses than occur in the rhizosphere (James and Olivares 1998). However, because the *nif*H gene was amplified from DNA, its presence indicates only the presence of nitrogen-fixing bacteria and not necessarily activity (Juraeva et al. 2006). Nonetheless, its abundance in endophytes indicates their nitrogen fixation potential. Detection and sequence analysis of *nif*H amplified from mRNA is required for information on the identities of nitrogen-fixing bacteria as well as evidence of nitrogen fixation.

Plants can synthesize IAA by many biosynthetic pathways using tryptophan as starter substrate (Zhao 2010). This phytohormone is not only potent in regulating plant stem and root growth, it has also been shown to trigger

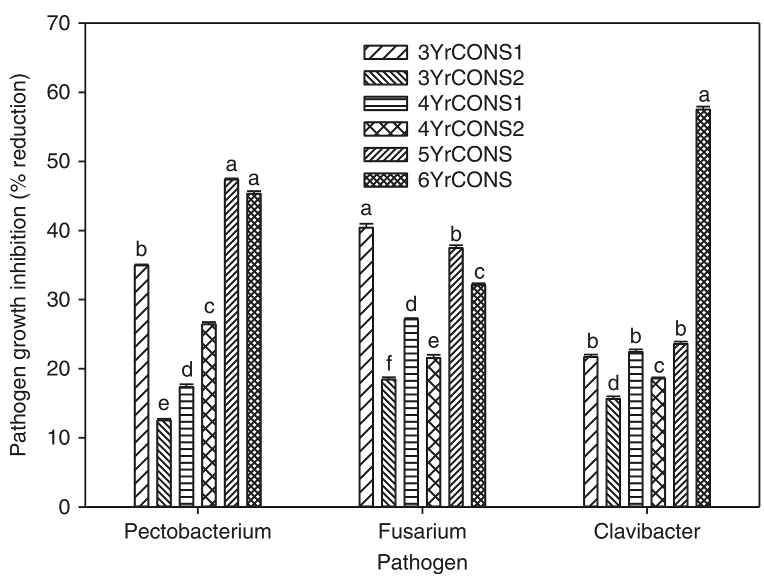

Fig. 5. Inhibition of bacterial and fungal pathogen growth (percentage) during culture of endophytes with pathogens. Each bar is an average of three replicates. Bars with identical letters within each pathogen are not significantly different ($P > 0.05$).

protection against external adverse conditions by co-ordinating the enhancement of different cellular defence mechanisms (Khan and Doty 2009). Endophytes from 5-yr and 6-yr CONS rotations produced more IAA than those in shorter rotations under CONS or CONV management, but IAA production tended to be greater (though not statistically) under CONS management CONV management in 3-yr and 4-yr rotations. Endophytic bacteria from many other plants have been shown to produce IAA (Khan and Doty 2009; Shi et al. 2009; Chauhan et al. 2013). Our results showing 27–34% increase in dry bean shoot biomass and 23–28% increase in total biomass when inoculated with some of the endophytes could be attributed to production of IAA, nitrogen fixation or other mechanisms that we did not study. Both *nif*H gene abundance and IAA production by endophytes increased with increasing rotation length, as did total biomass of beans inoculated with the endophytes.

Endophytic bacteria are able to reduce or prevent the deleterious effects of certain pathogenic organisms, and their beneficial effects on their host plant appear to be via mechanisms described for rhizosphere-associated bacteria (Ryan et al. 2008; Diallo et al. 2011). In our study, all six endophytes with antagonistic properties against potato pathogens were isolated from rotations under CONS soil management, indicating the positive impact of CONS soil management systems on disease control. Field observations showed that the wilt fungus *Verticillium dahliae*, a major contributor to potato early-dying complex, was less prevalent in CONS soil management than in CONV management (F. J. Larney, personal communication). The disease control capabilities of endophytic bacteria have been reported in other studies on potato (Hong-Xian et al. 2005; Pavlo et al. 2011) and other crops (Sapak et al. 2008; Wang et al. 2013).

The beneficial effects of CONS soil management on the functional characteristics of the endophytic bacteria in this study were slightly different from their beneficial effects on their previously published structural characteristics, i.e., population size, phylogenetic diversity and community structure. The length of the rotations seemed more important than CONV vs CONS rotations of the same length in functional characteristics, whereas the endophytes were more abundant and diverse in CONS soil management than in CONV management, and tended to be greater in longer than shorter rotations (Pageni et al. 2013). The community structures of the endophytes were different between CONV and CONS soil management practices. The reasons for these soil management effects have been discussed (Pageni et al. 2013). Essentially, the CONS management practices of reduced tillage, application of compost, inclusion of a fall-seeded cover crop, and using narrow-row solid-seeded beans increased soil organic C either by returning more C to the soil or by reducing losses due to decomposition or erosion (F. J. Larney, personal communication). Soil organic C is the major substrate that most soil microorganisms use for cell synthesis and energy (Fuhrmann 2005). Crop rotations increase soil microbial diversity because they diversify the types of organic C substrates added to the soil. Therefore, soil management practices that increase soil organic C and diversify the habitats of agro-ecosystems will result in large, diverse soil microbial communities, some of which will get into plant tissues to reside as endophytes and benefit the host plant through nitrogen fixation, phytohormone production and biological disease control in long rotations. Large and diverse soil microbial and plant endophytic communities improve soil and plant health.

CONCLUSION

Nitrogen fixation, production of IAA growth hormone and biological disease control are some of the mechanisms by which endophytic bacteria in long rotations probably benefit crops grown in the irrigated cropping systems studied here. Potato production in southern Alberta depends heavily on the use of fertilizers and pesticides for optimum yields. Use of extended rotations and their associated soil conservation management practices could reduce the reliance on these inputs by enhancing the nutritional and disease control capacities of the soil and plant microbial communities. Endophytic bacteria are better placed to deliver these biological services to crops than rhizospheric bacteria because endophytes reside within tissues of the receiving crop. Their bioactive secondary metabolites could also be extracted and used to control plant diseases. However, since our characterization was done in vitro, confirmation of these processes in potted soil and field experiments is required.

ACKNOWLEDGEMENTS

We are grateful to Parthiba Balasubramanian for providing the dry bean cultivars for inoculation experiments and to Derrick Kanashiro and Drusilla Pearson for technical assistance. The Potato Growers of Alberta, Alberta Pulse Growers, Alberta Agricultural Research Institute, Agriculture and Agri-Food Canada Matching Investment Initiative and the Pulse Science Cluster provided funding.

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