

Strategies to Reduce Inorganic Fertilizer Inputs in Crop Production through Integrated Crop-livestock Systems

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Abstract

Adequate nutrition is essential for crop growth, production, and profit potential for farmers, but chemical fertilizer costs alone can constitute a greater portion of the total variable costs for wheat and canola. The present study evaluated seven cropping treatments (CT) in a 3-year crop rotation under two different soil types. Five of the CTs consisted of a one-time application (year 1) of beef cattle manure, and growing of cover crop cocktails (CCC) for annual pasture, swath grazing, green manure, and green feed. Canola and wheat were respectively grown in years 2 and 3 of the 3-year crop rotation. In year 2, CTs impacted canola seed yield and seed protein (only at site 2). Wheat had similar protein content in year 3 at both sites. At both sites, the application of beef cattle manure in year 1 seemed to encourage higher plant tissue P at the expense of plant tissue Zn. Overall, beef cattle manure and CCCs based CTs improved soil N, P, and K, but beef cattle manure application consistently improved crop yield and significantly reduced the need for additional in-organic fertilizer application to canola and wheat in subsequent years.

Keywords: cover cropping, wheat, canola, integrated crop-livestock production, soil nutrients

1. Introduction

The study of the environmental impacts of crops, the reduced costs of production, and the balanced use of fertilization are among the main objectives of modern agriculture (Yousaf et al., 2016). In Alberta, Canada, a recent *AgriProfit\$* report showed that chemical fertilizer costs could constitute up to 30% of the total variable costs for wheat and 33% for canola (AAF, 2021) indicating that in-organic fertilizer alone could have the highest of any single input cost in wheat and canola production. Concomitant with this is that over the last four years, the costs of fertilizers have escalated by as much as 40% for urea, 37% for mono-ammonium phosphate, 22% for muriate of potash, and 9% for ammonium sulphate. The high fertilizer costs and the unstable prices of beef cattle and grains are causing producers to look for different ways to manage farming systems that will improve soil fertility and health, and reduce in-organic fertilizer application without sacrificing crop yields.

A preliminary study that examined the soil nutrient status after forage harvests of cover crop monocultures and a CCC in northern Alberta showed the potential of cover crops and their mixtures to improve soil fertility for subsequent crop production (Omokanye, 2019). Similarly, in eastern Alberta, initial evaluations of CCCs showed the potential of CCCs to provide a reduction in soil compaction, increased weed suppression and aggregation formation for the next cropping season, as well as improved biological activity (CARA, 2016), all of which will have positive impacts on crop production and overall farm profits. This further shows the need for a multifunctional low-input cropping system that includes CCCs. The benefits of CCCs are based on the multifunctional action of each crop species in the blend interacting with the soil attributes and stimulating the soil's biological activity (Barot et al., 2017).

Garrett et al. (2017) indicated that farmers' motivations for re-integrating animals into cropland are varied, but

often include risk reduction through diversification, increased nutrient and land-use efficiency, and climate resilience through enhanced adaptability of management options. Yet, crop production outcomes following livestock grazing across environments and management scenarios remain uncertain and are a potential barrier to adoption, as producers worry about the effects of livestock activity on the agronomic quality of their land. Integrated crop-livestock systems investigated using a meta-analysis on three soil types reported 5% higher yields than unintegrated systems for one soil type, and no difference between integrated and unintegrated systems on the other soils (Peterson et al., 2020). Crop nutrient uptake and crop yields are the principal factors that determine optimal fertilization practices (Ju and Christie, 2011), hence the need to apply fertilizers in an efficient way to minimize loss and to improve the nutrient use efficiency (Li et al., 2009). There is, therefore, the need for more integrated forms of agriculture to restore the sustainability of agricultural systems (Bell and Moore, 2012; Hendrickson et al., 2008; Russelle et al., 2007). Crop–livestock integration pursues three aims: reducing the openness of nutrient cycles, following the rationale of industrial ecology, organizing land use and farming practices to promote ecosystem services, and increasing farm resilience to adverse climatic and economic events (Bonaudo et al., 2014; Lemaire et al., 2014; Moraine et al., 2014).

In this study, 3-year field-scale experiments were conducted at two sites with different soil types to study the effectiveness of different cropping systems, including CCCs, livestock integration, and the use of manure and bio-stimulants on subsequent canola and wheat crop production and the impact on soil characteristics.

2. Materials and Methods

2.1 Experimental Site Description

Field experiments were conducted from 2018–2020 at two sites in Alberta, Canada. Site 1 was at Fairview Research Farm (Fairview) and site 2 was at Sedalia. The soil group at Fairview is dark gray chernozemics and brown chernozemics at Sedalia (AGRASID; GOA 2020). At the start of the project, the Fairview site had a soil pH of 5.19 (0–6”), 5.55 (6–12”) and 5.81 (12–18”), and a soil organic matter (SOM) content of 6.99% (0–6”), 3.06% (6–12”) and 2.32% (12–18”). The soil at Sedalia had a soil pH of 5.67 (0–6”), 6.59 (6–12”), and 6.80 (12–18”), while the SOM was 2.71%, 3.06%, and 2.32%, respectively from 0–6”, 6–12” and 12–18”. Both sites have a subarctic climate (also called boreal climate), which is characterized by long, usually very cold winters, and short, cool to mild summers. Fairview site was seeded to oats for greenfeed two years before the commencement of the experiment but left fallow the year before the experiment started. During the fallow period (uncultivated), the plants growing in the field were mowed down a few times during growing season. Sedalia had canola seeded the year before and combined harvested. Growing season precipitation, air temperatures, and growing degree days during the study and long-term averages for both sites acquired through the Alberta Climate Information System (ACIS, 2020) weather station are shown in Table 1.

Table 1. Monthly mean air temperature (°C), precipitation (mm), and growing degree days for the 3 growing seasons (2018, 2019 and 2020), and their long-term averages (LTA) at both sites

	Site 1: Fairview (Northwestern Alberta)				Site 2: Sedalia (Eastern Alberta)			
	2018	2019	2020	LTA	2018	2019	2020	LTA
Rainfall (mm):								
May	5.3	7.4	35.3	38.7	15	2.7	50.9	35.5
June	77.3	72.9	67.2	103	62.1	53.2	96.3	73.1
July	108.5	61.9	89.8	69.5	48.2	107	93.9	55.6
August	23.3	49.1	53.9	47.5	17.8	13.6	17.4	40.4
September	32.9	24.6	23.1	81.2	25.4	44.3	26.3	29.8
Total	247.3	215.9	269.3	339.9	168.5	220.8	284.8	234.4
Air temperatures (°C):								
May	14.3	11.5	9.9	9.9	14.5	10.1	10.4	10.7
June	14.9	14.1	14	14	16.5	15	15.1	15.1
July	16.3	15.1	15.6	15.8	18.2	17.1	17.4	17.9
August	14.7	12.9	14.1	14.6	17.4	15.8	17.7	17.1
September	4.41	9.68	10.3	9.57	7.29	11.3	12.3	11.3
Growing degree days (5°C):								
May	272	210	158	161	183	152	161	183
June	297	273	272	269	304	292	292.3	304
July	344	306	330	334	399	382	380.3	399
August	293	248	283	298	375	331	394.2	375
September	39	162	157	147	106	209	221.5	196
Total	1245	1199	1200	1209	1367	1366	1449.3	1457

2.2 Treatments and Experimental Design

This experiment was designed to examine the effect of a one-time application of seven CTs on soil fertility, and canola and wheat production over a 3-year period at both sites. The CTs were examined (Table 2) using a randomized complete block design with three replications.

Table 2. The seven cropping treatments (CT) investigated from 2018 to 2020

Brief description of CT	2018	2019	2020
Conventional rotation (control). P-C-W (control)	CDC Meadow peas (P)	Canola (C)	Wheat (W)
CCC _G (grazed as a standing crop) - canola - wheat rotation.	CCC mixture seeded. Fairview (used 6 cow-calf pairs to graze CCC) in fall.	Canola (C)	Wheat (W)
CCC _G -C-W	Sedalia (grazed by 5 dry cows) in fall.		
CCC _{SG} (swathed and grazed) - canola - wheat rotation.	CCC mixture seeded. CCC swathed when oats were at the soft dough stage.	Canola (C)	Wheat (W)
CCC _{SG} -C-W	Fairview (grazed by 6 cow-calf pairs) in fall. Sedalia (grazed by 5 dry cows) in fall.		
Barley (manure) - canola - wheat rotation. B _M -C-W	Stockpiled beef cattle manure was applied and harrowed into the soil before seeding. CDC Maverick barley was seeded. No additional chemical fertilizer was applied.	Canola (C)	Wheat (W)
CCC _R (rolled as green manure) - canola - wheat rotation. CCC _R -C-W	CCC mixture seeded. CCC was rolled onto the surface soil as green manure when the oats were at the late milk-soft dough stage.	Canola (C)	Wheat (W)
High legume-base CCC _F (40% cereals & 60% legumes for greenfeed) - canola - wheat rotation. CCC _F -C-W	CCC mixture seeded. Harvested for forage and removed from the field when the oats were at the late milk stage.	Canola (C)	Wheat (W)
Barley - canola - wheat rotation (Bio-stimulants applied yearly). B _P -C _P -W _P	CDC Maverick barley seeded. Penergetic K applied at seeding. Penergetic P applied as in-crop (foliar) application.	Canola (C) + PKP	Wheat (W) + PKP

Note.

Water and free choice trace mineralized stock salt were provided to the cows during grazing in 2018.

CCC_G and CCC_R consisted of oats, German millet, annual ryegrass, hairy vetch crimson clover, Winfred forage brassica, and sunflower.

CCC_{SG} was made up of oat, Italian ryegrass, frosty berseem clover, peas, and Winfred forage brassica.

CCC_F consisted of oats, peas, crimson clover, and hairy vetch.

For all CCCs, a substitutive approach (proportional replacement design) was used for calculating seeding rates (Omokanye et al., 2019).

No chemical fertilizer was applied to the CCCs and barley + manure (B_M) in 2018.

Except for B_M-C-W, crops were fertilized with inorganic fertilizers from 2018 to 2020.

Fairview (canola in 2018 and wheat in 2020) received half of the recommended in-organic fertilizer rates following soil test reports. Sedalia had a uniform in-organic fertilizer rate applied to all crops every year. In-organic fertilizer applications were at seeding.

At site 1, seeding dates were May 28 (2018), May 22 (2019), and May 21 (2020). Site 2 was seeded on May 25 (2018), May 27 (2019), and May 31 (2020). Plot size was about 1,102 m² with an alleyway of 1 m between plots. In 2019, a canola hybrid with Pioneer® Protector Harvest-Max CR traits (45CM39) was seeded. Canada Western Red Spring wheat (AAC Brandon wheat) was seeded in 2020. All crop monocultures from 2018 to 2020 were seeded using the desired plant population per ha (AAF, 2018). For combine harvesting, all monocultures were harvested for grain after they had reached physiological maturity stages.

2.3 Soil Measurements

Every year, prior to seeding, soil characteristics were measured. The soil physical properties measured were bulk density [BD: 0-15 cm soil depth, expressed as mass per unit volume of soil (g/cm³)] and water-stable aggregates. Soil samples for water-stable aggregates and biological activities (0-7.5 cm and 7.5-15 cm soil depths), which included microbial activity (CO₂ respiration) and active carbon (AC) were analyzed at the Chinook Applied Research Association's Soil Health Laboratory using the University of Cornell Soil Health protocols (Schindelbeck et al., 2016). Total carbon (TC), total organic carbon (TOC), and total nitrogen (TN) were analyzed at the University of Alberta Natural Resources Analytical Laboratory by combustion elemental analysis (Sparks et al., 2020; Schumacher, 2002). Soil samples were transported in a cooler and stored in a fridge before analysis. Calculation of the amount of soil C density or soil organic carbon (SOC) stock (carbon t ha⁻¹) to 30-cm depth in soil was calculated using SOC concentration (%) and bulk density (g cm⁻³) as per GOWA (2021).

Soil samples for soil chemical properties (at 0-15 cm soil depth) including nitrate-N, P, K, and S, and soil pH and organic matter were shipped to A&L Canada Laboratories Inc., London, Ontario for analysis. Using KCl extraction with the cadmium-reduction, nitrate-N concentration was quantified colorimetrically (Maynard et al., 2008) by an auto-analyzer (Technicon Auto-Analyzer II, Tarrytown, NY). A Mehlich III (Mehlich 1984) extraction was used for S and determination of S was by inductively-coupled plasma atomic emission spectrometry (ICP-OES). Concentration data for N, P, K, and S were converted to content (kg ha^{-1}).

2.4 Plant Measurements

For plant tissue analysis, canola and wheat plant tissue sampling was carried out as per the tissue sampling reference guide provided by A&L Analytical Experts (A&L Canada Lab., 2019). The growth stage for canola was pre-flower to 50% flower with the most recently matured leaf (5th from the top) sampled. Wheat was harvested at the bloom stage and most recently matured leaf sampled. Plant samples were sent to A & L Canada Laboratory for plant tissue analysis. The oven-dried samples were ground into a powder form and passed through a 1 mm sieve. The leaf nitrogen content (expressed as a percentage) was then measured using the Laboratory Equipment Company (LECO) FP628 nitrogen/protein analyzer that uses the total nitrogen combustion method (AOAC, 2006).

Grain yield, grain crude protein (CP), and test weight were measured for canola (year 2) and wheat (year 3). Straw yields and quality were determined for the canola (2019) and wheat (2020). Straw samples were sent to A&L Canada Laboratories for nutritive value.

2.5 Data Analysis

The data was analyzed on a site basis. As the experiment was designed to test the effect of a one-time application of seven CT treatments in year 1 (2018) on subsequent soil nutrients, soil biological activities, and crop grain and residue yields, the crop data in 2019 and 2020 was analyzed separately (on a yearly basis) using a pre-defined model procedure (1-way randomized block) from the CoStat – Statistics Software (version 6.2; CoStat 2005). Soil nutrients (N, P, K, and S) were analyzed using R statistical software (R-Studio, 2021) to determine the appropriate interactions, and CT and depth effects. Where ANOVA indicated significant effects, the means were separated by the least significant difference (LSD) at the 0.05 probability level. Significant differences in the text refer to $P < 0.05$.

3. Results and Discussion

3.1 Canola and Wheat Grain Yields and Protein

In year 2 of the rotation, canola yield differed significantly from prior CTs at both sites (Table 3). At both sites, B_M-C-W produced the highest seed yield (site 1: 2632 kg ha^{-1} , site 2: 2464 kg ha^{-1}), followed by $B_P-C_P-W_P$ with $2296-2352 \text{ kg ha}^{-1}$ at both sites. At site 1, only B_M-C-W and $B_P-C_P-W_P$ produced significantly higher seed yield than control ($P-C-W$), while at site 2, $B_P-C_P-W_P$, B_M-C-W , and CCC_R-C-W clearly showed significantly higher seed yield than control. At site 1, $B_P-C_P-W_P$ and B_M-C-W out-yielded other CTs by $280-1064 \text{ kg ha}^{-1}$ in canola seed yield, while at site 2, the yield differences from both $B_P-C_P-W_P$ and B_M-C-W over other CTs were $56-952 \text{ kg ha}^{-1}$. At site 1, CCC_F-C-W had the least canola seed yield. Unlike site 1, where CCC_G-C-W produced a similar canola yield to control, at site 2, both CTs that had CCC grazed the year before had lower canola seed yield than control. This shows that at both sites, the amounts of manure and urine from the CTs that involved grazing (CCC_G-C-W and $CCC_{SG}-C-W$) might not be substantial enough to provide any positive effect on the immediate subsequent crop. At site 2, four of the CTs (B_M-C-W , CCC_R-C-W , $B_P-C_P-W_P$, and CCC_F-C-W) produced $504-784 \text{ kg ha}^{-1}$ canola seed yield than projected canola yield for the study area (AAF, 2019). At site 1, only B_M-C-W and $B_P-C_P-W_P$ produced a higher canola seed yield than the projected canola yield for the area. With the reduction in inorganic fertilizer application to all CTs in year 2, B_M-C-W was still able to produce $448 - 784 \text{ kg ha}^{-1}$ canola seed yield between both sites.

Wheat grain yield in year 3 of the rotation was influenced significantly by CT at site 1, but this was not the case at site 2 (Table 3). B_M-C-W produced the highest wheat grain yield (5040 kg ha^{-1}). B_M-C-W had had similar ($P < 0.05$) grain yield to both CCC_R-C-W and $B_P-C_P-W_P$, but differed significantly from other CT. Other than B_M-C-W , both CCC_R-C-W and $B_P-C_P-W_P$ had some form of similarity ($P < 0.05$) in wheat grain yield to other CT investigated. At both sites (though treatments were not significantly different from each other at site 2), the control ($P-C-W$) seemed to consistently produce lower wheat grain value than other CT. The wheat grain yield from both B_M-C-W and CCC_R-C-W (though similar to control) at both sites in year 3 clearly indicates the carry-over of residual effects from year 1 from the spread of beef cattle manure and to some extent from CCC rolled as green manure (CCC_G-C-W). At site 1, even with the reduction in inorganic fertilizer application rates

for the different CTs, all CT surprisingly produced more wheat grain yield than the projected yield estimate for the study area (AAF, 2020). B_M-C-W , in particular, produced $\sim 1300 \text{ kg ha}^{-1}$ more yield than projected, followed by both CCC_R-C-W and $CCC_{SG}-C-W$, each with $\sim 875 \text{ ha}^{-1}$. At site 2, only $B_P-C_P-W_P$, B_M-C-W , and CCC_R-C-W seemed to produce some greater yield advantage than projected for the study area.

On a general note, in the present study, we used the continuous grazing method, where animals are allowed to have unrestricted, uninterrupted access to a specific unit of land throughout the entire grazing period of the treatment plots. This was thought to have accounted for the generally less impact (manure not evenly distributed) from both CCC_G-C-W and $CCC_{SG}-C-W$ on the immediate subsequent crop (canola) and even later for wheat in year 3 of the rotation. The greater impact from CCC_G-C-W and $CCC_{SG}-C-W$ would have been found in this study had strip grazing been used for each grazed plot. Strip grazing technique involves utilizing a movable, electric fence to allot enough forage for a short time period and then moving the fence forward providing a new allocation of forage. Strip grazing can increase utilization, decrease animal selectivity and allow even distribution of manure and urine.

Canola seed crude protein (CP) was similar for all CTs at site 1, but differed significantly for CTs at site 2 (Table 3). At site 2, $B_P-C_P-W_P$ had significantly lower canola seed CP than other CTs (except for B_M-C-W and CCC_R-C-W). Why canola seed CP was lower for $B_P-C_P-W_P$ than most CTs at site 2 in this study is difficult to explain.

3.3 Canola and Wheat Straw Yield and Nutritive Value

At site 1, the straw yield was influenced significantly by CTs, while at site 2, canola straw was similar ($P > 0.05$) for all CTs (Table 3). The highest straw yield came from B_M-C-W , followed by $B_P-C_P-W_P$ and then $P-C-W$ at site 1 in that order. The highest straw yield from B_M-C-W was probably a reflection of the higher seed yield produced by these CTs.

Both canola straw CP and energy in the form of total digestible nutrients (TDN) were not significantly affected by prior cropping management implemented in year 1 (2018) in this study at the two sites. The results of canola straw CP show that when integration of crop and livestock is involved and beef cattle are grazed on canola straw, the straw CP at both sites would be adequate and in most cases would be in excess of what a beef cow requires in early pregnancy according to NASEM recommendations (NASEM, 2016). At both sites 1 and 2, the straw TDN was short of meeting the TDN requirements of a beef cow in early pregnancy as recommended by NASEM (2016).

Wheat straw yield did not differ significantly for the CTs at both sites (Tables 3 and 4). Straw CP and TDN were significantly influenced by CTs at site 1 and greatly in favour of $B_P-C_P-W_P$ (8.46% CP, 54.3% TDN) than other CTs. The straw CP at both sites (5.43-9.33% CP) seemed to be sufficient in most cases for a beef cow in early to mid-pregnancy (NASEM, 2016). The straw TDN from both sites ($< 55\%$ TDN) on the other hand was generally below that suggested for a beef cow in early to mid-pregnancy (NASEM, 2016).

Table 3. Seed/grain yield and CP (DM basis), and straw yield and straw CP and TDN (DM basis) for cropping treatments investigated in year 2 (2019, canola crop) and year 3 (2020, wheat crop) at both sites 1 and 2

Cropping treatment	Canola									
	Seed yield		Seed CP		Straw yield		Straw CP		Straw TDN	
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
	Kg ha ⁻¹		%		Kg ha ⁻¹		%		%	
P-C-W	2072c [‡]	1736bc	24.8	22.1a	2442bc	2347	6.56	9.33	42.9	39.44
B _P -C _P -W _P	2352b	2296a	22.8	17.8c	3445ab	2709	6.26	6.64	41.9	36.92
B _M -C-W	2632a	2464a	23.2	20.4abc	3691a	3312	7.17	7.17	44.2	36.97
CCC _G -C-W	2072c	1624c	23.8	21.8a	2377c	2339	6.68	9.21	40.7	41.64
CCC _F -C-W	1568d	2184abc	23.2	22.3a	2191c	2658	8.12	7.95	44.2	39.21
CCC _R -C-W	NA	2240a	NA	18.8bc	NA	3224	NA	8.12	NA	37.17
CCC _{SG} -C-W	1624d	1512	24.4	21.4ab	2552c	2321	7.31	7.82	42.7	38.26
CV [§] , %	4.50	13.7	5.74	8.04	24.2	19	15.6	11.3	6.55	6.23
Cropping treatment	Wheat									
	Grain yield		Grain CP		Straw yield		Straw CP		Straw TDN	
	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
	Kg ha ⁻¹		%		Kg ha ⁻¹		%		%	
P-C-W	4032bc	2352	18.7	12.83	2597	1415	7.07c	9.33	50.9c	39.4
B _P -C _P -W _P	4166bc	2890	18.2	9.86	2163	1340	8.46a	6.63	54.3a	36.9
B _M -C-W	5040a	3091	18.3	11.23	2897	1431	6.73d	7.17	51.5c	36.9
CCC _G -C-W	4634ab	2486	19	10.55	2178	1184	5.43g	9.2	45.0e	41.6
CCC _F -C-W	3629c	2755	18.4	10.8	2572	1585	7.40b	7.95	53.6b	39.2
CCC _R -C-W	4637ab	2890	19	10.01	2197	1485	6.18f	8.11	47.6d	37.2
CCC _{SG} -C-W	3898c	2419	18.6	10.63	2189	1260	6.55e	7.82	51.3c	38.2
CV, %	8.85	22.9	5.14	6.76	24.3	22	1.35	14.1	0.62	4.50

[§]CV, coefficient of variation.

[‡]Within a particular column, means followed by the same letter are not different according to LSD at P = 0.05.

[‡]NA, data not available.

3.4 Plant Tissue

In year 2, at site 1, only canola plant tissue P, Ca, and Zn of the thirteen minerals (N, P, K, Ca, Mg, S, Zn, Mn, Fe, Cu, B, Al, Na) were analyzed for here in the present study showed significant differences for the CTs investigated, while no canola plant tissue was impacted at site 2 (full data not presented). At site 1, B_M-C-W had the highest plant tissue P and the lowest level of plant tissue Zn for canola. Marschner (2011) reported that increases in the levels of P in the plant tissue could lead to a decrease in Zn uptake. Both CCC_F-C-W and CCC_{SG}-C-W had similar plant tissue Ca to P-C-W, but significantly higher than others. Going by the critical nutrient levels recommended by Holmes (1980) and Schwab et al. (2007) for annual crops, at site 1, canola tissue was deficient in N (<3.99% N) for P-C-W, CCC_F-C-W and CCC_{SG}-C-W. All CCC CTs in year 2 had insufficient Cu (<4 ppm). In general, all CTs were deficient in B (<29 ppm) and K (<2.79% K). Other minerals measured here were mostly well within the critical nutrient levels for canola (year 2). For canola in year 2 at site 2, nutrients in plant tissue were as follow: Cu was deficient in all CTs (<4 ppm Cu), B was adequate only in P-C-W (control) and CCC_G-C-W, while Na was only deficient in B_M-C-W (<0.11% Na).

In year 3, only wheat plant tissue Ca, Mg and Zn differed for the CT (data not shown). B_M-C-W had the highest plant tissue P. P-C-W (control) had the highest K. Plant tissue Ca and Zn were higher for cropping treatments that had peas and CCC (regardless of the use of the CCC) in year 1 than both CTs that had barley seeded in year 1 (B_P-C_P-W_P and B_M-C-W). The highest level of Zn uptake was done by the CCC_G-C-W cropping system regardless of the crop (canola or wheat). This seems to suggest that peas or CCC might improve Ca and Zn availability for the benefit of subsequent crop production. This observation was also reflected in year 3 with wheat plant tissue (except for Zn with B_P-C_P-W_P). CTs did not impact plant tissue minerals at site 2 in year 3. In year 3, the wheat nutrient uptake was adequate for all CTs but deficient for Cu (<4ppm) for P-C-W. It is important to note that the nutrient concentration that is considered adequate will change as the plant grows and matures.

3.5 Soil Properties

Soil nutrients were impacted by CT x year interaction effects at both sites. In the year following application, at site 1, B_M-C-W produced significantly higher soil N, P, K and S than others (Figures 1-4). At site 2, B_M-C-W also produced the higher soil N (Figure 5), while CCC_R-C-W had the most soil P and K (Figures 6 and 7). Except for B_M-C-W and CCC_R-C-W (in a few cases), in general, at both sites, soil N and P availability had a pattern of

increasing their availability for year 2 but decreasing to below their initial levels of year 1. The manure treatment (B_M-C-W) in year 3 had soil N and P levels that were similar to year 1. The generally higher soil N, P, K, and S levels observed for all CTs in year 2, particularly for soil N and P seems to suggest that soil N and P credits were most apparent to the year following the implementation of CTs examined here (bio-stimulants, manure application, CCC for green manure, and grazing of CCC) compared with the control crop rotation. At site 1, soil K availability was particularly influenced by the first year manure application treatment (B_M-C-W) which doubled its initial content (year 1) and remained remarkably similar for the following two years. It is important to state here that the inclusion or integration of CCC with grazing or when used for green manure reduced the amount of soil N and P depletion over the duration of this study at site 2. This shows that crop-livestock integration or the use of CCC for green manure would greatly benefit the producers in terms of reduction in-organic fertilizer application over most of the other cropping systems. As stated earlier in this paper, strip grazing would have been ideal for maximizing the impact of both grazed CCCs and the residual soil N and P would have been much more significant than obtained in the present study. Future research studies aimed at planned strip grazing to investigate yearly fertility savings and cost: benefit ratio for subsequent crop production on a short and long-term basis are needed.

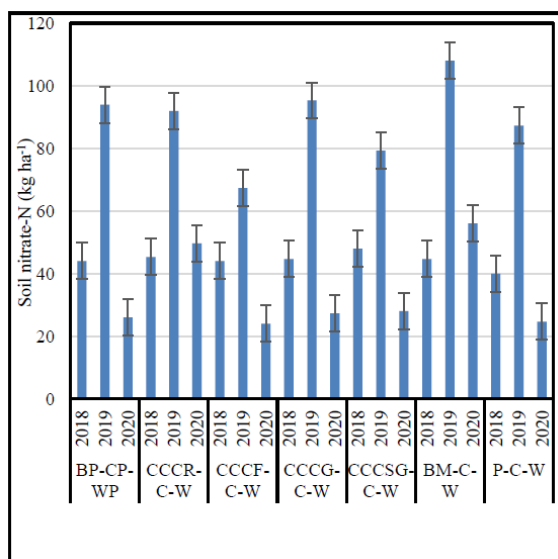


Figure 1. Soil nitrate-N for cropping treatments at site 1 for 3 years

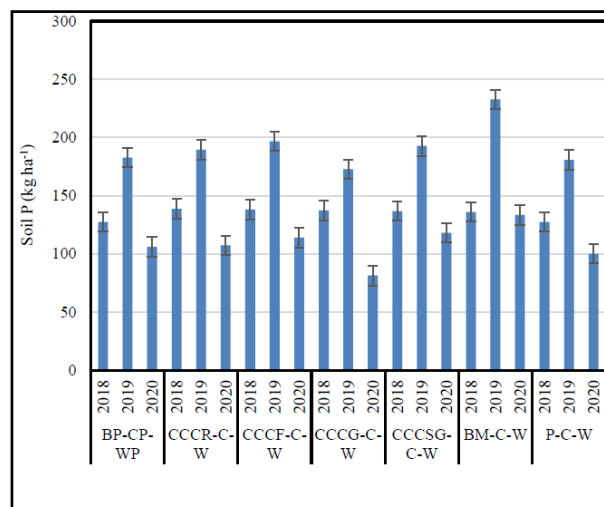


Figure 2. Soil P cropping treatments at site 1 for 3 years

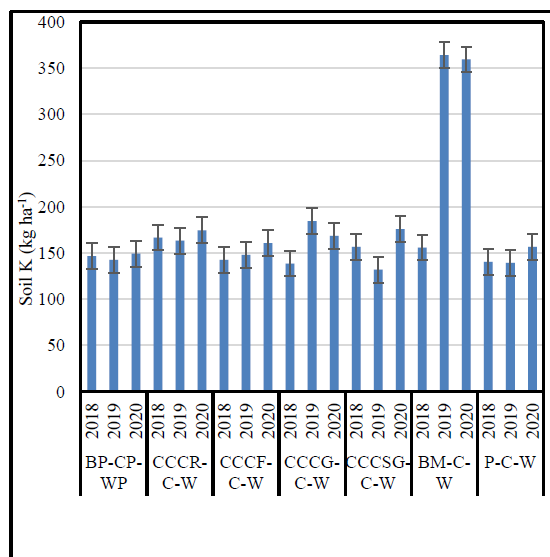


Figure 3. Soil K for cropping treatments at site 1 for 3 years

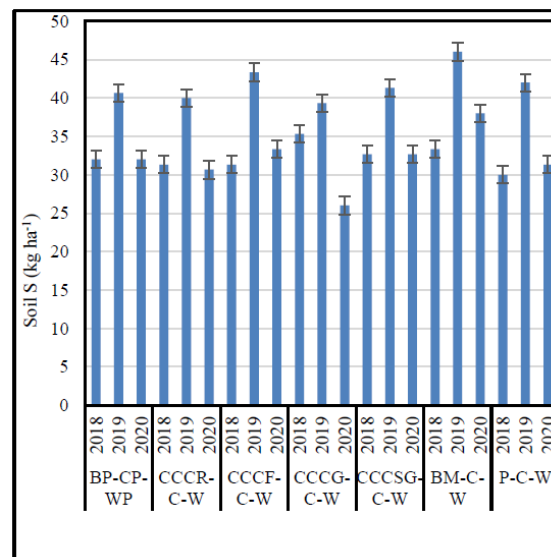


Figure 4. Soil S for cropping treatments at site 1 for 3 years

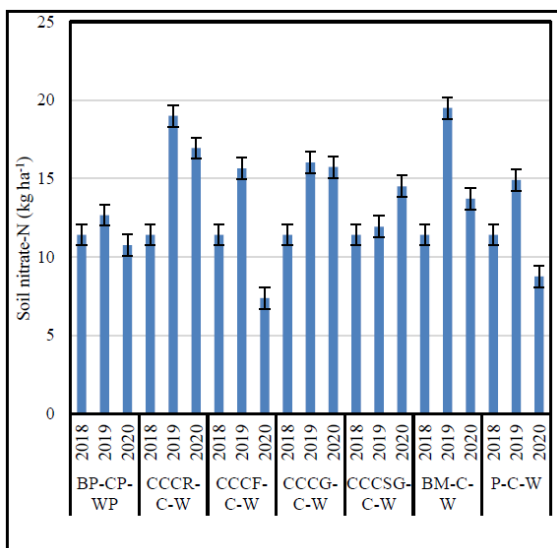


Figure 5. Soil nitrate-N for cropping treatments at site 2

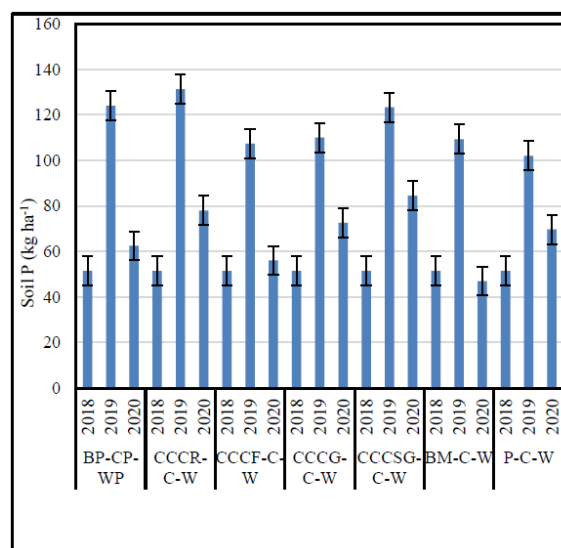


Figure 6. Soil P for cropping treatments at site 2 for 3 years.

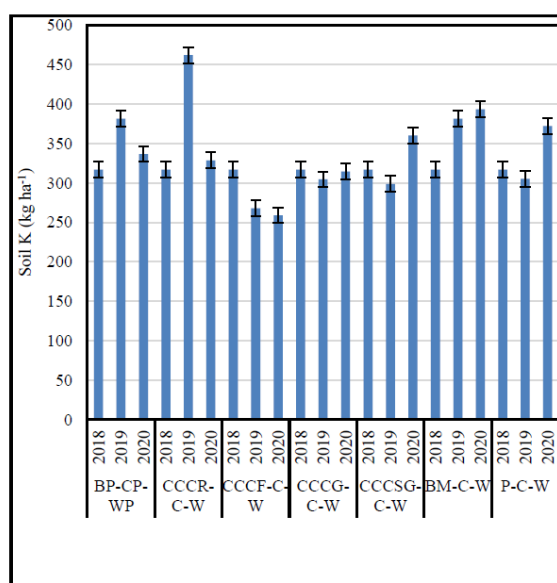


Figure 7. Soil K for CT cropping treatments at site 2 for 3 years

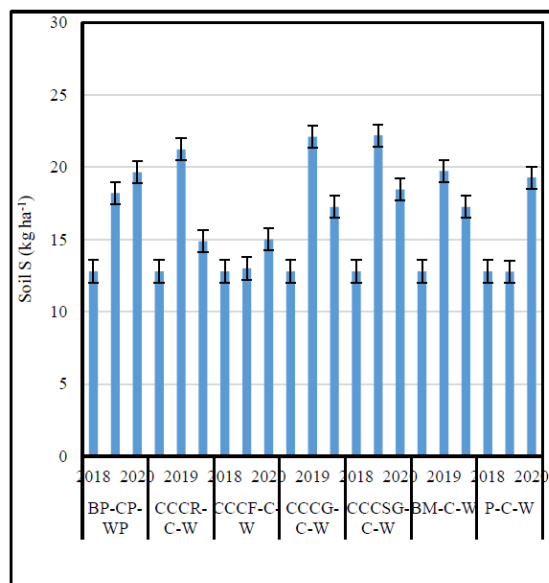


Figure 8. Soil S for cropping treatments at site 2 for 3 years

3.6 Soil Quality Characteristics and Biological Activities

CT was not significantly different for surface SOM and pH, as well as all the following soil physical and biological activities: BD, SOC, TN, and TC (data not shown).

For the SWAggr, AC, and SMResp, which were examined at two soil depths (0-7.5 and 7.5-15.0 cm), there were no significant CTs by soil depths interactions at both sites. The CTs did not have significant impacts on SWAggr, AC, and SMResp at each site. However, both AC and SMResp were influenced ($P < 0.05$) by soil depths at both sites, but not SWAggr in any of the sites. As expected, AC and SMResp were consistently higher at 0-7.5 cm than 7.5-15.0 cm at both sites (Table 4). The higher AC in 0-7.5 cm at both sites indicates a trend toward more SOM building up in the soil through biological activity (Hoffland et al., 2020; Obalum et al., 2017). The higher SMResp in the 0-7.5 than 7.5-15.0 cm is an indication of presence of a larger, more active soil community (Hoffland et al., 2020). Surprisingly, SMResp values were similar for both sites at each examined soil depth. With the exception of SMResp, in general, all soil characteristics measured here were higher in values at site 1

than site 2.

Table 4. Means of SWAggr, AC and SMResp for cropping treatments and soil depths for both sites 1 and 2

Cropping treatment	Site 1								
	SWAggr			AC			SMResp		
	0-7.5 cm	7.5-15 cm	Mean	0-7.5 cm	7.5-15 cm	mean	0-7.5 cm	7.5-15 cm	mean
P-C-W (C)	33.5	30.4	32.0a	472	385	429a	0.72	0.48	0.60a
CCC _G -C-W	29.9	27.8	28.9a	445	370	408a	0.7	0.51	0.61a
CCC _R -C-W	27.1	28.3	27.7a	482	335	409a	0.72	0.44	0.58a
BM-C-W	29.3	24.5	26.9a	456	332	394a	0.71	0.48	0.60a
CCC _{SG} -C-W	27.1	30.5	28.8a	461	343	402a	0.74	0.48	0.61a
CCC _F -C-W	28.6	31.2	29.9a	410	315	363a	0.65	0.46	0.56a
B _P -C _P -W _P	28.2	23.1	25.7a	427	348	388a	0.7	0.48	0.59a
Mean [†]	29.1a	28.0a		450a	347b		0.71a	0.48b	

Cropping treatment	Site 2								
	SWAggr			AC			SMResp		
	0-7.5 cm	7.5-15 cm	Mean	0-7.5 cm	7.5-15 cm	mean	0-7.5 cm	7.5-15 cm	mean
P-C-W (C)	23.8	21.2	22.5a	259	235	247a	0.63	0.38	0.51a
CCC _G -C-W	20	18.2	19.1a	281	216	249a	0.74	0.48	0.61a
CCC _R -C-W	24.6	24.3	24.5a	279	176	228a	0.72	0.48	0.60a
BM-C-W	22.2	22.9	22.6a	232	147	190a	0.67	0.68	0.68a
CCC _{SG} -C-W	22	24.4	23.2a	257	169	213a	0.74	0.51	0.63a
CCC _F -C-W	22.8	22.3	22.6a	214	149	182a	0.8	0.64	0.72a
B _P -C _P -W _P	21.1	28.6	24.9a	223	171	197a	0.6	0.44	0.52a
Mean [†]	22.4a	23.1a		249a	180b		0.70a	0.51b	

[†]Within a particular soil parameter, means followed by the same letter in the same row are not different according to LSD at P = 0.05.

4. Conclusion

The evaluation of mixed crop-livestock systems during a 3-year period gave an indication of the potentiality of these systems to minimize the use of chemical fertilizer inputs for annual crops. Canola yields were significantly influenced by prior CTs at both sites. Three of the top yields over control (P-C-W) were for treatments: B_M-C-W, B_P-C_P-W_P, and CCC_R-C-W. Canola straw CP and TDN can also be considered for utilization in these ecosystems. But their use will depend on what kind of livestock production is targeted. The effect of the first year was more pronounced on wheat grain yield at site 1 than site 2. At site 1, manure (B_M-C-W) produced high wheat grains, and was statistically similar to 2 of the CCC (CCC_G-C-W and CCC_R-C-W). Wheat grain protein for the overall study was not influenced by the cropping system. Site 1 had a higher percentage of protein (18.6%) than site 2 (10.8 %). Soil P levels at both sites for B_M-C-W had a higher level of soil P for year 2. A crop-livestock integration or the use of CCC for green manure would have great benefit to producers in terms of savings in fertility cost for canola and wheat production over most of the other cropping systems. More studies need to be carried out to evaluate the appropriate cropping system to target specific constraints in the soil.

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