NRC Research Press

ARTICLE

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

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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.

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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.

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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.

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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

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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}.

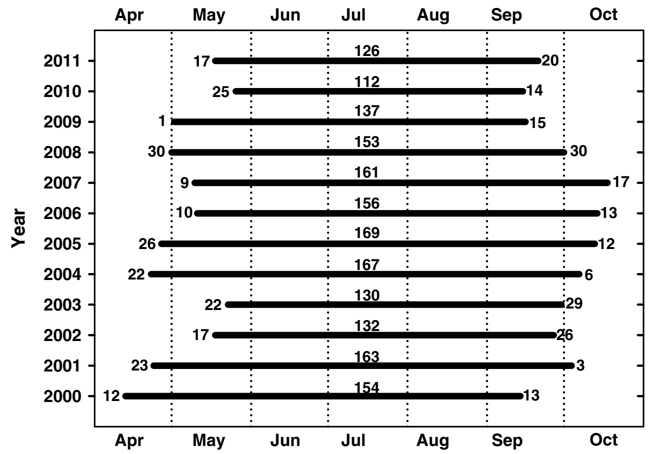
Cover crops were used at three entry points in the CONS rotations (Table 1): between potato and wheat in 4- and 5-CONS, and between potato and oat in 6-CONS. Initially (fall 2000–2002) oat was used as a cover crop (Table 1) to provide fall cover and then winterkill so as to minimize spring seeding problems. 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)

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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:

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

Extractable sugar yield was calculated as:

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

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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) × 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).

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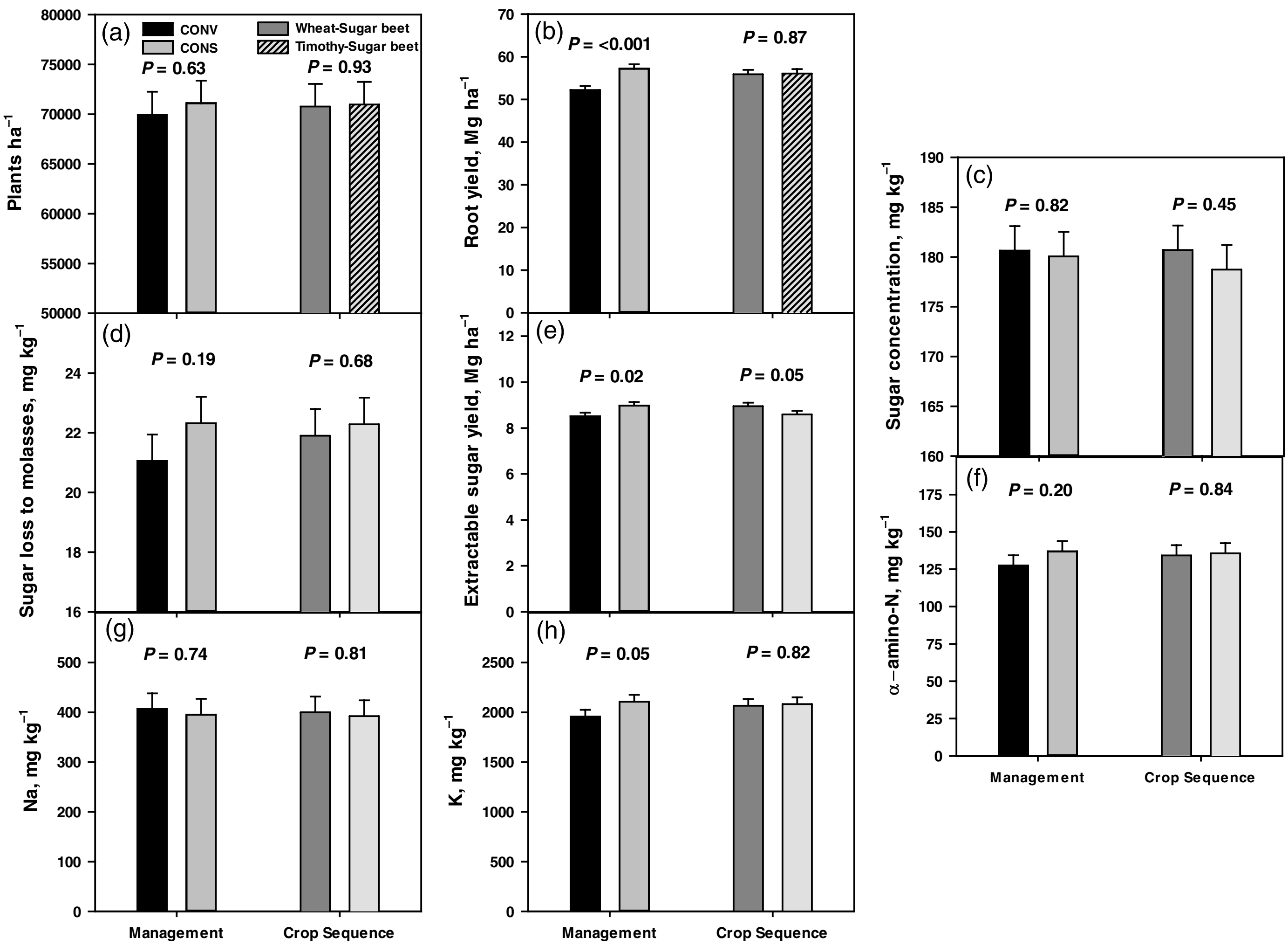
Fig. 2. Management (4-CONV vs. mean of 4-, 5-, and 6-CONS rotations) and crop sequence [Wheat–sugar beet vs. Timothy–sugar beet (mean of 4-CONV, 4- and 5-CONS vs. 6-CONS)] contrasts, with associated *P*-values and standard error bars, for second 6 yr (2006–2011) average (*a*) plant stand; (*b*) root 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

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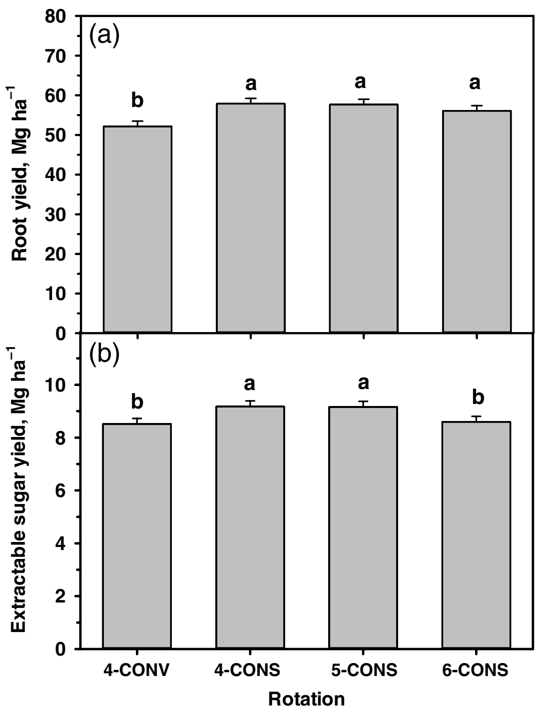
Table 4. Rotation effects on total sugar beet root yield and sugar concentration, 2000–2011.

	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.

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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

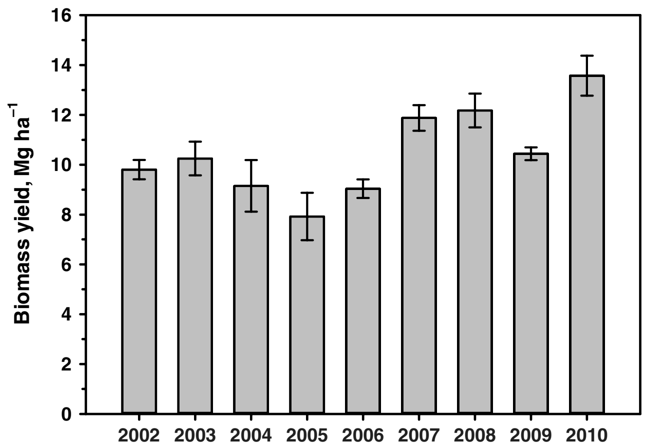
Compared with the other crops in this rotation study (particularly dry bean and potato), there was less opportunity for direct impact of the four CONS management practices on sugar beet performance. The CONS practice of narrow-row production pertained to dry bean only. As discussed previously, the reduced 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

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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, nonsugar 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

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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

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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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