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Article

Twenty-four years of contrasting cropping systems on a brown chernozem in Southern Alberta: crop yields, soil carbon, and subsoil salinity

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Abstract

Cropping systems with perennial forages and reduced fallow frequency generally increase soil organic carbon and thus subsequent soil health and crop yield. We evaluated the impact of prior cropping systems on subsequent yields and soil properties in a semiarid region by using crop yields as a bioassay of soil health following the termination of a 24-year crop rotation study in the Brown soil zone in Alberta. During 24 growing seasons from 1992 to 2015, the study included three fallow-containing rotations, two annual crop rotations that were cropped continuously, and perennial grass hay, each with two to six fertilizer treatments. During the bioassay period from 2016 through 2020, all plots in the study were uniformly cropped. Compared to unfertilized fallow wheat, soil organic C in the fall of 2015 was 54% higher after 24 years of fertilized grass and up to 14% higher following annual crops in rotations without fallow. The most notable impact of the previous cropping system on yield during the bioassay years was low yield following perennial grass in 2016 and 2018. Soil electrical conductivity measurements showed that subsoil salinity was elevated following perennial grass, demonstrating the importance of subsoil characteristics for healthy soils. Crop yields in the fifth year of the crop bioassay were 10%–20% greater due to reduced fallow frequency or increased crop diversity. The long-term impact of the cropping system on crop yield in this study depended on drought intensity due to counteracting changes in soil organic matter and subsoil salinity.

Key words: soil health, drought stress, soil organic matter

Résumé

En général, les systèmes culturaux combinant vivaces fourragères et jachères moins fréquentes haussent la concentration de carbone organique dans le sol, donc rendent celui-ci plus fertile et accroissent le rendement des cultures. Les auteurs ont évalué l'incidence des systèmes culturaux antérieurs sur la productivité et les propriétés du sol subséquentes dans une région semi-aride en utilisant le rendement des cultures comme indicateur biologique de la vitalité du sol, après interruption d'une étude d'assolement de 24 ans, dans la zone des sols bruns de l'Alberta. De 1992 à 2015 (24 périodes végétatives), l'étude en question a porté sur trois assolements avec jachère, l'assolement de deux monocultures annuelles et la culture de foin de graminées vivaces, avec deux à six applications d'engrais par année dans chaque cas. Lors de l'essai biologique, soit de 2016 à 2020, toutes les parcelles de l'étude ont été cultivées de la même manière. Comparativement à l'assolement jachère-blé sans fertilisation, la concentration du carbone organique dans le sol à l'automne 2015 était de 54 % plus élevée pour les parcelles fertilisées de graminées au terme de 24 années de culture et de 14 % plus élevée pour les parcelles des assolements de cultures annuelles, sans jachère. Le faible rendement relevé après la culture de graminées vivaces en 2016 et 2018 constitue l'impact le plus notable du système cultural antérieur sur le rendement lors de l'essai biologique. La conductivité électrique du sol révèle une hausse de la salinité du sous-sol après la culture des graminées vivaces, signe que les particularités du sous-sol jouent un rôle important dans la vitalité du sol. La cinquième année de l'essai, le rendement des cultures avait augmenté de 10 à 20 % à cause des jachères moins fréquentes ou d'une plus grande diversité des cultures. L'impact à long terme du système cultural sur le rendement agricole illustré dans le cadre de ce projet dépend de la gravité de la sécheresse qui découle des changements subis par la teneur en matière organique du sol et la salinité du sous-sol. [Traduit par la Rédaction]

Mots-clés : vitalité du sol, stress de la sécheresse, matière organique du sol

Introduction

The health of agricultural soils can be modified by cropping practices such as crop rotation and fertilization (Karlen et al. 2006; Bowles et al. 2020). These practices influence soil functions through their impact on soil properties such as organic matter, structure, porosity, pH, microbial biomass, and nutrient supply. The contribution of soil properties to soil health is complex due to dependence on agoecosystem, slow change in soil properties, and nonlinear relationships to soil functions. Due to these factors, long-term cropping system studies are of considerable value to quantify management impacts on soil properties and crop yield (Janzen 1995; Peterson et al. 2012).

A recent study relevant for the semiarid Canadian prairies was conducted by Smith et al. (2015) at Lethbridge, Alberta, in the Dark Brown soil zone. A cropping system experiment with 13 different crop management treatments that had been in place for 10–44 years was interrupted for 6 years during which all plots were uniformly maintained under a single "bioassay crop". Compared to a fallow–wheat (FW) rotation, cropping systems with less frequent fallow and greater N inputs increased wheat yield over 4 years (excluding initial 2 transition years) by up to 85% when no N fertilizer was applied and by up to 19% when fertilizer N was applied. Wheat yield without applied N was positively correlated with soil organic C (SOC). The relationship of SOC to wheat yield was largely masked by the application of fertilizer N.

Soil properties that control available water will increase in importance with increasing aridity. Soil water-holding capacity and rate of water depletion are controlled primarily by texture, organic matter, and soil thickness (Saxton and Rawls 2006). Salinity also limits soil water availability. Cropping systems that use less water increase percolation and downward movement of salts that may otherwise contribute to salinity issues in other areas, while cropping systems that use more water may increase net upward movement of salts (Beke et al. 1994). The impact of the cropping system on salinity depends on subsoil hydrology and salinity levels, the dominant factors controlling salinity issues. Most of the agricultural land on the Canadian prairies has some risk of being salt-affected (Coote et al. 1981).

The termination of a long-term cropping study at Bow Island in the Brown soil zone in Alberta provided an opportunity to evaluate the impact of long-term crop management practices in the Brown soil zone, the driest soil zone in the prairies. The study was conducted from 1992 to 2015 by Alberta Agriculture to evaluate long-term impacts due to intensification of cropping practices. Prior to 1990, almost all nonirrigated cropland in the Brown soil zone of Alberta was managed as tilled FW, but as of 2016, summerfallow had been largely eliminated (<10% of dryland area fallowed in a given year; Alberta Agriculture and Forestry 2020) and no-till was adopted widely. Results from the first 18 years of the long-term cropping study showed that annual crop yields were highest in wheat-pulse and fertilized continuous wheat (CW) treatments, with increases in SOC of up to 4 Mg C ha^{-1} (11%) under continuous cropping and up to 12 Mg C ha^{-1} (30%) under perennial grass (Bremer et al. 2011). We conducted a crop bioassay for 5 years after the study had run for 24 growing seasons to determine the impact of prior cropping practices on soil properties and crop yield.

Materials and methods

The Bow Island long-term cropping study consisted of six crop rotation treatments with two to six fertilizer treatments in each rotation (Fig. 1). All rotation phases were present each year. The experiment was set up in split-plot design with six main plot treatments, six subplot treatments, and four blocks. However, subplot treatments were not randomized between each block. Plots were 4 m × 16 m in size.

During the bioassay years, all plots were uniformly cropped to spring wheat in 2016, yellow mustard (*Sinapis alba* L.) in 2017, barley in 2018, and winter wheat in 2019–2020 (Table 1). Due to extremely dry conditions in the spring of 2019, a spring crop was not planted and the site was kept fallow until the fall when winter wheat was planted. Nitrogen fertilizer was applied to the same half of each plot (split lengthwise) at a rate of 80 kg N ha^{-1} $year^{-1}$ in 2016, 2017, and 2018. No N fertilizer was applied to the other half of each plot or to winter wheat in 2020.

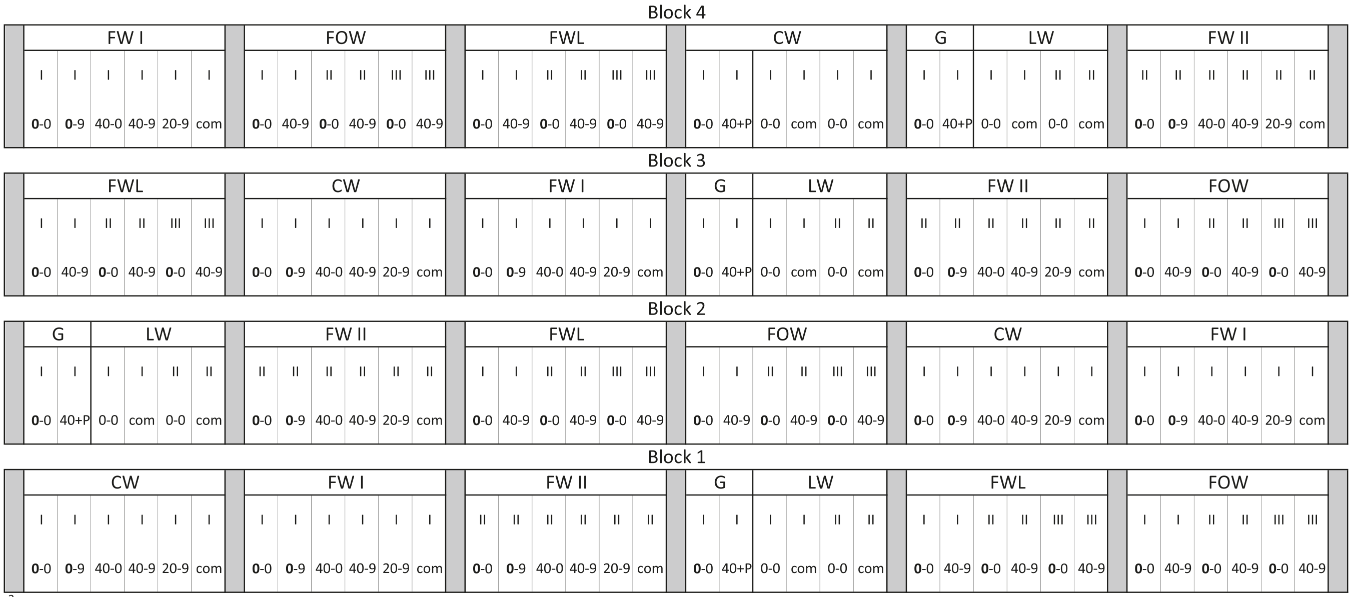
Conventional zero-tillage practices for the region were followed. Glyphosate was applied in fall 2015 and spring 2016 to all plots for weed control and termination of the grass stand. Plots were seeded without tillage and P fertilizer (triple superphosphate, 0-45-0) was seed-placed at 9 kg P ha^{-1} on the entire cropped area, while N fertilizer (urea, 46-0-0) was side-banded at 80 kg N ha^{-1} in half of each plot in 2016, 2017, and 2018, as described above. In-crop weeds were controlled with herbicide applications. Seed yields were determined by harvesting all rows within subplots (25 m^2) by using a small plot combine. Seed yields were adjusted to standard moisture content: 13.5% for wheat and barley and 8.5% for mustard.

In 2017, mustard was seeded on 4 May following soil application of ethalfluralin (Edge) and sulfentrazone (Authority). Herbicide interaction caused variable emergence, with almost no emergence in compost treatments, and therefore the original crop was sprayed out and re-seeded on 9 June. Due to high temperatures and negligible precipitation after re-seeding (Table 1), 50 mm of irrigation was applied on 4 July to ensure survival.

To monitor drought stress in 2018, crop canopy temperatures in the mid-afternoon of clear days were obtained weekly from 6 June until 18 July using a narrow field-of-view infrared radiometer (MI-220, Apogee Instruments, Logan, UT). Crop canopy temperature increase under drought stress due to lower rates of evapotranspiration (Jackson 1982). Soil moisture depletion over the growing season was also determined each year in one or two subplot treatments of each rotation by determining gravimetric soil moisture on soil cores obtained to a depth of 0.9 m within a few days of seeding and harvest.

Soil samples were collected from all plots in the fall of 2015 and analyzed for total and organic C and N using the same methodology used previously (Bremer et al. 2011). In brief, four cores with a diameter of 6.7 cm were taken with a hydraulic soil corer and composited into 0–7.5, 7.5–15, and 15–30 cm depth increments. Crop residues on the soil surface

Fig. 1. Plot plan and treatments in the long-term cropping system experiment at Bow Island, AB, during rotation phase (1992–2015).



[a]Abbreviations: F, fallow; W, wheat; L, annual legume; O, oilseed; com, compost.

Main plot treatments:

- CW Continuous wheat.
- FW I Fallow-wheat (wheat in 2015).
- FW II Fallow-wheat (fallow in 2015).
- G Perennial grass (pubescent wheatgrass, *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey) harvested for hay.
- LW Pulse legume-wheat: the legume phase was chickling vetch green manure from 1992-1995, pea from 1996-2012, and lentil from 2013-2015.
- FWL Fallow-winter wheat-legume: the legume phase was chickpea from 2004-2005 and lentil from 2006-2015. The crop rotation was fallow-wheat-wheat from 1992-2003.
- FOW Fallow-oilseed-wheat: the oilseed phase was flax from 1992-2003 and mustard from 2004-2015.

Subplot treatments:

- I, II, III Phase of crop rotation.
- 0-0, etc. Paired values denote annual rates of synthetic N and P fertilization to cropped phase (kg ha^{-1} yr^{-1}). From 2013 to 2015, 0N treatments with bold font received 80 kg N ha^{-1} to address weed issues under N-deficient conditions.
- com Compost applied every three to six years at 22 Mg ha^{-1} (wet weight). Cumulative compost additions (moist basis) were 80 Mg ha^{-1} in the FW rotation, 66 Mg ha^{-1} in the LW rotation, and 146 Mg ha-^{1} in the CW rotation. Due to incomplete analysis, C and N concentrations were not available of all applications. Typical composition was 110 kg C Mg^{-1} and 9 kg N Mg^{-1}.

were not included in the sample. Whole soil samples, including root and crop residue fragments present, were ground to <2 mm on a rotating sieve. Representative subsamples were then ground to <0.15 mm and analyzed for total C and N with an automated combustion analyzer (CE Elantech, Lakewood, NJ). Soil organic C was determined in the same way after removal of carbonates with the addition of excess hydrochloric acid to the combustion capsule (Ellert and Rock 2008). Soil inorganic N was determined by colorimetric determination of nitrate and ammonium after KCl extraction (Keeney and Nelson 1982). Total SOC and N were calculated on an equivalent mass basis (4348 Mg ha^{-1} to 30 cm) (Ellert and Bettany 1995). Mineralization of soil C and N was quantified by determining respired CO_2 and the increase in inorganic N during a 10-week incubation of a 75 g subsample maintained at 25 °C and 80% of field capacity (Bremer et al. 1994). Soil pH was determined in 0.01 mol/L $CaCl_2$ (2:1 solution:soil suspension) (Hendershot et al. 2008).

Soil nutrient supply was determined in situ in 2016 through 2018 in one to three subplot treatments of each rotation. Three pairs (anion and cation) of Plant Root Simulator (PRS®) probes (Western Ag Innovations, Saskatoon, SK) were buried in each plot for 4 weeks starting 10–14 days after seeding. Nutrients adsorbed by the ion-exchange membranes over the burial period were determined by eluting the ions with 0.5 mol/L HCl and analyzing the eluant for NO_3–N and NH_4–N using an automated continuous-flow analyzer with a colorimetric detector (Skalar Inc., Netherlands) and other nutrients (P, K, S, Ca, Mg, Fe, Mn, Cu, Zn, and B) by using an inductively coupled plasma optical emission spectrometer (Optima ICP-OES 8300, PerkinElmer Inc., USA).

Inductive sensing of electrical conductivity (EC) was determined in all plots on three dates in 2017 and 2018 using an inductive electromagnetic sensor (EM38-MK2, Geonics, Mississauga, ON). Lab-based measurements of soil conductivity (2:1 water:soil suspensions) to a depth of 0.9 m were determined on all soil samples collected for gravimetric soil moisture in April 2018 (two subplot treatments in each rotation, ±N fertilizer).

Statistical analysis of crop and soil variables was conducted with the MIXED procedure (SAS Institute Inc. 2002), with prior cropping treatment (main plot and subplot) as fixed ef-

Table 1. Cropping and weather conditions during crop bioassay (2016–2020).

Parameter	2016	2017	2018	2019	2020	Normal
Crop	Spring wheat	Mustard	Barley	Fallow	Winter wheat	
Cultivar	Lillian	Andante	Austenson		Wildfire	
Seeding date	2 May 2016	9 June 2017[b]	8 May 2018		18 September 2019	
Harvest date	20 July 16	8 September 2017	8 August 2018		10 August 2020	
Precipitation (mm)						
Fall + winter[a]	174	131	152	102	136	163
May	64	32	19	35	78	46
June	44	71	37	24	104	68
July	101	59[c]	21	23	11	33
August	49	15	17	36	4	34
May–July	208	162	77	82	192	147
Potential evapotranspiration (mm, standard grass)						
May	124	154	152	125	130	
June	161	161	155	152	143	
July	150	198	170	170	171	
May–July	435	513	477	447	444	
Soil water to 0.9 m (mm)						
Seeding	251	276	272		ND	
Harvest	238	187	148		154	
Depletion	13	89	124		ND	

[a]1 September to 30 March.
[b]Re-seeding date. Mustard seeded on 4 May was terminated due to poor and uneven impact of soil-applied herbicides on crop emergence.
[c]Includes 50 mm of irrigation applied on 4 July to ensure survival of re-seeded mustard.

fects and block as a random effect. Initial analysis indicated that prior P fertilization and rotation phase had negligible impacts on soil organic matter or pH. Thus, soil variables were also analyzed with the main plot as fixed effects and block and subplot treatment as random effects for treatments with a similar fertilizer history: 0N ± P, N-fertilized treatments ± P and compost. Grass and annual legume–wheat (LW) rotations were included in this analysis as separate main plot treatments. In situ soil nutrient supply was analyzed for 2017 and 2018 with year included as a random effect; 2016 was excluded due to different treatments being monitored. Post-rotation N fertilizer rates were included as a fixed effect for crop yield in each year, but crop yields were not analyzed across years due to strong dependence of treatment effects on growing conditions. Crop yields were normalized across years by expressing as a fraction of the average yield of all FW treatments at the same post-rotation N rate each year. Statistical significance of treatment differences was evaluated with the Tukey–Kramer's test ($p = 0.05$). The correlation of crop yield with soil properties was determined with the CORR procedure.

Results and discussion

Soil properties

Cropping practices from 1992 to 2015 had a large impact on SOC (Table 2). Application of N fertilizer did not increase SOC in annual crop rotations, but increased SOC in the perennial grass treatment by 9 Mg C ha^{-1}. Application of compost in annual crop rotations increased SOC by an average of 6 Mg C ha^{-1}. Compared to FW, continuously cropped rotations (CW and LW) increased SOC by an average of 4 Mg C ha^{-1}. Compared to annual crop rotations, perennial grass increased SOC by an average of 11 Mg C ha^{-1} when unfertilized and 19 Mg C ha^{-1} when fertilized. These differences are similar to those observed previously, but with continued increases of SOC in the perennial grass treatment (Bremer et al. 2011).

The increase in SOC in the perennial grass treatment was largely composed of undecomposed roots and other organic materials with a wide C:N ratio (Table 2). Soil C mineralization and mineralizable C:N ratio were also much greater in perennial grass than annual cropping systems. This gain was greater than observed under perennial crops in other long-term cropping studies in Canada (3–14 Mg C ha^{-1}) determined with the same sampling and analytical methods and comparable stand age (VandenBygaart et al. 2010). The greater impact of perennial grass in this study may be due to greater proliferation of roots in the surface 0.3 m due to elevated subsoil salinity (Fig. 2, discussed below).

Soil C mineralization over a 10-week incubation period was influenced similarly by rotation treatment as SOC, although with a larger relative gain due to perennial grass (Table 2). Nitrogen mineralization was highest in perennial grass and cropping systems with an annual legume (LW and fallow-winter wheat–legume (FWL)) and least in FW and CW treatments. Soil N supply determined in situ with PRS probes in 2017 and 2018 were also influenced similarly by prior cropping system (Table 2). Application of compost did not increase

Table 2. Effect of 24 years of cropping management on soil properties.

Main plot[a]	Fertility treatment from 1992 to 2015[b]					
	0N ± P	NF ± P	Compost	0N ± P	NF ± P	Compost
	SOC to 0.3 m (Mg C ha^{-1})			**Total N to 0.3 m (Mg N ha^{-1})**		
FW I	39.4c[c]	40.4c	44.0b†[d]	4.5b	4.6c	4.9b†
FW II	40.7bc	41.3c	47.4ab†	4.6b	4.7c	5.2ab†
FWL	42.2bc	42.4bc	ND	4.7b	4.7bc	ND
FOW	41.7bc	42.6bc	ND	4.7b	4.8bc	ND
CW	44.1b	45.5b	52.2a†	4.9ab	5.0b	5.7a†
LW	44.3b	ND	50.1a†	4.9ab	ND	5.4ab†
Grass	52.9a	61.8a†	ND	5.3a	5.8a†	ND
p	<0.01	<0.01	0.02	<0.01	<0.01	0.06
SE	1.0	1.0	1.9	0.1	0.1	0.2
	10-week C mineralization (mg CO_2–C kg^{-1})			**10-week N mineralization (mg N kg^{-1})**		
FW I	517b	528bc	573ab	34abc	28c	28ab
FW II	380b	440c	387b	28bc	27c	23b
FWL	588b	613bc	ND	40abc	41ab	ND
FOW	511b	578bc	ND	26c	31bc†	ND
CW	686b	674b	694a	28bc	28c	33ab
LW	700b	ND	693a	44ab	ND	39a
Grass	1910a	2538a	ND	55.6a	51.6a	ND
p	<0.01	<0.01	0.01	<0.01	<0.01	0.03
SE	84	55	65	4.5	3.0	4.5
	Soil pH to 0.15 m			**In situ soil NO_3 supply (mg N m^{-2} 4 wk^{-1})**		
FW I	6.0	5.8	6.5†	ND	216cd	257ab
FW II	6.0	6.0	6.7†	ND	171d	224b
FWL	6.1	5.7†	ND	ND	329abc	ND
FOW	6.2	5.9†	ND	ND	278bcd	ND
CW	6.1	5.8†	7.0†	ND	364abc	365a
LW	6.1	ND	6.8†	313b	ND	374a
Grass	6.1	5.9†	ND	504a	434a	ND
p	0.31	0.49	0.26	0.05	<0.01	<0.01
SE	0.1	0.1	0.1	59	32	38

[a]See Fig. 1 for treatment descriptions.
[b]0N ± P received no N fertilizer from 1992 to 2012; NF ± P received 20 or 40 kg N ha^{-1} $year^{-1}$ from 1992 to 2015.
[c]Values within a column not followed by a common letter are significantly different (Tukey–Kramer's test, $p = 0.05$).
[d]† indicates that the value is significantly different from 0N ± P (Tukey–Kramer's test, $p = 0.05$).

lab mineralization or in situ NO_3 supply, but increased P, K, and Zn supply (data not presented). The organic N in feedlot compost is only very slowly mineralized (Helgason et al. 2007).

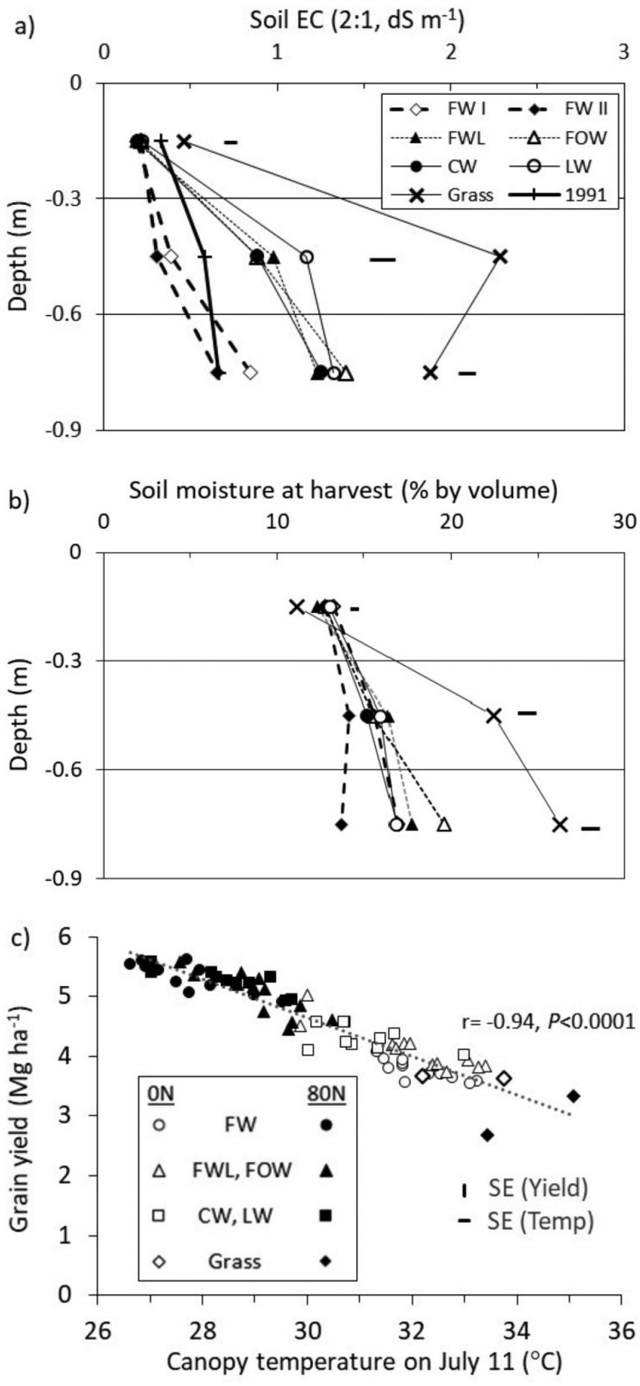
Soil pH in the surface 0.15 m ranged from 5.7 to 7.0 (Table 2). Soil pH was reduced by an average of 0.5 with long-term application of N fertilizer, consistent with other long-term studies on the Canadian prairies (Bouman et al. 1995). Application of compost increased soil pH by an average of 0.8 due to the addition of $CaCO_3$ in feed rations (Eghball 1999).

Inductive sensing of soil EC using an EM38 in 2017 and 2018 revealed that grass plots consistently had the highest conductivity and FW treatments had the lowest conductivity. Lab measurements of EC in soil samples obtained in April 2018 were greatest in grass and least in FW treatments in both the 0.3–0.6 and 0.6–0.9 m depths (Fig. 2*a*). Soil EC below 0.3 m was elevated in all rotations except FW compared to 1991 measurements. Thus, subsoil salinity had been altered by the prior cropping system. Crops can induce subsoil salinity by removing water from the root zone by evaporation and transpiration in the presence of a perched or rising water table that is high in soluble salts (Rengasamy 2002). Transient subsoil salinity occurs without the influence of groundwater when leaching is limited by low permeability of deeper soil layers and low rainfall, while seepage salinity occurs due to the presence of a shallow and saline water table.

Crop bioassay yield

Drought conditions during the crop bioassay, particularly from 2017 through 2019, limited yield potential and increased crop dependence on stored soil moisture (Tables 1 and 3). Growing season precipitation was considerably below normal in 2017, 2018, and 2019. Supplemental irrigation in 2017 increased precipitation to normal, but mustard yields

Fig. 2. Salinity and water relations: (*a*) subsoil salinity in spring 2018 was elevated in prior rotations with grass or less frequent fallow, (*b*) subsoil moisture after barley harvest in 2018 was not depleted following grass, and (*c*) grain yields in 2018 declined with increasing mid-afternoon canopy temperature on 11 July. See Fig. 1 for treatment descriptions.



were still low due to high evapotranspiration and temperatures following re-seeding required due to herbicide injury. In 2018, barley effectively depleted soil water during the growing season, thus supporting moderately high yields. In 2020, above-average precipitation in May and June supported high winter wheat yields.

Application of N fertilizer during the crop bioassay period (2016–2018) increased crop yield by 34%–61% ($p < 0.0001$) in former CW and FW rotations (Table 3). Residual impacts of N fertilizer applied from 2016 to 2018 increased winter wheat yield in 2020 by 9% ($p < 0.0001$). Nitrogen mineralized during the fallow period in 2019 contributed to N uptake of winter wheat in 2020.

The impact of prior rotation on subsequent crop yield was greater in 2016 than in subsequent years of the bioassay (Fig. 3). This was partly due to short-term impacts of fallow in the previous year as evident by the higher yield following the fallow phase of the FW rotation (FW II) in 2016 but similar crop yields between phases in subsequent years (Table 3). The most notable impact of prior rotation in 2016 was the low yield following perennial grass that we initially attributed to soil N immobilization from decomposing grass residues. However, spring measurements of soil N supply in 2016 in the perennial grass treatment were not different from those in the CW and FW rotations (not presented) and the protein concentration of wheat in 2016 without N was the same following perennial grass and FW (110 vs. 112 g kg^{-1}). Elevated subsoil salinity in the perennial grass treatment may have limited available water during a critical period for grain yield, even though soil moisture depletion over the growing season was similar among treatments.

Differences in crop productivity in 2017 were also evident (Fig. 3 and Table 3). However, low crop yields following herbicide injury that was partly related to soil pH complicated interpretation of yield differences and reduced their reliability as an indicator of long-term impacts.

Differences in barley yield in 2018 and winter wheat yield in 2020 were the most reliable indicators of long-term management impacts because short-term factors had dissipated and crop establishment was satisfactory. Similarly, Smith et al. (2015) used total wheat yield from 3–6 years after initiation of uniform cropping as the indicator of long-term crop management impacts.

The most notable impact of prior rotation on crop yield in 2018 was again the low yield following perennial grass, particularly in the N-fertilized treatment (Fig. 3). This was in contrast to most previous studies (Entz et al. 2002; Franco et al. 2018 and citations therein). Negative or neutral impacts may occur for 1 or 2 years after breaking of perennial crops in semiarid regions due to reduced water availability (Cutforth et al. 2010). Perennial grass had clearly increased rather than decreased soil N supply by 2018: in situ spring measurements of soil N supply in grass treatments were 2.2-fold higher than FW treatments and 1.5-fold higher than CW and LW treatments (Fig. 4*c*) and grain protein concentrations were the highest in the perennial grass treatment (135 g kg^{-1}, compared to 94–111 g kg^{-1} in other N-fertilized treatments). The negative impact of perennial grass on crop yields was not associated with deficiencies in nutrients other than N as in situ supply rates of P, K, and other nutrients were similar for grass to those in other rotations with equivalent prior fertilization. The negative impact of perennial grass on crop yields was also not associated with low soil pH (Table 2). Instead, subsoil salinity reduced barley yield by reducing the availability of soil water in a year where subsoil moisture

Table 3. Average crop yield (Mg ha^{-1}) following 24 years of continuous wheat (CW) and fallow-wheat (FW) under six fertility treatments.

Treatment	Year 1 (2016) wheat	Year 2 (2017) mustard	Year 3 (2018) barley	Year 5 (2020) winter wheat
CW, 0N	2.18b	0.28	4.27a	7.65a
FW I,[a] 0N	2.21b	0.33	3.92ab	6.82b
FW II, 0N	3.52a	0.29	3.63b	6.43b
CW, 80N	3.50b	0.40b	5.22	8.26a
FW I, 80N	3.58b	0.52a	5.38	7.30b
FW II, 80N	4.28a	0.53a	5.28	7.23b
SE	0.06	0.06	0.14	0.18
0N-0P	3.23ab	0.37bc	4.62	7.08b
0N-9P	3.20b	0.33c	4.63	7.11b
40N-0P	3.24ab	0.41b	4.65	7.28ab
40N-9P	3.14b	0.36bc	4.53	7.38ab
20N-9P	3.11b	0.38bc	4.63	7.26ab
Compost	3.35a	0.49a	4.63	7.57a
SE	0.05	0.02	0.12	0.12
Probability of treatment effects				
MP	<0.01	0.04	0.28	<0.01
SP	<0.01	<0.01	0.96	<0.01
MP×SP	<0.01	0.01	0.59	0.25
Nrate	<0.01	<0.01	<0.01	<0.01
MP×Nrate	<0.01	<0.01	<0.01	0.16
SP×Nrate	0.05	<0.01	0.75	0.83
MP×SP×Nrate	0.55	0.78	0.81	0.99

[a]FW I was cropped to wheat in 2015; FW II was fallow in 2015.
[b]Values within a column not followed by a common letter are significantly different (Tukey–Kramer's test, $p = 0.05$).

was critical for yield. Barley was unable to deplete soil moisture below 0.3 m as effectively in the perennial grass treatment as other treatments (Fig. 2*b*) and N-fertilized barley had greater mid-afternoon canopy temperatures on 11 July than other treatments (Fig. 2*c*; also observed on 20 June, 28 June, and 18 July), indicative of increased drought stress (Jackson 1982). Mid-afternoon canopy temperatures were negatively correlated with final barley grain yield on all of these dates (r ranged from −0.89 to −0.94, $p < 0.001$). The application of N fertilizer exacerbated the negative impact of subsoil salinity by further stimulating vegetative growth and depletion of soil moisture early in the growing season and increasing drought stress during periods critical for grain yield later in the growing season (van Herwaarden et al. 1998).

Winter wheat yields in 2020 were not lower following perennial grass but were still lower than expected based on the relationship with SOC (Fig. 4*b*). Drought stress and crop dependence on subsoil moisture were considerably less in 2020 than 2018 due to greater precipitation that was better synchronized with crop use (Table 1).

Relative to FW, prior rotations with continuous cropping or pulse legumes (CW, LW, FWL) increased barley yields in 2018 by 13%–19% in the non-N-fertilized treatment and increased winter wheat yields in 2020 by 10%–20% (Fig. 3). Prior rotations other than perennial grass did not impact barley yields in bioassay years with N fertilizer. In comparison, Smith et al. (2015) reported that cropping systems with less frequent fallow and greater N inputs increased wheat yield by up to 85% when no N fertilizer was applied and by up to 19% when fertilizer N was applied. The smaller benefit in our study primarily reflects reduced N fertility benefits following low crop yields in 2017 and fallow in 2019.

Crop yields in 2018 and 2020 were not strongly impacted by long-term fertilization treatments (Table 3). In 2018, prior fertilization treatments had no impact on barley yield. In 2020, compost increased winter wheat yield by 7% compared to prior 0N treatments, which is attributable to improved moisture conditions and increased soil organic matter and/or nutrient supply (P, K, and Zn, data not presented).

Models relating bioassay crop yields to soil properties are useful for interpretation and extrapolation due to the multiple factors controlling yield. Compared to FW rotation, the SimPLE.ca model (Bremer et al. 2008) estimated that crop yield in the perennial grass treatment would be reduced by 30% in 2018 due to the reduction in available water. The model also estimated yield benefits of up to 20% due to continuous cropping or inclusion of annual legumes when unfertilized but none when fertilized, similar to observed (Fig. 3). Simulation of winter wheat yields without the fallow period increased yield differences to similar levels reported by Smith et al. (2015). Semiarid regions are characterized by large annual variation in available moisture, which strongly interacts

Fig. 3. Impact of prior rotation (1992–2015) at Bow Island, AB, on crop yields during bioassay period, expressed as a fraction of average FW yield: (*a*) without N fertilizer and (*b*) with 80 kg N ha^{-1} (no N fertilizer applied in 2020 (residual impacts)). See Fig. 1 for treatment descriptions. Error bars are standard errors.

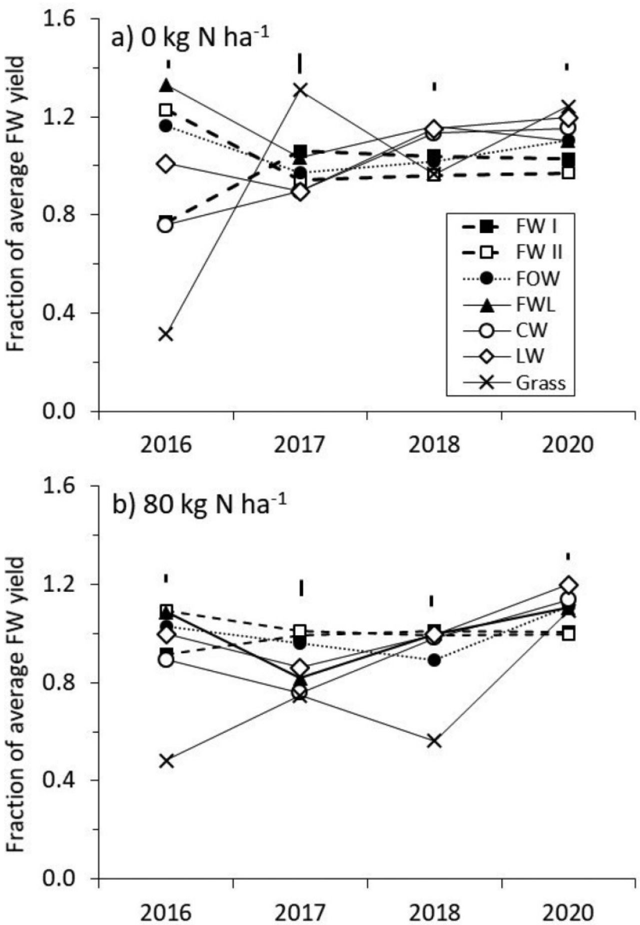
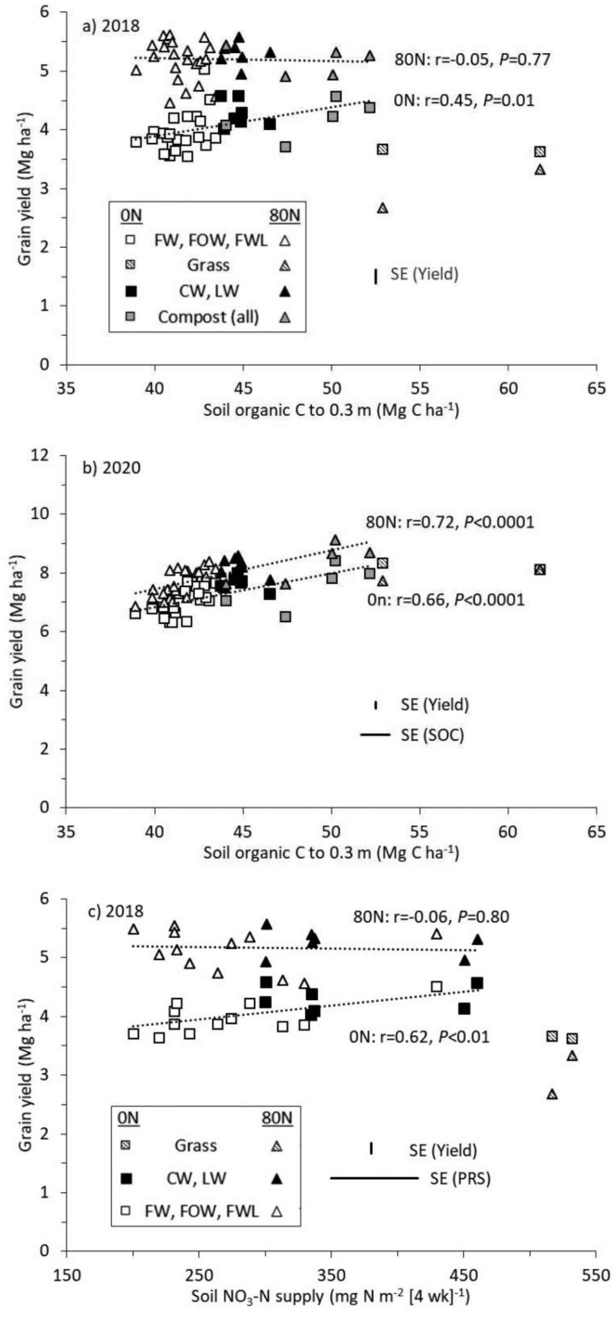


Fig. 4. Relationship of crop yields to soil properties: (*a*) 2018 barley yields vs. soil organic C, (*b*) 2020 winter wheat yields vs. soil organic C, and (*c*) 2018 barley yields vs. soil NO_3–N supply. Yields following grass were excluded from correlations. See Fig. 1 for rotation descriptions.



with nutrient supply and soil organic matter to impact crop yields.

Conclusions

The bioassay approach, whereby the changes in soil health influencing crop yields accruing to rival long-term cropping systems are inferred from crop yields deployed uniformly over the entire study, was influenced by drought (2017, 2018, and 2019) and by herbicide damage (2017) in this study. Benefits of the keystone property for soil health, SOC, were counteracted by increased subsoil salinity under drought conditions. This may not apply to years with excessive precipitation as SOC may support increased infiltration, more stable aggregation, and greater resistance to erosion.

The benefits of annual cropping systems with reduced fallow frequency or greater crop diversity to crop yields persisted to the fifth and final year of the crop bioassay. These benefits were positively correlated with SOC.

The long-term perennial grass forage was an outlier in this bioassay. Despite substantially increased SOC after 24 years, the expectation that this would support greater productivity was trumped by elevated subsoil salinity. Subsoil salinity primarily depends on hydrology and groundwater salinity and may have been exacerbated by the surrounding land management in this study. Nevertheless, these results highlight the importance of including subsoil salinity in soil health assessment in arid and semiarid regions. The presence of subsoils that limit crop yield is often not recognized as they are not readily observable and their impact varies with precipitation and crop dependence on subsoil moisture reserves.

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