European Journal of Agronomy 121 (2020) 126155

Contents lists available at ScienceDirect

European Journal of Agronomy

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

Rotational benefit of pulse crop with no-till increase over time in a semiarid climate

Jianling Fan[a], Brian G. McConkey[b,*], Mervin St. Luce[b], Kelsey Brandt[b]

[a] Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, 219 Ningliu Road, Nanjing, 210044, China

[b] Swift Current Research and Development Centre, Agriculture and Agri-Food Canada, Swift Current, SK, S9H 3X2, Canada

ARTICLE INFO

Keywords:
No-till
Crop rotation
Yield
Water use efficiency
Nitrogen use efficiency
Soil organic carbon

ABSTRACT

Water deficit is the major constraint to crop production in dry temperate climates and no-till (NT) has been widely recommended to increase water conservation, crop yields, and soil organic carbon (SOC) content. In this study, tillage practice [conventional tillage (CT), minimum tillage (MT), NT and annually alternating tillage with NT (NT/MT)]] and crop rotation [fallow-wheat (*Triticum aestivum* L.; FW), continuous wheat (CW), and wheat-pulse (WP) rotation] effects were investigated in a long-term experiment over three decades. Although NT increased soil water conservation and water use efficiency (WUE) compared to CT and MT, wheat yields were not higher for NT during the first 13 years when nitrogen (N) fertilizer was broadcast in the soil. After 1996, when N fertilizer was side-banded during seeding, CW-NT had 6% higher yields than CW-MT although not significant. The mean yield of pulse crops was 14 % higher for NT than MT, where the greatest yield benefit was found in warmer and drier years so NT is also adaptation to weather variability. The yield advantage of wheat after pulse in WP compared to CW increased by 41 kg ha^{-1} yr^{-1} ($P < 0.001$), indicating that the benefits of pulse crop on wheat production increases with time. Annual grain N uptake was greater in WP than CW or FW and greater for NT than MT for WP. The biennial tillage in CW-NT/MT benefitted the wheat yield in the following NT year so that it was greater than those of both CW-MT and CW-NT in those years. The rankings of SOC stock to 15 cm or 30 cm were generally the same as to 7.5 cm but differences were only significant to 15 cm in some samplings and only a trend ($P < 0.10$) was detected to 30 cm after 29 years. Unexpectedly, the CW-NT/MT had the highest SOC stocks and such regular periodic tillage warrants further investigation. The pulse-wheat rotation under NT was the best cropping system for achieving a combination of efficient use of fertilizer N and high annual crop yield and quality, for which the benefit of pulse in rotation increases over time.

1. Introduction

Agricultural ecosystems need to feed a growing and more demanding world population (Foley et al., 2011; Godfray and Garnett, 2014), while contributing to mitigation of greenhouse gas emissions (Paustian et al., 2016). Conservation agriculture (CA), involving minimal soil disturbance, especially no-till (NT), permanent crop residue retention or cover crop, and crop rotation with diversified crops, has been shown to be an effective practice to reduce soil erosion risk and energy consumption, improve soil quality and ensure food security (Lal, 2004; Montgomery, 2018).

In dry temperate climates without irrigation, water is usually the greatest limitation on productivity so water conservation benefits of crop residue retention with NT often increases productivity (Cutforth et al., 2011; Giambalvo et al., 2012; Carefoot et al., 1990; Brandt, 1992). From their global meta-analysis, Pittelkow et al. (2015) found that NT overall decreases crop yields by 5.7 %, although it produces equivalent, and, specifically in dry rainfed situations, greater yields than conventional tillage systems (CT). Recently, Gristina et al. (2018) found that the relative ratio of durum wheat (*Triticum turgidum* L) yield under NT compared with CT was linearly related with aridity index, where relative yield was higher with NT when the aridity index was lower than 0.55. However, there are many observations where no-till has resulted in equal productivity to tilled cropping systems (Fan et al., 2018a; López-Fando and Almendros, 1995; McConkey et al., 1996; Sainju et al., 2017). Compared with tilled systems in these climates, NT can have some negative effects on yields including occasionally resulting in excessively wet soils for planting (Seddaiu et al., 2016),

---

[*] Corresponding author.
E-mail address: brian.mcconkey.agr.gc.ca@gmail.com (B.G. McConkey).

https://doi.org/10.1016/j.eja.2020.126155
Received 16 January 2020; Received in revised form 28 July 2020; Accepted 3 August 2020

reduced nitrogen (N) uptake attributed to less N mineralization from organic matter (McConkey et al., 2002), and inadequate weed control (Giambalvo et al., 2012; Machado et al., 2008). The effect of NT on productivity is not only critical to food production but also to carbon (C) input to the soil.

Traditionally, cereals have dominated crop rotations in dry temperate climates, but crop diversification with CA provide important productivity benefits (Álvaro-Fuentes et al., 2009; Burgess et al., 2012). Pulse crops (i.e. legumes grown for their dry, non-oily seed) in rotation with cereals have been shown to increase economic returns (Khakbazan et al., 2009; MacWilliam et al., 2014), soil quality (Laudicina et al., 2014; Liebig et al., 2006; Masri and Ryan, 2006), and cropping system productivity (Burgess et al., 2012; Fan et al., 2018b; Gan et al., 2015; Khakbazan et al., 2009; López-Bellido et al., 1997; MacWilliam et al., 2018; Melero et al., 2008; Miller et al., 2003; Sainju et al., 2006).

Conservation agriculture has been widely recommended as a potential way to mitigate climate change by sequestering atmospheric C as soil organic C (SOC) (Lal, 2015; UNEP, 2013). Increases in SOC with CA have been mostly attributed to differences in C input from crop residues (Campbell et al., 2007; Engel et al., 2017; Maillard et al., 2018; Shrestha et al., 2013). In dry temperate climates, bare fallow is common in conventional non-CA cropping systems and, compared to crop-fallow, continuously cropped rotations have higher C input to the soil leading to about 200–250 kg C ha^{-1} increase in SOC stocks for each additional Mg C ha^{-1} input in the North American Great Plains (Campbell et al., 2005). Pulses produce less residue than cereals so usually the diversification from monoculture cereals to diversified rotations with cereal and pulses under CA reduces SOC (Laudicina et al., 2014; Maillard et al., 2018; Sainju et al., 2006) although Mohammad et al. (2012) found SOC was increased by include a pulse crop in rotation with wheat. The effect of NT, a central practice of CA, on SOC stocks is not consistent (Powlson et al., 2014; VandenBygaart, 2016). Some studies have shown that SOC stocks increase in upper 15 − 20 cm in NT compared to conventional minimum tillage (Farina et al., 2011; Laudicina et al., 2014; Maillard et al., 2018; McConkey et al., 2003; Melero et al., 2008; Mohammad et al., 2012) while other studies show no significant difference between NT and tilled systems (Sainju et al., 2015, 2011; Shrestha et al., 2013).

Meeting N demand efficiently with low N losses is a critical challenge for the food production system that will be difficult to address (Conijn et al., 2018). The role of CA on N cycling are complex, variable, and can change with the duration of CA (Grahmann et al., 2013). In the short term, the immobilization of N with crop residues can decrease nitrogen use efficiency (NUE) compared to conventional systems and increase need for higher mineral N additions to maintain yields (Grahmann et al., 2013). In the longer term, CA will increase potentially mineralizable N (Mahal et al., 2018) and can reduce losses of N in mineral forms from leaching, so that uptake of N fertilizer is lower than conventional systems (Meena et al., 2016). Diversification with pulse crops within CA is also important since that has been shown increase available N for non-legume crops in the rotation (Miller et al., 2003; Sainju et al., 2018; Williams et al., 2014).

The objectives of this study was to investigate how the components of conservation agriculture, continual crop cover (no bare fallow + NT), minimal disturbance (NT), and adding diversification (from monoculture cereal to cereal-legume rotation), act individually and together as conservation agriculture system on crop productivity, water use efficiency (WUE), N status, and SOC in a Vertisol in a semi-arid, temperate climate over three decades (1982–2011).

2. Material and methods

2.1. Site and experiment description

The experiment was conducted at Stewart Valley, Saskatchewan, Canada (50°36´N, 107°48´W). The climate, as recorded from a weather station located in the Swift Current, 50 km S of the study site, is semi-arid, with 30-year mean annual temperature of 3.3 °C and annual precipitation of 334 mm. The soil is Sceptre clay, with 42.7 % clay, 31.6 % silt, and 25.7 % sand, and classified as Vertisol under the Canadian system and as Haplic Vertisol under the FAO system [note in papers covering the early results of this study (Campbell et al., 1996; McConkey et al., 1996, 2003; Tessier et al., 1990) the soil was referred to as Chernozemic because the Vertisolic soil order was introduced into Canadian soil classification after study started (Soil Classification Working Group, 1998)]. The topsoil (A horizon) is 8 cm deep over undifferentiated clay parent material (C horizon) (Ayres et al., 1985). The soil (0–8 cm) prior to the initiation of the experiment had a pH of 7.0, bulk density of 1.28 g cm^{-3}, and contained 16 g kg^{-1} organic C.

The experiment was initiated in 1982 on wheat stubble as a randomized complete block design with three replicates and a plot size of 15 × 30 m. In the previous 60–80 years, the land was managed in a fallow-wheat rotation using CT methods, which was the predominant farming system in the region. Initially, four cropping systems were implemented with monoculture spring wheat (*Triticum aestivum* L.); fallow-wheat (FW) rotation under two levels of tillage (MT: minimum tillage; NT: no tillage) and continuous wheat (CW) rotation under MT and NT. Both rotation phases for FW rotation were present each year.

A FW-CT system was added in 1990 on a former FW-NT treatment that had been seeded with a different seed drill than the reported system. A CW-NT/MT system was added in 1995 on an unreported CW-NT treatment that had been seeded with same seed drill used in the CW-CT and CW-MT systems. The CW-NT/MT had biennial tillage – it was MT in odd years and NT in even years. In 1996, the FW-MT system was converted to wheat-pulse (WP)-MT rotation, while FW-NT was converted to WP-NT rotation. Both rotation phases were present each year and the pulse crop rotated between lentil (*Lens culinaris* Medik.; in 2000, 2001, 2003, 2006, 2007, 2010, and 2011), chickpea (*Cicer arietinum* L.; in 1998 and 1999), and pea (*Pisum sativum* L.; in 1996, 1997, 2002, 2004, 2005, 2008, and 2009) so that the same pulse type was on one plot no more frequently than one year in four. Cultivars for all crops were chosen based on annual recommendations by Saskatchewan Ministry of Agriculture and changed throughout the study.

Commercially available machinery was used to perform all field operations with exception of NT seeding prior to 1996 that used a research NT drill (Dyck and Tessier, 1986). All land, whether being fallow or cropped the next year, received an application of 2,4-D ester in October to control winter annual broadleaf weeds.

The fallow phase of FW-CT had two to four tillage operations for weed control during over the late May to early September period using a heavy duty cultivator. The fallow phase of the FW-MT had an application of glyphosate, in a mixture with 2,4-D or Dicamba, in late May or June plus one to three tillage operations over July to early September. The tillage depth for CT and MT was 5–8 cm. The fallow phase of the FW-NT system had two to four applications of glyphosate, in a mixture with 2,4-D or Dicamba. For all the fallow phases, the number and timing of herbicide applications and/or tillage operations varied by year based on weather-related need to have good weed control over the growing season of May to September.

During the crop phase of the rotations, under the CT and MT tillage systems, there was a single pre-seeding tillage operation with cultivator and mounted spring-tooth harrows to 5 − 8 cm depth. Up to 1996, The NT systems were seeded with a research offset-disc seed drill while the CT and MT systems were seeded with a hoe-press drill. For 1996 onwards, all tillage systems were seeded with a commercial NT drill having 5 cm wide knives with seed and fertilizer conveyed to the knives by air through tubing (Flexi-Coil 5000, Flexi-Coil, Saskatoon, Saskatchewan). All crops were seeded 2.5–5 cm deep. Seeding rates were 67, 75, 120, and 80 kg ha^{-1} for wheat, chickpea, lentil and pea, respectively.

The rate of N fertilizer for wheat was based on a target of the total of fertilizer N + soil NO_3^--N to 60 cm from fall sampling equal to 65 kg ha^{-1} before 1990 (Saskatchewan Agriculture, 1985) and to 90 kg ha^{-1} from 1990 onward (Saskatchewan Soil Testing Laboratory, 1990). Before 1996, fertilizer N was applied as ammonium nitrate, with up to 45 kg N ha^{-1} seed placed and the remainder, if any, broadcast before any spring tillage. From 1996 onwards, N was applied with the seeding operation as urea and was side-banded 2.5 cm below and 2.5 cm to the side of the seed row. Throughout the study, wheat and pulse crops had recommended annual application of 10 kg P ha^{-1} as mono-ammonium phosphate that was seed-placed. Consequently, although N was not recommended for pulse crops, they received 5 kg N ha^{-1} with the fertilizer P. Each year, the pulse crops had a recommended rhizobium inoculant applied as peat-based formulation adhered to the seed. In general, the annual N fertilizer application rates in FW were about 1/3 of the corresponding values in CW systems while those for WP were about 1/2 of CW.

In-crop herbicides were applied in June based on weed situation and according to annual recommendations in the crop protection guide (Government of Saskatchewan, Regina, SK); the herbicides thus varied over the duration of experiment. For practical reasons, all plots in the same crop received the same in-crop herbicide application in any one year. The wheat received a selective herbicide for grassy weed control, often in a mixture with an herbicide for broadleaf weed control. The pulses received an herbicide for control of grassy weeds. Chickpea received prophylactic foliar applications of the fungicide, chlorothalonil, in late June and again in July to control ascochyta blight caused by *Didymella rabiei.* Foxtail barley (*Hordeum jubatum* L.) became a problem in CW-NT only (Hume et al., 1991) and this weed was believed to decrease the agronomic performance of that system compared with CW-MT (McConkey et al., 1996). From 1996 onwards, this perennial weed was effectively controlled with a post-harvest application of glyphosate every two to four years as necessary. Other than foxtail barley for CW-NT before 1996, weeds or diseases were judged to be not important agronomic factors nor important to differences between rotations or tillage systems.

Up to 1996, grain yield was determined at crop maturity from three manually harvested 1 m^2 quadrats and, thereafter, from a 1.5 × 10 m area harvested with a plot combine. Grain samples were analyzed for grain protein, which were determined as 0.57 × Kjeldahl N (Kirk, 1950) from 1981 to 1998 and by near infrared reflectance spectrophotometry (Dalal and Henry, 1986) afterward. After yield sampling, the plots were harvested with full-size combine that also chopped and spread the crop residues over the plot area. The amount of crop residue after harvest, including stubble, was determined by manual samples regularly to 1993 and intermittently afterward by taking five 0.5 m^2 samples per plot, removing soil in the sample by washing in a water bath, and determining remaining mass after drying at 60 °C for 16–24 h.

2.2. Soil sampling and organic carbon analysis

Soil samples were collected in November 1982, April 1986, April 1990, October 1993, April 1998, October 2003, October 2007, and October 2011. For 1982, three 2-cm core samples were taken randomly per plot and composited for the 0–15 and 15–30 cm depths. For 1986, 1990, and 1993 samplings, six 4-cm soil cores for 0–7.5 and 7.5–15 cm were taken randomly over each plot, with at least 5 m between sampling locations, and composited by depth. For 1982–1993, three additional 5-cm soil cores per plot were randomly taken for bulk density determination using the method described by Tessier and Steppuhn (1990). The mean of all the bulk density samples within a plot was used as the plot mean. For 1998, 2003, 2007, and 2011 samplings, three 7.5-cm soil cores were taken per plot for depths of 0–7.5 cm, 7.5–15 cm, and 15–30 cm and composited by depth. The WP rotation systems were not sampled in 1998. The sampling location was random except, for 1998–2011 sampling, when one core was on the previous crop row and the other two were somewhere between the rows, which approximately took soil from the entire row width as crop row width was 23 cm. For 1998–2011 sampling, the samples were composited by depth and the bulk density was also determined for the same samples based on the moisture content of a subsample determined by drying for 16 − 24 h at 105 °C.

The soil samples were air dried and sieved (2 mm) by hand and large residue pieces and the rare stone larger than 2 mm was removed by hand. A representative subsample of the soil was ground in a roller mill (< 153 μm) and analyzed for organic C by an automated dry combustion technique (Carlo Erba™, Milan Italy). To remove carbonates, soil samples were pre-treated with phosphoric acid in a tin capsule after weighing, then drying the sample for 16 h at 75 °C prior to analysis for C.

For each soil layer, the total organic C stock (Mg ha^{-1}) was computed by multiplying the C concentration (g kg^{-1} soil) by the layer thickness and the respective bulk density. To account for the possible changes in bulk density as a result of crop rotation and tillage practices, the C stock was calculated on an equivalent soil mass basis (Ellert et al., 2007). The soil equivalent masses were set to the mean of the observation for the respective 0–7.5, 0–15, and 0–30 cm soil layers and the correction of C stock involved either adding soil mass from the lower depth or subtracting soil mass for the current depth as required to obtain total mass equal to the mean equivalent mass.

The total C input to the soil from above-ground and below ground crop residue was calculated from measured grain yield using published relationships (Thiagarajan et al., 2018).

2.3. Environmental variables measurements

Gravimetric soil water content to 120 cm was measured before seeding in spring from 1983 to 2011. The precipitation and air temperature were monitored with an automatic weather station in the Swift Current, Saskatchewan, Canada. Aridity index (AI) (Cherlet et al., 2018) was calculated as annual precipitation divided by annual potential evapotranspiration, which was calculated according to FAO's Penman-Monteith ET approach (Allen et al., 1998).

2.4. Water use efficiency

To address water use efficiency (WUE) for crop production, WUE (kg ha^{-1} mm^{-1}) was calculated as:

$$WUE = \frac{Y_G}{(W_p - W_h) + GSP}$$

where Y_G is the grain yield (kg ha^{-1}), W_p and W_h are the soil water at planting and at harvest (mm 30 cm^{-1}), respectively, and *GSP* is the growing season precipitation (mm), calculated as that from 1 May to 31 July as precipitation over that period is most important to crop growth in this region (Campbell et al., 1988). However, WUE does not take into account the water that is not used during the summer fallow phase because yield is zero (Kröbel et al., 2012). Therefore, precipitation use efficiency (*PUE*, kg ha^{-1} mm^{-1}) is an effective way to compare WUE between different cropping systems with and without summer fallow in rotations and was calculated as below:

$$PUE = \frac{Y_G}{P}$$

where Y_G is the grain yield (kg ha^{-1}), P is the precipitation (mm) from harvest to harvest.

2.5. Nitrogen use efficiency

N fertilizer use efficiency (FUE) and available N use efficiency (NUE) were calculated to estimate N use efficiency for crop grain production. The FUE (kg^{-1} kg^{-1}) was calculated as:

$$FUE = \frac{Y_G}{Fertilizer\ N}$$

where Y_G is the grain yield (kg ha^{-1}), and fertilizer N (kg N ha^{-1}) is the amount of fertilizer N added. The NUE of grain production (kg^{-1} kg^{-1}) was calculated by including spring NO_3-N and apparent net N mineralization (ANM) in addition to N fertilizer applied as described below:

$$NUE = \frac{Y_G}{Fertilizer\ N + Soil\ NO_3 + ANM}$$

where Y_G is the grain yield (kg ha^{-1}), fertilizer N (kg N ha^{-1}) is the amount of fertilizer N added, soil NO_3 is the soil NO_3-N (0 − 30 cm; kg N ha^{-1}) measured before planting, and ANM (kg N ha^{-1}) is the apparent in-season net N mineralization calculated as below:

$$ANM = (crop\ uptake + harvest\ soil\ N_{a,b}) - (spring\ soil\ N + N\ fertilizer)$$

where crop uptake (kg N ha^{-1}) is total above-ground crop N uptake, harvest soil $N_{a,\ b}$ (0 − 30 cm; kg N ha^{-1}) is soil NO_3-N measured soon after crop harvest (a = crop phase) or in late fall (b = fallow phase), spring soil N (0 − 30 cm; kg N ha^{-1}) is soil NO_3-N measured before planting and fertilizer application, and N fertilizer (kg N ha^{-1}) is the amount of fertilizer N added. For the fallow phase, crop N uptake and fertilizer N added were set to zero. For the pulse phase, ANM includes fixed N during the growing season.

2.6. Statistical analysis

The effects of crop rotations and tillage practices on soil water content, crop yield, wheat grain protein content, WUE, PUE, FUE, NUE, and SOC stocks were analyzed for each year using mixed effects model by the "*lme4*" R package (Bates et al., 2015), where crop systems were considered as fixed effect and blocks were considered as random effect. When multi-year comparison was conducted, year was treated as random effect as well. Tests of contrasts were used to further compare the crop rotations and tillage systems by using the "*multcomp*" R package (Hothorn et al., 2008). A *post-hoc* comparisons of crop variables between NT and MT or CT under the same rotation were performed via multiple comparison tests with a Tukey's adjustment of *P*-values, using the "*lsmeans*" R package (Lenth, 2016). All treatment effects were considered significant at $P < 0.05$. The natural logarithm of yield relative ratio (*LnRR*) was calculated as the ratio between NT and MT yields (Hedges et al., 1999) to evaluate the relationship between NT yield advantage and climate variables. All statistical analyses were performed with the R software (R Core Team, 2019).

3. Results

3.1. Environment variables

The annual precipitation during 1982–2011 was in the range of 189 − 639 mm, where ~49 % occurred in the growing season (1 May to 31 July, Fig. 1). Annual mean air temperature ranged from 1.6 °C in 1996 to 6.7 °C in 1987, while growing season temperature ranged from 13.0–18.6 °C with an average of 14.9 °C. Averaged AI (0.48) was less than 0.5, indicating a semiarid climate (Cherlet et al., 2018), with only four years meeting a humid classification of AI > 0.65 (1993, 1995, 2002, and 2010).

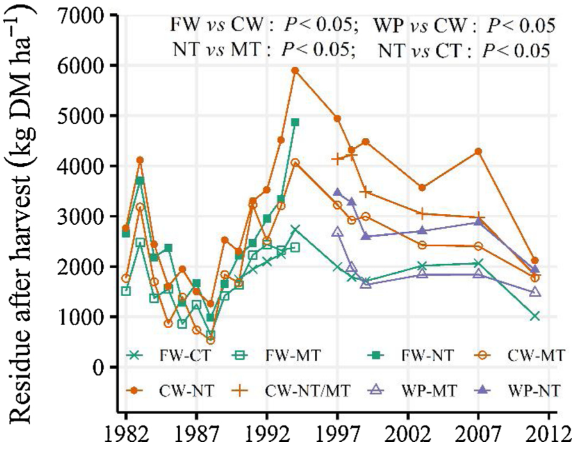

Fig. 2. Crop residue after harvest (kg DM ha^{-1}) from 1982 to 2011. (FW-CT was implemented in 1990).

Crop residue after harvest on the soil surface was significantly affected by both rotation and tillage (Fig. 2). The 1982–2011 average residue amounts under CW (2538 kg DM ha^{-1}) were 20 % and 50 % higher than FW and WP respectively ($P < 0.05$). Furthermore, NT (2768 kg DM ha^{-1}) showed 49 % and 92 % higher crop residue than MT and CT respectively ($P < 0.05$).

Generally, all treatments showed similar temporal variation of soil water content (Fig. 3), which was mainly driven by annual weather. Soil water content was significantly higher under FW rotations than CW ($P < 0.05$) for both the 0 − 30 and 30 − 120 cm depths. There was no significant difference ($P > 0.05$) between WP and CW rotations in 0 − 30 cm but WP had higher ($P < 0.05$) soil water than CW for 30 − 120 cm. NT increased soil water content for both the 0 − 30 and 30 − 120 cm compared to MT. There were no significant differences in soil water content between the NT and MT in FW or WP rotation.

3.2. Crop yields, wheat grain protein, and grain N yield

Significant rotation effect on wheat yield was observed in the present study (Table 1), where the averaged wheat yield of CW was 26 % lower than FW in 1982 − 1995 and was 10 % lower than WP in 1996 − 2011 respectively ($P < 0.05$). The 1996 − 2011 average wheat yield under NT was 5% higher than MT ($P < 0.05$; Table 1). Furthermore, the 1996 − 2011 average wheat yield in CW-NT/MT treatment was 6% higher than that in CW-MT ($P < 0.05$; Table 1).

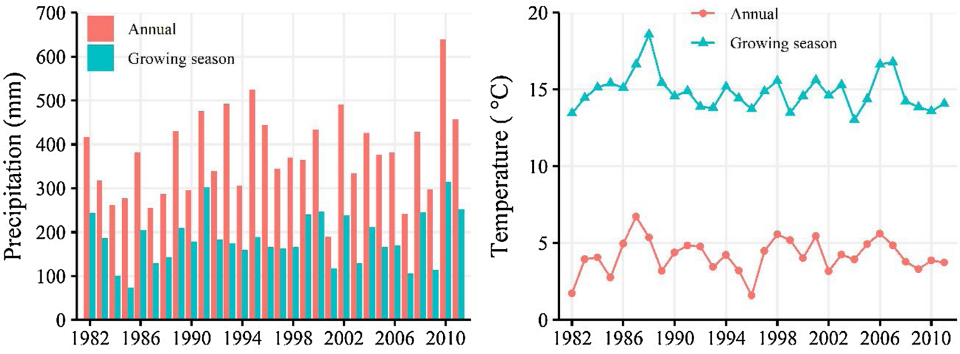

Fig. 1. Temporal variations in annual and growing season (1 May to 31 July) precipitation (mm) and mean air temperature (°C) from 1982 to 2011.

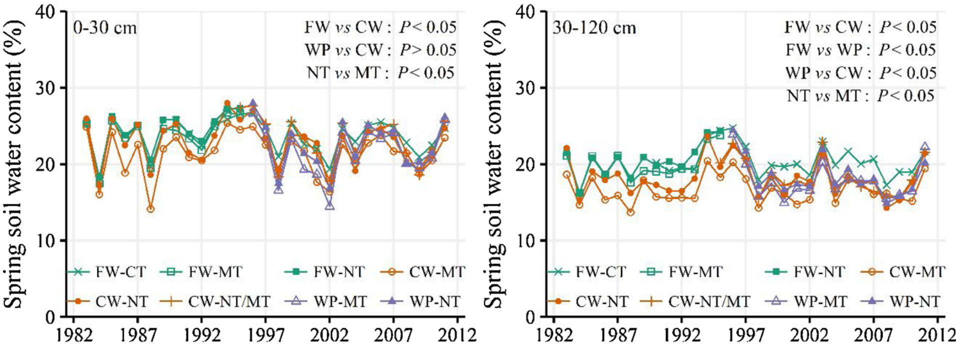

Fig. 3. Spring soil water content (%) for 0-30 cm and 30-120 cm soils in different treatments from 1982 to 2011.

However, at system level by including zero yield for the fallow phase in FW rotation, crop productivity in FW was 34 % lower than CW in 1982 – 1995 and 33 % lower than WP in 1996 – 2011, respectively ($P < 0.05$, Table S1).

The 1996 – 2011 average pulse yield under NT was 14 % higher than MT ($P < 0.05$) although, for individual years, this tillage effect was only statistically significant for lentil in 2003, 2006, and 2007 (Table 1). When analyzed separately for each rotation, the significance of the tillage effect was more variable across time. There was a significant difference between FW-NT and FW-MT in 1988, 1989, and 1991. But the difference in wheat yield between NT and MT was only significant in 1989 under CW rotation and in 2011 under WP rotation (Table 1).

In the period of 1982 – 1995, there was no significant rotation effect on wheat protein content ($P > 0.05$), while protein content under NT was 6% lower than MT ($P < 0.05$; Fig. 4). In the period of 1996 – 2011, the average wheat protein in WP was 6% higher than CW but there was no significant tillage effect on protein content.

Wheat N yield, calculated as wheat grain yield multiply N content, was 40 % higher under CW rotations than FW rotations in the period of

Table 1
Effect of rotation and tillage system on crop yield (kg ha^{-1})[a].

	FW[b]			CW			(W)P		W(P)[c]		(W)P *vs* CW[d]
	CT	MT	NT	MT	NT	NT/MT	MT	NT	MT	NT	
1982	–	1645	2084	1577	1897						
1984	–	2005	2146	1166	1286						
1985	–	1964	1993	1156	1265						
1987	–	2313	2226	783	794						
1988	–	1091b	1391a	0	0						
1989	–	2612b	2738a	1663b	2276a						
1990	3317	3173	3552	2159	2385						
1991	3411a	3533a	2555b	3052	2788						
1992	3804	3530	3471	2017	1953						
1993	3738	3726	3051	2783	2758						
1994	3043	2852	2774	2518	2291						
1995	3287	2932	2685	2499	2310	2527					
1982 – 1995		2615	2555	1943	2000						
1990 – 1995	3433a	3291a	3014b	2505	2414						
1996	3015			2276	2147	2210	–	–	3070	3238	
1997	3212			2511	2861	2944	2908	2903	2205	2557	ns
1998	3352			1337	1440	1448	1161	1108	1194	1425	*
1999	3667			3234	3139	2925	3170	3349	2513	2380	ns
2000	2892			1962	1748	2299	1626	2137	1882	2780	ns
2001	2287			663	969	771	824	895	419	710	ns
2002	2755			2100b	2533ab	2691a	2449	2608	2288	2436	ns
2003	2553			2145	2158	2031	2320	2142	1082b	1536a	ns
2004	3704			2690	2412	2612	3143	2874	2607	2755	**
2005	3606			2948	3205	3342	3461	3603	3047	3184	ns
2006	3405			2037	1907	1999	1988	2235	1061b	1397a	ns
2007	3050			2193	2467	2212	2648	2648	1379b	1778a	+
2008	3663			2970	3230	3426	3287	3688	2829	3323	ns
2009	3459			2278	2476	2262	2612	2582	1633	1704	ns
2010	2964			2932	3005	3006	3326	3661	2001	1816	*
2011	2556			2638	3040	2899	3304b	3859a	1938	2335	***
1997 – 2011	3142			2309b	2439a	2458a	2548b	2686a	1872b	2142a	***
1996 – 2011	3134			2307b	2421ab	2442a	2548b	2686a	1947b	2210a	***

[a] FW, fallow-wheat rotation; CW, continuous wheat; WP, wheat-pulse rotation; CT, conventional tillage; NT, no tillage; MT, minimum tillage; NT/MT, no tillage-minimum tillage rotation. Different lower-case letters indicates significant tillage effect for each rotation at $P < 0.05$; no yield in 1983 due to hail.

[b] Wheat yield in FW is for the crop year only since both rotation phases (fallow and wheat) were present each year in the experiment; Yield could be divided by 2 to obtain the average annual yield that includes the fallow year.

[c] The pulse crop was alternated between lentil (2000, 2001, 2003, 2006, 2007, 2010, 2011), chickpea (1998, 1999), and pea (1996, 1997, 2002, 2004, 2005, 2008, 2009); (W)P means wheat yield in WP rotation, while W(P) refer to pulse yield in WP rotation.

[d] (W)P *vs* CW, comparison of wheat yield between WP and CW system. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; + $P < 0.10$; ns, not significant.

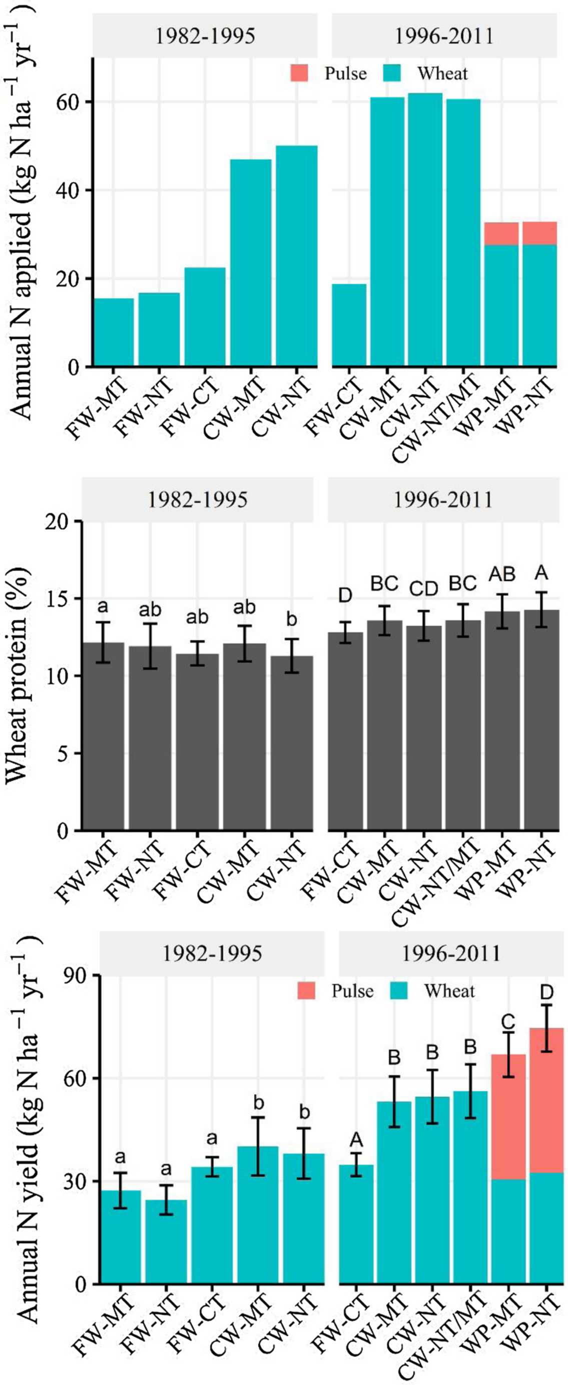

Fig. 4. Annual N fertilization rates (kg N ha^{-1}), protein content (%) in wheat, and crop N yield (kg N ha^{-1}) in different treatments in 1982-1995 and 1996-2011. About 5 kg ha^{-1} N fertilizer was applied to pulse crops from P fertilizer as mono-ammonium phosphate.

1982 – 1995 ($P < 0.05$), but no significant difference was obtained between NT and MT in the same period (Fig. 4). In the period of 1996 – 2011, the crop N yield (wheat plus pulse) was significantly affected by both rotation and tillage ($P < 0.05$) that WP induced 17 % higher wheat N yield than CW and NT resulted in 5% higher values than MT. For the 1996 – 2011 period, average grain N for CW systems accounted for about 90 % of fertilizer N applied (Fig. 4). In contrast, the grain N removed from FW and WP systems during this period were 105 % and 139 % fertilizer N applied.

3.3. *Water and nitrogen use efficiency*

PUE for wheat production under CW rotations were 42 % and 48 % higher ($P < 0.05$) than FW rotations in the period of 1982 – 1995 and 1996 – 2011, respectively, while no significant difference was obtained between NT and MT in the same period for wheat production (Fig. 5). In the period of 1996 – 2011, PUE for pulse production was 14 % higher ($P < 0.05$) under NT than MT. In contrast, WUE for wheat production under FW were 54 % and 36 % higher than CW rotations in the period of 1982 – 1995 and 1996 – 2011, respectively. There was no significant difference between NT and MT other than WUE for pulse was 15 % higher ($P < 0.05$) under NT (Fig. 5).

FUE for wheat production under FW rotations were 2.9- and 2.4-fold greater ($P < 0.05$) than CW rotations in the period of 1982 – 1995 and 1996 – 2011, respectively (Fig. 6). Under FW rotations, FUE for MT was 28 % higher ($P < 0.05$) than NT in the period of 1982 – 1995, but no significant tillage effect on FUE was obtained under CW rotations in the period of both 1982 – 1995 and 1996 – 2011. On the contrary, FUE for pulse production under NT was 14 % ($P < 0.05$) higher than under MT in the period of 1996 – 2011. Furthermore, significant tillage effect on NUE for wheat production was observed under both FW and CW rotations in the period of 1982 – 1995 that NT showed 9% and 12 % higher values than MT, respectively. However, no significant tillage effect on NUE was obtained for either wheat or pulse production in the period of 1996 – 2011.

The ANM was much higher for the pulse crops than wheat (Fig. 6). For 1982 – 95 period, the ANM for FW was higher for both the fallow and crop phase than the crop phase for CW. For the 1996 – 2011 period, the ANM for crop phase of WF was higher than wheat in continuous rotations, although the difference was not significant for WP-NT.

3.4. *SOC stocks*

The SOC stocks in the 0–7.5 cm soil layer were notably affected by cropping system from 1986 to 2011 (Table 2). The SOC stocks in the CW rotations were 25–29 % higher ($P < 0.05$) than those in the FW rotations from 1998 to 2011, while no significant difference was observed between CW and FW rotations before 1998. In general, the SOC stocks in the 0–7.5 cm soil layer were markedly higher in NT systems than in tilled systems (CT & MT) from 1986 to 2011. Nevertheless, when each rotation was analyzed separately, the significant tillage effects were only obtained between FW-NT and FW-MT in 1990 (22 % higher in NT) and between CW-NT and CW-MT in 1986 (29 % higher in NT). The CW-NT/MT showed 21–27 % higher ($P < 0.05$) SOC stocks than CW-MT in 2007 and 2011, while no significant difference was obtained between CW-NT and CW-MT or between CW-NT/MT and CW-NT. Furthermore, WP-NT also resulted in 15–24 % higher SOC stocks than WP-MT from 2003 to 2011 albeit not significant ($P > 0.10$).

The effect of cropping system on SOC stocks in the 0–15 cm soil layer was significant in 1990 and 2011 ($P < 0.05$) but were marginal ($P < 0.10$) in 1986 and 2007 (Table 2). Although no significant difference of SOC stocks in the 0–15 cm soil layer was observed between different rotations ($P > 0.10$), they were significantly higher in NT systems than in tilled systems (CT & MT) in 1986 and 1990. When each rotation was analyzed separately, however, the significant tillage effects were only detectable between FW-NT and FW-MT in 1990 (22 % higher in NT, $P < 0.05$). Furthermore, the CW-NT/MT showed significantly higher SOC in 15 cm than the FW-CT in 2011.

For 0–30 cm soil layer, no significant effect of crop rotation or tillage system on SOC stock was observed for any sampling period in the present study (Table 2)..

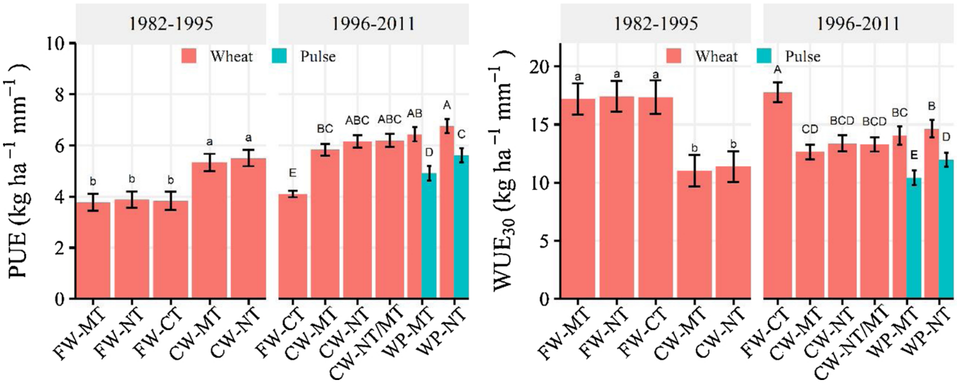

Fig. 5. Precipitation use efficiency (PUE), water use efficiency for 0-30 cm depth (WUE$_{30}$).

4. Discussion

4.1. Residue, productivity, water and N use efficiencies as affected by rotation and tillage

The surface residue followed the weather pattern where lowest amount of residue occurred in 1988 following a number of dry years but increased rapidly to highest measured in 1994 following wetter years from 1989 to 1994 (Fig. 2). Since yields were relatively high from 2008 to 2011 (Table 1), the relatively low amount of surface residue in 2011 was unexpected and may be related to much increased decomposition during the above-average annual and growing season precipitation in 2010 and 2011.

Expectedly, since a major reason for fallowing is to have more stored soil water, wheat on fallow had higher soil water content, which reduced water stress and contributed to higher yields, WUE, and NUE for FW, with wheat yield in crop years were more than double those of CW in dry years including 1987, 1988, 1998, and 2001 (Table 1). However, FW makes relatively inefficient use of land and water as indicated by lower PUE than the continuous rotations (Fig. 5) and total wheat production about two-thirds that of CW at system level (Table S1). The 1990–95 results including CT suggest that tillage is clearly beneficial for wheat production on fallow. This can be related to tillage increasing N mineralized from soil organic matter (McConkey et al., 2002), a critical source of N since harvested grain N typically exceeds N fertilizer added (Fig. 4), which further suggests that N fertilization rates, based on a target of the total of fertilizer N + soil NO_3^--N to 60 cm from fall sampling equal to 90 kg ha^{-1}, were suboptimal for relatively high-yielding FW.

For 1982 – 95, the CW-NT had higher NUE (Fig. 6) than the CW-MT with trend for lower grain protein and grain N (Fig. 4). The results indicate that CW-NT had lower N availability than CW-MT, which can likely be related to the loss of N fertilizer that was surface broadcast for the NT versus all soil incorporated for the MT (Malhi et al., 2001) with equivalent grain N between tillage systems. With higher rates of N fertilizer that was banded to the side of the seed, grain N and protein were higher for 1996 – 2011 than 1982 – 95 (Fig. 4).

Our hypothesis was that the CW-NT/MT would have intermediate yields between CW-NT and CW-MT but, in fact, it had average yields equal to CW-NT and higher than CW-MT (Table 1). There were no obviously apparent differences between tillage systems regarding weeds, diseases, crop establishment, although no measurements for those factors were made to substantiate those perceptions. The yield advantage of biennial tillage was largest in the NT phase (even years) when CW-NT/MT had higher ($P < 0.05$) average yield (2461 kg ha^{-1}) than either CW-NT (2303 kg ha^{-1}) or CW-MT (2288 kg ha^{-1}). In the MT phase, the average yield of CW-NT/MT (2423 kg ha^{-1}) was intermediate and not different ($P > 0.05$) from CW-NT (2539 kg ha^{-1}) or CW-MT (2326 kg ha^{-1}). The surface residue for CW-NT/MT was equal to CW-NT in the NT phase (1998) but, as expected, was intermediate between CW-NT and CW-MT in the MT phase (1997, 1999, 2003, and 2011) (Fig. 2). The higher yield for CW-NT/MT when in NT indicate that wheat productivity under NT benefits from less surface residue than is the case for CW-NT and/or from the amelioration by MT of some unidentified soil or biological impediment that, otherwise, restrains the yield of continuous NT from reaching its potential. The trend was for CW-NT/MT to have slightly higher ANM than other CW systems suggesting it had higher N availability. Venterea et al. (2006) also found that alternating between NT and CT in successive years did not have intermediate grain yields between NT and CT but instead had yields equal to the higher yielding CT. Reviews of infrequent tillage of NT show that the practice can both increase and decrease productivity compared to continual NT (Dang et al., 2015), so our finding of increased productivity for periodic tillage with NT is not inconsistent with the literature.

The greater pulse yield under NT than MT was in agreement with several studies (Cutforth et al., 2002; Huggins and Pan, 1991), although some have shown no effect of tillage system for pea (Deibert and Utter, 2004; Lenssen et al., 2018; Soon and Clayton, 2002). The yield advantage of NT was most pronounced under drier years for lentil and under warmer years for pea (Table 1 and Fig. 7). Other studies in dry temperate climates have also found that NT increases pulse crop yields compared to tillage with the increase being most pronounced in dry years (Giambalvo et al., 2012; Ruisi et al., 2012). Such advantage could be attributed to greater water storage under NT than MT ($P < 0.05$, Fig. 3). This is generally due to lower soil water evaporation because of higher crop residues on the soil surface under NT (Fig. 2). On the other hand, NT might increase infiltration rates because of the more stable structure resulting from a more continuous pore system from dead roots and from soil macrofauna activity (Giambalvo et al., 2012; Guzha, 2004).

The rotation advantage of pulse on yield, grain protein, N uptake, and ANM for the following wheat crop compared to wheat after wheat is consistent with that found in other studies and can be related to more mineralizable N in pulse crop residues, more residual water in the subsoil, and general rotational advantages of having different preceding crop type (Burgess et al., 2012; Fan et al., 2018b; Miller et al., 2003). Another key benefit of pulses is that they fix atmospheric N_2 by root nodule symbiosis and the slow-release of N from pulse residues and roots favors the growth of succeeding crop (Boddey et al., 2010). The yield advantage of wheat after pulse compared to CW increased by 41 kg ha^{-1} yr^{-1} ($P < 0.001$, Fig. 8), indicating that the benefits of pulse crop on wheat production increases with time with pulse crops in rotation. Our results that wheat in WP rotation showed 4–8 % higher grain protein content than in CW rotation (Fig. 4), which thereby confirmed that this benefit as pulses in rotations fundamentally changed the N regime. In this region, wheat price generally increases with protein content, so this protein difference for wheat following a

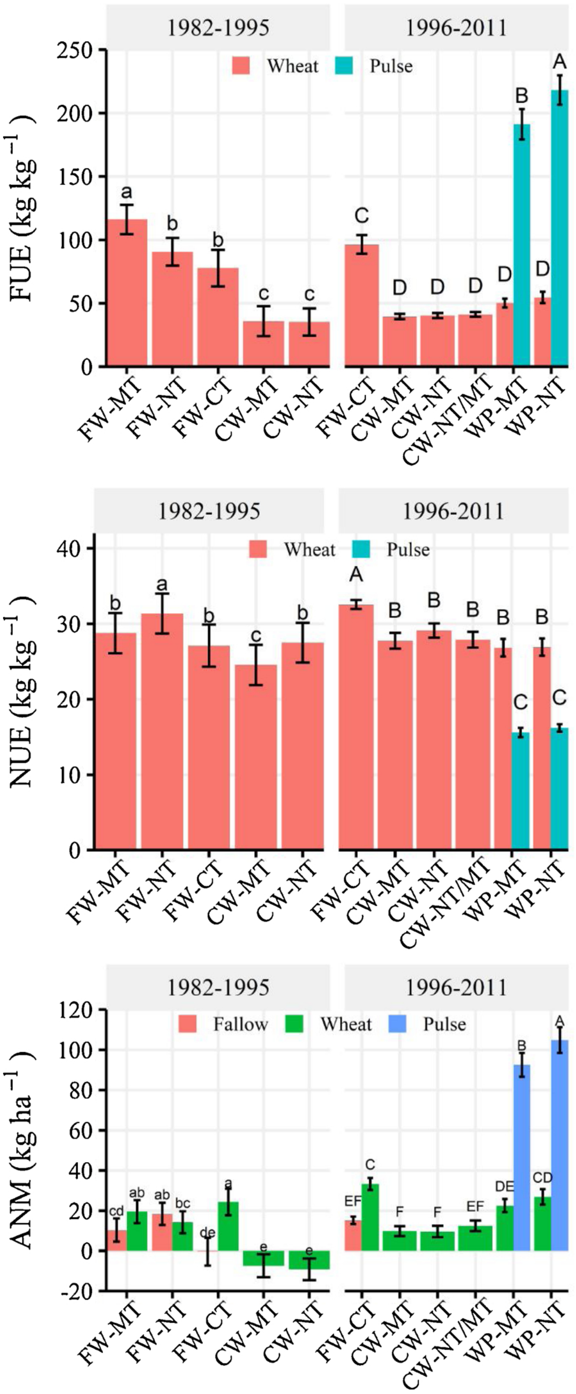

Fig. 6. Fertilizer N use efficiency (FUE), available N use efficiency (NUE), and apparent N mineralization and fixation (ANM) in different treatments in 1982-1995 and 1996-2011.

pulse crop is important economically. However, there was no evidence of a tillage by rotation interaction as relative benefit of wheat after pulse to wheat after wheat was the same under both tillage systems.

4.2. Effect of cropping systems on topsoil SOC stocks over time

For all tillage and crop rotations, the SOC stocks peaked in 1998 or 2003 samplings and then decreased in 2011, especially for 0 − 7.5 cm soils (Table 2). Observations of dropping SOC has been observed in other studies in the region. At a location 50 km south under the same weather and over the same time period as this study, Maillard et al. (2018) found even more dramatic decrease of SOC from 1998 to 2003 to 2011. They showed that SOC change was closely correlated with annual precipitation such that SOC decomposition increased more with increased precipitation than C input so that SOC declined in wetter years. Therefore, in their study as in ours, SOC increased during the drier 1980s and decreased during the wetter 2000s. Also, as in our study, the SOC decrease to 2011 was similar across all tillage and crop rotations. Several other studies in the region have observed generally declining SOC (Sainju et al., 2015), particularly with fallow (Aase and Pikul, 1995; Shrestha et al., 2013). Based on general settlement history, the semiarid region of northern Great Plains was broken from original grassland during the first three decades of the 20th century. Although practically all loss of SOC from conversion of grassland to cropland is expected in the first 20 − 30 years (Kim and Kirschbaum, 2015; Poeplau et al., 2011), turnover of C is particularly slow in the cold, dry climate of the region (Frank et al., 2012). Therefore, given the observations of declining SOC, it is not unreasonable to postulate that SOC stock in this region is still tending to decrease from the SOC stock levels under grassland to a lower SOC stock level consistent with the balance of C input and decomposition as cropland. Against the background of declining cropland SOC, absolute increases in SOC would therefore be exceptional and only occur when cropland C input minus SOC decomposition is unusually positive, a situation that, evidently, occurred for our study only during the 1980s.

In this study, significant effects of crop systems on SOC stocks were found in the 0–7.5 cm soil layer from 1986 to 2011 and occasionally (in 1990 and 2011) in the 0–15 cm soil layer, which were primarily induced by no-till implementation (Table 2). Our result is consistent with the reported SOC response to agricultural management practice only in the surface 7.5 cm (Campbell et al., 2000) to 15 cm (Maillard et al., 2018) in the same region of Canada. There was no indication of an interaction between soil depth and tillage systems, as the ranking of SOC for the 0 − 30 cm depth was similar to the 0 − 7.5 and 0 − 15 cm depths with lowest SOC for FW-CT, highest for CW-NT/MT, and with CW-NT and WP-NT with more SOC than CW-MT and WP-CT (Table 2).

The ranking of SOC to 7.5 cm for the cropping systems at the termination of the experiment in 2011 was the same as the ranking in soil C inputs for the 1996–2011 period, ranged from a low of 2.7 Mg ha^{-1} yr^{-1} for FW-CT to a high of 4.2 Mg ha^{-1} yr^{-1} for CW-NT/MT (data not shown). This provides strong evidence that recent C input is an important driver of current SOC stocks.

Our initial hypothesis was that CW-NT/MT would have intermediate SOC between CW-NT and CW-MT, but its SOC ranked highest among treatments to 30 cm in the latest samplings (2007 and 2011, Table 2). In a moist, cold temperate climate, Venterea et al. (2006) also found that alternating tillage and NT had highest SOC, higher than the NT but not significantly different from CT. Generally, though, infrequent tillage generally causes a decrease of SOC compared to continuous NT (Conant et al., 2007; Dang et al., 2015), in contrast to our findings. Given our unexpected results regarding both SOC and grain yield, further research of frequent tillage with NT is warranted to determine the soil-type-crop rotation-climate situations for which it provides any productivity or SOC benefit and to then determine the cause of the benefit.

For the 1996 − 2011 period, there was no evidence of an interaction between tillage system and continuous rotations of CW and WP, agreeing with the findings of other studies in dry temperate climates (López-Bellido et al., 1997; Sainju et al., 2006). WP provides a greenhouse gas (GHG) mitigation through C sequestration compared with FW but not with CW (Table 2). However, the substituting pulse for a non-legume crop within the rotation provides important GHG mitigation because the symbiotic N fixation for the pulse reduces dependence on N from fossil-fuel derived fertilizer (Khakbazan et al., 2009; MacWilliam et al., 2018).

Table 2
Effect of crop rotation and tillage system on SOC stocks for the 0–7.5, 0–15, and 0–30 cm soil layers.

	0 – 7.5								0 – 15									0 – 30			
Systems [a]	1982	1986	1990	1993	1998	2003	2007	2011	1982	1986	1990	1993	1998	2003	2007	2011	1982	1998	2003	2007	2011
FW-MT	10.9	12.5	12.0	11.8					24.9	28.4	26.1	25.6					46.8				
FW-NT	11.0	14.1	14.6	13.7					24.8	31.6	31.7	30.2					49.1				
FW-CT				12.6	13.0	12.3	12.1	11.6				27.1	27.9	24.7	24.8	24.0		52.9	44.9	45.5	43.8
CW-MT	10.1	11.9	12.5	13.1	15.2	14.5	13.3	13.4	23.0	27.1	25.9	26.8	28.2	28.1	26.2	25.6	43.8	50.8	47.5	46.5	48.1
CW-NT	12.3	15.3	14.3	14.6	16.4	16.5	16.2	15.4	25.5	31.6	29.4	29.7	28.9	30.6	28.4	29.0	48.0	51.7	54.2	48.2	49.8
CW-NT/MT					17.4	16.4	17.0	16.1					31.9	29.6	32.0	30.4		57.7	50.1	54.9	54.3
WP-MT						14.2	13.3	12.5						26.7	25.7	25.8			48.0	46.5	46.9
WP-NT						17.5	16.1	14.4						32.9	29.6	27.9			55.2	53.6	51.8
Fixed effect	ns	**	*	*	***	*	***	***	ns	+	**	ns	ns	ns	+	*	ns	ns	ns	ns	+
Contrast [b]																					
FW vs CW	ns	ns	ns	ns	***	+	**	***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CW vs WP						ns	ns	*						ns	ns	ns			ns	ns	ns
FW-CT vs CW-NT/MT					***	+	***	***					ns	ns	+	*		ns	ns	ns	ns
FW-CT vs WP						*	*	**						+	ns	ns			ns	ns	ns
NT vs CT & MT	ns	**	**	*	+	*	***	***	ns	*	**	+	ns	+	ns	ns	ns	ns	ns	ns	ns
FW-NT vs FW-MT	ns	ns	*	ns					ns	ns	*	ns					ns				
CW-NT vs CW-MT	ns	**	ns	ns	ns	ns	ns	+	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
CW-NT/MT vs CW-MT					ns	ns	*	**					ns	ns	ns	ns		ns	ns	ns	ns

[a] Abbreviations are same as in Table 1. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; + $P < 0.10$; ns, not significant.

[b] All comparison were considered but only contrasts with at least one occurrence of $P < 0.10$ are shown in the Table.

5. Conclusions

We found both tillage system and crop rotation had significant effects on crop yield, N uptake in grain, and topsoil SOC stocks over three decades for a Vertisol in a dry temperate climate. Rotation effect on wheat yield was significant with higher yields for FW than CW, while WP rotation had higher wheat yield than CW that the benefit increased by 41 kg ha^{-1} yr^{-1} in 1997 – 2011. Our results indicate that the wheat-pulse rotation is beneficial to productivity under both MT and NT and these benefits increase linearly with time.

Within FW, NT had the lower yields than CT, attributable to less N mineralization from organic matter under NT, with MT yield intermediate and not significantly different from either CT or NT. The pulse crops yielded more under NT than MT, which was most pronounced under drier and warmer years. Of importance for climate change adaptation to warmer climate with more severe droughts, NT had greatest pulse yield benefit over MT in warmer and drier years.

Annual grain N uptake was greater in WP than in CW or FW and greater for NT than MT for WP. Wheat grain protein was higher in WP-NT than CW or FW while wheat protein in WP-MT was higher than CW-NT or FW-CT. The biennial tillage in CW-NT/MT benefitted the wheat yield in the following NT year so that it was significantly greater than that of CW-MT and CW-NT in those years.

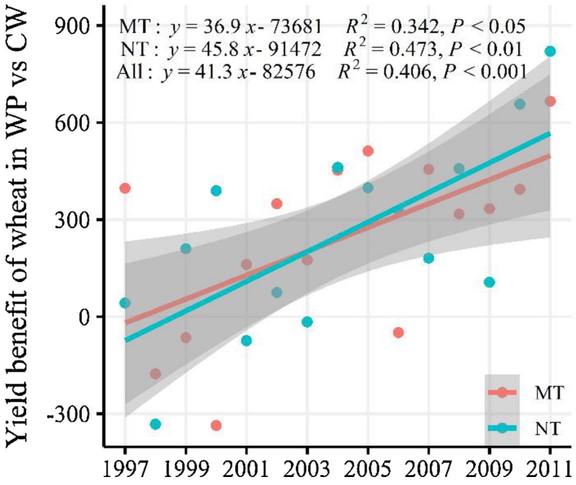

Fig. 8. Dynamics of yield advantage of wheat after pulse compared to CW, calculated as the difference between wheat yield in WP and CW from 1997 to 2011.

The SOC stocks in the 0–7.5 cm soil layer were higher in NT systems than in tilled systems for all sampling period. The CW and WP rotations had higher SOC than the FW by the end of the experiment in 2011. Due to lower C input, the WP had marginally lower SOC than CW.

In the semiarid, temperate climate, the cropping system consistent with conservation agriculture, the pulse-wheat rotation under NT, was

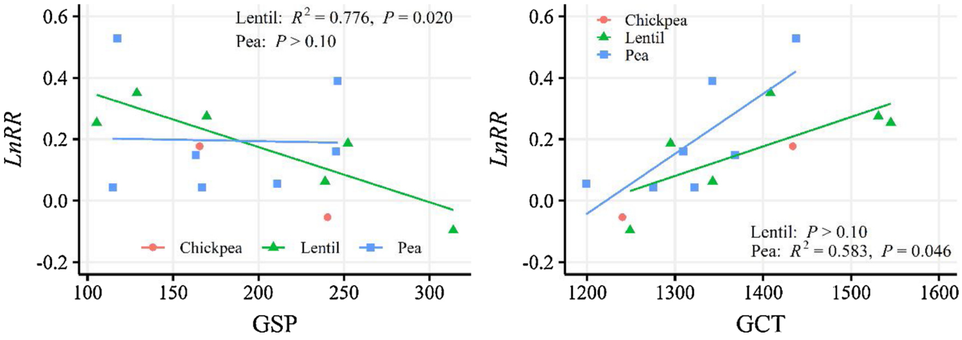

Fig. 7. Correlation between the natural logarithm of yield relative ration (*LnRR*) and growing season precipitation (GSP) or growing season cumulative temperature (GCT).

the system that had the most efficient use of fertilizer N and highest annual wheat yield and quality. However, due to lower yield of pulses than wheat, continuous wheat had the highest precipitation use efficiency, and, at the end of the study in 2011, also had higher SOC. However, SOC in WP-NT consistently ranked higher than any tilled monoculture wheat system, and there was no clear tradeoff for WP-NT compared to monoculture wheat.

CRediT authorship contribution statement

Jianling Fan: Writing - original draft, Software, Visualization, Writing - review & editing. **Brian G. McConkey:** Conceptualization, Supervision, Writing - review & editing. **Mervin St. Luce:** Writing - review & editing. **Kelsey Brandt:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The experiment was funded by Agriculture and Agri-Food Canada. JF is funded by the Startup Foundation for Introducing Talent of NUIST. We express our profound appreciation to Marty Peru, who was the technician in charge of the experiment throughout its existence, for his dedication and competence. We also acknowledge Mr. Richard Weetman on whose land the experiment was located.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2020.126155.

References

Aase, J.K., Pikul, J.L., 1995. Crop and soil response to long-term tillage practices in the Northern Great Plains. Agron. J. 87, 652–656.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration-guidelines for Computing Crop Water requirements-FAO Irrigation and Drainage Paper 56. Natural Resources Management and Environment Department, Rome, Italy.

Álvaro-Fuentes, J., Lampurlanés, J., Cantero-Martínez, C., 2009. Alternative crop rotations under Mediterranean no-tillage conditions: biomass, grain yield, and water-use efficiency. Agron. J. 101, 1227–1233.

Ayres, K.W., Acton, D.F., Ellis, J.C., 1985. The Soils of the Swift Current Map Area. Saskatchewan Institute of Pedology, Saskatoon, SK.

Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.

Boddey, R.M., Jantalia, C.P., Conceiçao, P.C., Zanatta, J.A., Bayer, C., Mielniczuk, J., Dieckow, J., Dos Santos, H.P., Denardin, J.E., Aita, C., Giacomini, S.J., Alves, B.J.R., Urquiaga, S., 2010. Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture. Glob. Change Biol. Bioenergy 16, 784–795.

Burgess, M.H., Miller, P.R., Jones, C.A., 2012. Pulse crops improve energy intensity and productivity of cereal production in Montana, USA. J. Sustain. Agric. 36, 699–718.

Campbell, C.A., Zentner, R.P., Johnson, P.J., 1988. Effect of crop rotation and fertilization on the quantitative relationship between spring wheat yield and moisture use in southwestern Saskatchewan. Can. J. Soil Sci. 68, 1–16.

Campbell, C.A., McConkey, B.G., Zentner, R.P., Selles, F., Curtin, D., 1996. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Can. J. Soil Sci. 76, 395–401.

Campbell, C.A., Zentner, R.P., Selles, F., Biederbeck, V.O., McConkey, B.G., Blomert, B., Jefferson, P.G., 2000. Quantifying short-term effects of crop rotations on soil organic carbon in southwestern Saskatchewan. Can. J. Soil Sci. 80, 193–202.

Campbell, C.A., Janzen, H.H., Paustian, K., Gregorich, E.G., Sherrod, L., Liang, B.C., Zentner, R.P., 2005. Carbon storage in soils of the North American Great Plains: effect of cropping frequency. Agron. J. 97, 349–363.

Campbell, C.A., VandenBygaart, A.J., Zentner, R.P., McConkey, B.G., Smith, W., Lemke, R., Grant, B., Jefferson, P.G., 2007. Quantifying carbon sequestration in a minimum tillage crop rotation study in semiarid southwestern Saskatchewan. Can. J. Soil Sci. 87, 235–250.

Carefoot, J.M., Nyborg, M., Lindwall, C.W., 1990. Tillage-induced soil changes and related grain yield in a semi-arid region. Can. J Soil Sci 70, 203–214.

Cherlet, M., Hutchinson, C., Reynolds, J., Hill, J., Sommer, S., von Maltitz, G., 2018. World Atlas of Desertification. Publication Office of the European Union, Luxembourg.

Conant, R.T., Easter, M., Paustian, K., Swan, A., Williams, S., 2007. Impacts of periodic tillage on soil C stocks: a synthesis. Soil Tillage Res 95, 1–10.

Conijn, J.G., Bindraban, P.S., Schröder, J.J., Jongschaap, R.E.E., 2018. Can our global food system meet food demand within planetary boundaries? Agric. Ecosyst. Environ. 251, 244–256.

Cutforth, H.W., McConkey, B.G., Ulrich, D., Miller, P.R., Angadi, S.V., 2002. Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian Prairie. Can. J. Plant Sci. 82, 681–686.

Cutforth, H., McConkey, B., Angadi, S., Judiesch, D., 2011. Extra-tall stubble can increase crop yield in the semiarid Canadian prairie. Can. J. Plant Sci. 91, 783–785.

Dalal, R.C., Henry, R.J., 1986. Simultaneous determination of moisture, organic carbon, and total nitrogen by near infrared reflectance spectrophotometry. Soil Sci. Soc. Am. J. 50, 120–123.

Dang, Y.P., Seymour, N.P., Walker, S.R., Bell, M.J., Freebairn, D.M., 2015. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. Soil Tillage Res 152, 104–114.

Deibert, E.J., Utter, R.A., 2004. Field pea growth and nutrient uptake: response to tillage systems and nitrogen fertilizer applications. Commun. Soil Sci. Plant Anal. 35, 1141–1165.

Dyck, F.B., Tessier, S., 1986. Zero Till Drill Developments at the Swift Current Research Station. CSAE Paper No 86-210. Canadian Society of Agricultural Engineering Meeting, Saskatoon, SK.

Ellert, B.H., Janzen, H.H., VandenBygaart, A.J., Bremer, E., 2007. Measuring Change in Soil Organic Carbon Storage, Soil Sampling and Methods of Analysis, second edition. CRC Press.

Engel, R.E., Miller, P.R., McConkey, B.G., Wallander, R., 2017. Soil organic carbon changes to increasing cropping intensity and no-till in a semiarid climate. Soil Sci. Soc. Am. J. 81, 404–413.

Fan, J., Luo, R., Liu, D., Chen, Z., Luo, J., Boland, N., Tang, J., Hao, M., McConkey, B., Ding, W., 2018a. Stover retention rather than no-till decreases the global warming potential of rainfed continuous maize cropland. Field Crop Res 219, 14–23.

Fan, J., McConkey, B.G., Janzen, H.H., Miller, P.R., 2018b. Emergy and energy analysis as an integrative indicator of sustainability: a case study in semi-arid Canadian farmlands. J. Clean. Prod. 172, 428–437.

Farina, R., Seddaiu, G., Orsini, R., Steglich, E., Roggero, P.P., Francaviglia, R., 2011. Soil carbon dynamics and crop productivity as influenced by climate change in a rainfed cereal system under contrasting tillage using EPIC. Soil Tillage Res. 112, 36–46.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337.

Frank, D.A., Pontes, A.W., McFarlane, K.J., 2012. Controls on soil organic carbon stocks and turnover among North American ecosystems. Ecosystems 15, 604–615.

Gan, Y., Hamel, C., O'Donovan, J.T., Cutforth, H., Zentner, R.P., Campbell, C.A., Niu, Y., Poppy, L., 2015. Diversifying crop rotations with pulses enhances system productivity. Sci. Rep. 5, 14625.

Giambalvo, D., Ruisi, P., Saia, S., Di Miceli, G., Frenda, A.S., Amato, G., 2012. Faba bean grain yield, N_2 fixation, and weed infestation in a long-term tillage experiment under rainfed Mediterranean conditions. Plant Soil 360, 215–227.

Godfray, H.C.J., Garnett, T., 2014. Food security and sustainable intensification. Philos. Trans. Biol. Sci. 369, 20120273.

Grahmann, K., Verhulst, N., Buerkert, A., Ortiz-Monasterio, I., Govaerts, B., 2013. Nitrogen use efficiency and optimization of nitrogen fertilization in conservation agriculture. CAB Reviews 8, 1–19.

Gristina, L., Keesstra, S., Novara, A., 2018. No-till durum wheat yield success probability in semi arid climate: a methodological framework. Soil Tillage Res 181, 29–36.

Guzha, A.C., 2004. Effects of tillage on soil microrelief, surface depression storage and soil water storage. Soil Tillage Res. 76, 105–114.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous inference in general parametric models. Biom. J. 50, 346–363.

Huggins, D.R., Pan, W.L., 1991. Wheat stubble management affects growth, survival, and yield of winter grain legumes. Soil Sci. Soc. Am. J. 55, 823–829.

Hume, L., Tessier, S., Dyck, F.B., 1991. Tillage and rotation influences on weed community composition in wheat (*Triticum aestivum* L.) in southwestern saskatchewan. Can. J. Plant Sci. 71, 783–789.

Khakbazan, M., Mohr, R.M., Derksen, D.A., Monreal, M.A., Grant, C.A., Zentner, R.P., Moulin, A.P., McLaren, D.L., Irvine, R.B., Nagy, C.N., 2009. Effects of alternative management practices on the economics, energy and GHG emissions of a wheat–pea cropping system in the Canadian prairies. Soil Tillage Res 104, 30–38.

Kim, D.-G., Kirschbaum, M.U.F., 2015. The effect of land-use change on the net exchange rates of greenhouse gases: a compilation of estimates. Agric. Ecosyst. Environ. 208, 114–126.

Kirk, P.L., 1950. Kjeldahl method for total nitrogen. Anal. Chem. 22, 354–358.

Kröbel, R., Campbell, C.A., Zentner, R.P., Lemke, R., Steppuhn, H., Desjardins, R.L., De Jong, R., 2012. Nitrogen and phosphorus effects on water use efficiency of spring wheat grown in a semi-arid region of the Canadian prairies. Can. J. Soil Sci. 92, 573–587.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Lal, R., 2015. Sequestering carbon and increasing productivity by conservation agriculture. J. Soil Water Conserv. 70, 55A–62A.

Laudicina, V.A., Novara, A., Gristina, L., Badalucco, L., 2014. Soil carbon dynamics as affected by long-term contrasting cropping systems and tillages under semiarid Mediterranean climate. Appl. Soil Ecol. 73, 140–147.

Lenssen, A.W., Sainju, U.M., Jabro, J.D., Allen, B.L., Stevens, W.B., 2018. Dryland pea production and water use responses to tillage, crop rotation, and weed management practice. Agron. J. 110, 1843–1853.

Lenth, R.V., 2016. Least-squares means: the r package lsmeans. J. Stat. Softw. 69, 1–33.

Liebig, M., Carpenter-Boggs, L., Johnson, J.M.F., Wright, S., Barbour, N., 2006. Cropping system effects on soil biological characteristics in the Great Plains. Renew. Agric. Food Syst. 21, 36–48.

López-Bellido, L., López-Garrido, F.J., Fuentes, M., Castillo, J.E., Fernández, E.J., 1997. Influence of tillage, crop rotation and nitrogen fertilization on soil organic matter and nitrogen under rain-fed Mediterranean conditions. Soil Tillage Res. 43, 277–293.

López-Fando, C., Almendros, G., 1995. Interactive effects of tillage and crop rotations on yield and chemical properties of soils in semi-arid central Spain. Soil Tillage Res. 36, 45–57.

Machado, S., Petrie, S., Rhinhart, K., Ramig, R.E., 2008. Tillage effects on water use and grain yield of winter wheat and green pea in rotation. Agron. J. 100, 154–162.

MacWilliam, S., Wismer, M., Kulshreshtha, S., 2014. Life cycle and economic assessment of Western Canadian pulse systems: the inclusion of pulses in crop rotations. Agric. Syst. 123, 43–53.

MacWilliam, S., Parker, D., Marinangeli, C.P.F., Trémorin, D., 2018. A meta-analysis approach to examining the greenhouse gas implications of including dry peas (*Pisum sativum* L.) and lentils (*Lens culinaris* M.) in crop rotations in western Canada. Agric. Syst. 166, 101–110.

Mahal, N.K., Castellano, M.J., Miguez, F.E., 2018. Conservation agriculture practices increase potentially mineralizable nitrogen: a meta-analysis. Soil Sci. Soc. Am. J. 82, 1270–1278.

Maillard, É., McConkey, B.G., St. Luce, M., Angers, D.A., Fan, J., 2018. Crop rotation, tillage system, and precipitation regime effects on soil carbon stocks over 1 to 30 years in Saskatchewan, Canada. Soil Tillage Res. 177, 97–104.

Malhi, S.S., Grant, C.A., Johnston, A.M., Gill, K.S., 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: a review. Soil Tillage Res. 60, 101–122.

Masri, Z., Ryan, J., 2006. Soil organic matter and related physical properties in a Mediterranean wheat-based rotation trial. Soil Tillage Res. 87, 146–154.

McConkey, B.G., Campbell, C.A., Zentner, R.P., Dyck, F.B., Selles, F., 1996. Long-term tillage effects on spring wheat production on three soil textures in the Brown soil zone. Can. J. Plant Sci. 76, 747–756.

McConkey, B.G., Curtin, D., Campbell, C.A., Brandt, S.A., Selles, F., 2002. Crop and soil nitrogen status of tilled and no-tillage systems in semiarid regions of Saskatchewan. Can. J. Soil Sci. 82, 489–498.

McConkey, B.G., Liang, B.C., Campbell, C.A., Curtin, D., Moulin, A., Brandt, S.A., Lafond, G.P., 2003. Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils. Soil Tillage Res. 74, 81–90.

Meena, B.P., Shirale, A.O., Dotaniya, M.L., Jha, P., Meena, A.L., Biswas, A.K., Patra, A.K., 2016. Conservation agriculture: a new paradigm for improving input use efficiency and crop productivity. In: Bisht, J.K., Meena, V.S., Mishra, P.K., Pattanayak, A. (Eds.), Conservation Agriculture: An Approach to Combat Climate Change in Indian Himalaya. Springer, Singapore, Singapore, pp. 39–69.

Melero, S., Vanderlinden, K., Ruiz, J.C., Madejon, E., 2008. Long-term effect on soil biochemical status of a Vertisol under conservation tillage system in semi-arid Mediterranean conditions. Eur. J. Soil Biol. 44, 437–442.

Miller, P.R., Gan, Y., McConkey, B.G., McDonald, C.L., 2003. Pulse crops for the Northern Great Plains: II. Cropping sequence effects on cereal, oilseed, and pulse crops. Agron. J. 95, 980–986.

Mohammad, W., Shah, S.M., Shehzadi, S., Shah, S.A., 2012. Effect of tillage, rotation and crop residues on wheat crop productivity, fertilizer nitrogen and water use efficiency and soil organic carbon status in dry area (rainfed) of north-west Pakistan. J. Soil Sci. Plant Nutr. 12, 715–727.

Montgomery, D.R., 2018. Growing a Revolution: Bringing Our Soil Back to Life. W. W. Norton Incorporated.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49–57.

Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517, 365–368.

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. Glob. Change Biol. Bioenergy 17, 2415–2427.

Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat Clim. Change 4, 678–683.

R Core Team, 2019. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Ruisi, P., Giambalvo, D., Miceli, G.D., Frenda, A.S., Saia, S., Amato, G., 2012. Tillage effects on yield and nitrogen fixation of legumes in Mediterranean conditions. Agron. J. 104, 1459–1466.

Sainju, U.M., Lenssen, A., Caesar-Tonthat, T., Waddell, J., 2006. Tillage and crop rotation effects on dryland soil and residue carbon and nitrogen. Soil Sci. Soc. Am. J. 70, 668–678.

Sainju, U.M., Lenssen, A.W., Caesar-TonThat, T., Jabro, J.D., Lartey, R.T., Evans, R.G., Allen, B.L., 2011. Dryland residue and soil organic matter as influenced by tillage, crop rotation, and cultural practice. Plant Soil 338, 27–41.

Sainju, U.M., Allen, B.A., Caesar-TonThat, T., Lenssen, A.W., 2015. Dryland soil carbon and nitrogen after thirty years of tillage and cropping sequence combination. Agron. J. 107, 1822–1830.

Sainju, U.M., Lenssen, A.W., Allen, B.L., Stevens, W.B., Jabro, J.D., 2017. Soil total carbon and crop yield affected by crop rotation and cultural practice. Agron. J. 109, 388–396.

Sainju, U.M., Lenssen, A.W., Allen, B.L., Stevens, W.B., Jabro, J.D., 2018. Nitrogen balance in dryland agroecosystem in response to tillage, crop rotation, and cultural practice. Nutr. Cycl. Agroecosyst. 110, 467–483.

Saskatchewan Agriculture, 1985. Saskatchewan Fertilizer Practices. Saskatchewan Agriculture, Regina, SK p. 12.

Saskatchewan Soil Testing Laboratory, 1990. Nutrient Requirement Guidelines for Field Crops in Saskatchewan. University of Saskatchewan, Saskatoon, SK.

Seddaiu, G., Iocola, I., Farina, R., Orsini, R., Iezzi, G., Roggero, P.P., 2016. Long term effects of tillage practices and N fertilization in rainfed Mediterranean cropping systems: durum wheat, sunflower and maize grain yield. Eur. J. Agron. 77, 166–178.

Shrestha, B.M., McConkey, B.G., Smith, W.N., Desjardins, R.L., Campbell, C.A., Grant, B.B., Miller, P.R., 2013. Effects of crop rotation, crop type and tillage on soil organic carbon in a semiarid climate. Can. J. Soil Sci. 93, 137–146.

Soil Classification Working Group, 1998. The Canadian System of Soil Classification, 3rd ed. Agriculture and Agri-Food Canada Ottawa, ON.

Soon, Y.K., Clayton, G.W., 2002. Eight years of crop rotation and tillage effects on crop production and N fertilizer use. Can. J. Soil Sci. 82, 165–172.

Tessier, S., Steppuhn, H., 1990. Quick-mount soil core sampler for measuring bulk density. Can. J. Soil Sci. 70, 115–118.

Tessier, S., Peru, M., Dyck, F.B., Zentner, F.P., Campbell, C.A., 1990. Conservation tillage for spring wheat production in semi-arid Saskatchewan. Soil Tillage Res. 18, 73–89.

Thiagarajan, A., Fan, J., McConkey, B.G., Janzen, H.H., Campbell, C.A., 2018. Dry matter partitioning and residue N content for 11 major field crops in Canada adjusted for rooting depth and yield. Can. J. Soil Sci. 98, 574–579.

UNEP, 2013. The Emissions Gap Report 2013. United Nations Environment Programme (UNEP), United Nations Environment Programme, Nairobi.

VandenBygaart, A.J., 2016. The myth that no-till can mitigate global climate change. Agric. Ecosyst. Environ. 216, 98–99.

Venterea, R.T., Baker, J.M., Dolan, M.S., Spokas, K.A., 2006. Carbon and nitrogen storage are greater under biennial tillage in a Minnesota corn–soybean rotation. Soil Sci. Soc. Am. J. 70, 1752–1762.

Williams, C.M., King, J.R., Ross, S.M., Olson, M.A., Hoy, C.F., Lopetinsky, K.J., 2014. Effects of three pulse crops on subsequent barley, canola, and wheat. Agron. J. 106, 343–350.