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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.

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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

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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.

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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,

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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 $P < 0.05$.

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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 ± 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.

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Literature Cited

Alberta Agriculture Rural Development (2014) Alberta Irrigation Information 2013 http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/irr7401. Accessed March 25, 2015

Anderson RL, Tanaka DL, Black AL, Schweizer EE (1998) Weed community and species response to crop rotation, tillage and nitrogen fertility. Weed Technol 12:531–536

Ball DA (1992) Weed seedbank response to tillage, herbicides, and crop rotation sequence. Weed Sci 40:654–659

Blackshaw RE (1994) Crop rotation reduces downy brome (*Bromus tectorum*) populations in winter wheat. Weed Technol 8:728–732

Blackshaw RE (2005a) Nitrogen fertilizer, manure and compost effects on weed growth and competition with spring wheat. Agron J 97:1612–1621

Blackshaw RE (2005b) Tillage intensity affects weed communities in agroecosystems. Pages 209–221 *in*Inderjit, ed. Invasive Plants: Ecological and Agricultural Aspects. Basel, Switzerland: Birkhauser Verlag

Blackshaw RE, Moyer JR, Huang HC (2005) Beneficial effects of cover crops on soil health and crop management. Recent Res Dev Soil Sci 1:15–35
Booth BD, Swanton CJ (2002) Assembly theory applied to weed communities. Weed Sci 50:2–13
Cardina J, Herms CP, Doohan DJ (2002) Crop rotation and tillage system effects on weed seedbanks. Weed Sci 50:448–460
Cardina J, Sparrow DH (1996) A comparison of methods to predict weed seedlings populations from the soil seedbank. Weed Sci 44:46–51
Cudney DW, Wright SD, Shultz TA, Reints JS (1992) Weed seed in dairy manure depends on collection site. Calif Agric 46:31–32
Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal 32:1221–1250
Entz MH, Bullied WJ, Katepa F (1995) Rotational benefits of forage crops in Canadian prairie cropping systems. J Prod Agric 8:521–529
Grandy AS, Porter GA, Erich MS (2002) Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. Soil Sci Soc Am J 66:1311–1319
Gulden RH, Lewis DW, Froese JC, Van Acker RC, Martens GB, Entz MH, Derksen DA, Bell LW (2011) The effect of rotation and in-crop weed management on the germinable weed seedbank after 10 years. Weed Sci 59:553–561
Hartwig NL, Ammon HU (2002) Cover crops and living mulches. Weed Sci 50:688–699
Larney FJ, Blackshaw RE (2003) Weed seed viability in composted beef cattle feedlot manure. J Environ Qual 32:1105–1113
Larney FJ, Hao X, Topp E (2011) Manure management. Pages 247–264 *in* Hatfield JL, Sauer TJ, eds. Soil Management: Building a Stable Base for Agriculture. Madison, WI: American Society of Agronomy/Soil Science Society of America
Larney FJ, Lindwall CW, Izaurralde RC, Moulin AP (1994) Tillage systems for soil and water conservation on the Canadian prairie. Pages 305–328 *in* Carter MR, ed. Conservation Tillage in Temperate Agroecosystems—Development and Adaptation to Soil, Climatic and Biological Constraints. Boca Raton, FL: CRC Press Inc
Larney FJ, Olson AF (2006) Windrow temperatures and chemical properties during active and passive aeration composting of beef cattle feedlot manure. Can J Soil Sci 86:783–797
Légère A, Samson N (1999) Relative influence of crop rotation, tillage, and weed management on weed associations in spring barley cropping systems. Weed Sci 47:112–122
Li L, Larney FJ, Angers DA, Blackshaw RE (2015) Surface soil quality attributes following 12 years of conventional and conservation management on irrigated rotations in southern Alberta. Soil Sci Soc Am J 79:930–942
Liebman M, Dyck E (1993) Crop rotation and intercropping strategies for weed management. Ecol Appl 3:92–122
Liebman M, Staver CP (2001) Crop diversification for weed management. Pages 322–374 *in* Liebman M, Mohler CL, and Staver CP, eds. Ecological Management of Agricultural Weeds. Cambridge, UK: Cambridge University Press
Menalled FD, Gross KL, Hammond M (2001) Weed aboveground and seedbank community responses to agricultural management systems. Ecol Appl 11:1586–1601
Menalled FD, Liebman M, Buhler DD (2004) Impact of composted swine manure and tillage on common waterhemp (*Amaranthus rudis*) competition with soybean. Weed Sci 52:605–613
Parham JA, Deng SP, Raun WR, Johnson GV (2002) Long-term cattle manure application in soil. I. Effect on soil phosphorus levels, microbial biomass C, and dehydrogenase and phosphatase activities. Biol Fertil Soils 35:328–337
SAS Institute Inc. 2012. SAS OnlineDoc® 9.3. Cary, NC: SAS Institute Inc
Sarrantonio M, Gallandt ER (2003) The role of cover crops in North American cropping systems. J Crop Prod 8:53–73
Schoofs A, Entz MH (2000) Influence of annual forages on weed dynamics in a cropping system. Can J Plant Sci 80:187–198
Sosnoskie LM, Herms CP, Cardina J (2006) Weed seedbank community composition in a 35-yr-old tillage and rotation experiment. Weed Sci 54:263–273
Sosnoskie LM, Herms CP, Cardina J, Webster TM (2009) Seedbank and emerged weed communities following adoption of glyphosate-resistant crops in a long-term tillage and rotation study. Weed Sci 55:261–270
Sturz AV, Matheson BG, Arsenault W, Kimpinski J, Christie BR (2001) Weeds as a source of plant growth promoting rhizobacteria in agricultural soils. Can J Microbiol 47:1013–1024
Swift MJ, Anderson JM (1993) Biodiversity and ecosystem function in agricultural systems. Pages 14–41 *in* Schultz ED, Mooney HA, eds. Biodiversity and Ecosystem Function. Berlin: Springer
Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. J Prod Agric 9:475–479

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