CrossMark

REGULAR ARTICLE

Decline in soil organic carbon and nitrogen limits yield in wheat-fallow systems

Rajan Ghimire · Stephen Machado · Prakriti Bista

Abstract

Aims This study evaluated long-term trends of soil organic carbon (SOC), soil total nitrogen (N), and wheat (*Triticum aestivum* L.) yield to glean information for improving the sustainability of dryland winter wheat-summer fallow (WW-SF) systems in the inland Pacific Northwest (IPNW).

Methods Effects of fall burn (FB), no burn (NB), manure application (MN), and pea vine incorporation (PV) treatments on SOC, N, and wheat grain yield from 1931 to 2010 were evaluated in an on-going Crop Residue Long-term experiment (CR-LTE). A medium tall wheat variety (Rex-M) was planted during 1931–1966 and several semi-dwarf varieties were planted since then.

Results We observed a slight but gradual decrease in wheat yield in all treatments from 1931 to 1966 and in FB and NB from 1967 to 2010. Wheat yield in PV and MN increased until 1995 and decreased thereafter. The SOC and N content in 0–30 cm depth declined in FB, NB, and PV treatments with the highest rates of SOC

and N loss under FB. The SOC content in 0–30 cm depth in MN was maintained.

Conclusion Growers should match organic matter and nitrogen (N) inputs to C and N loss to maintain SOC, N and crop yields, and improve the sustainability of dryland WW-SF systems.

Introduction

Maintenance of SOC (proxy for soil organic matter-SOM) and N is one of the greatest challenges for sustainable crop production in dryland farming across the world. In the Pacific northwest of USA, dryland crop production is practiced on about 3.72×10^6 ha, 71% of which is dedicated to the WW – SF system (Schillinger and Papendick 2008; Schillinger et al. 2006). Traditionally, dryland producers burned or removed crop residues in the fall, cultivated soils with a mold-board plow, and left the ground fallow for 13–14 months after harvest (Schillinger and Papendick 2008). However, repeated tillage, long fallow periods, and continuous mining of soil caused loss of 30–45 Mg C ha^{-1} in the first 50 years (Tiessen et al. 1982). At present, fields under WW-SF system have 50–70% less SOC content in the surface soil than undisturbed soils (Ghimire et al. 2015). Besides, 37–70 kg N ha^{-1} is lost through grain harvest each crop year and continuously

R. Ghimire (✉) · S. Machado · P. Bista
Columbia Basin Agricultural Research Center, Oregon State University, Pendleton, OR, USA
e-mail: rghimire@nmsu.edu

Present Address:
R. Ghimire

Agricultural Science Center, Clovis, New Mexico State University, 2346 State Road 288, Clovis, NM 88101, USA

Springer

deplete soil N reservoir (Rasmussen and Parton 1994). The depletion of SOC, nutrients, and associated depletion in plant available N may have caused a consistent decrease in soil fertility status and crop yields (Camara et al. 2003; Lemke et al. 2010). Increased understanding of SOC, soil N and crop yield dynamics as influenced by long-term management practices may lead to improvements in the sustainability of dryland cropping systems in the IPNW.

Crop residue retention contributes a significant amount of biomass C to the soil and increases SOC storage (Hooker et al. 2005). Long-term studies such as Morrow plots (Illinois) and Sanborn field (Missouri) experiments revealed a positive relationship between biomass C input and SOC content (Miles and Brown 2011; Nafziger and Dunker 2011). Similarly, fertilizer N addition increases crop production (Camara et al. 2003), soil biological activity (Peacock et al. 2001), and SOC sequestration (Guo et al. 2012). However, a recent study comparing tillage systems and N rates in eastern Oregon revealed no significant improvement in SOC accumulation with N addition (Ghimire et al. 2017). Nutrient management through organic sources such as green manure, compost, and biosolids application can increase SOC compared to a control treatment with no organic residues additions (Rasmussen and Parton 1994; Wuest and Gollany 2013) suggesting a need for balanced C and N input to increase SOC storage.

Long-term cropping systems studies evaluating trends of SOC and N have significantly contributed to improvements in soil C and N sequestration, soil health, and ecosystem services (Miles and Brown 2011; Nafziger and Dunker 2011). However, dryland producers in the IPNW still face challenges in maintaining or sustainably increasing crop production because of the continuous depletion of SOC and nutrients in WW-SF systems (Horner et al. 1960; Machado et al. 2006; Oveson 1966). Specifically, soil N dynamics and N balance in the long-term agroecosystems and their relationship with yield loss are relatively less studied compared to C dynamics (Ghimire et al. 2015). Data from the Pendleton long-term experiments (PLTEs), the oldest experiments in the western US, have been a great resource for studying SOC and N dynamics in dryland cropping systems (Machado 2011; Rasmussen and Parton 1994). Nevertheless, the effect of long-term trends of decreasing SOC and nutrients stocks on long-term crop yield in dryland farming is not adequately

documented (Lemke et al. 2010). Specifically, >50 years of field data are rarely reported.

Organic residues and manure application can increase crop production by increasing SOC accrual and nutrient cycling (Schillinger and Papendick 2008; Wuest and Gollany 2013). Management practices that increase SOC and N accumulation can also enhance crop production by maintaining soil structure and moderating soil microbial activities (Ghimire et al. 2014). The PLTEs have a unique inventory of long-term (> 80 years) SOC, soil total N, and crop yield data that could reveal how SOC and N dynamics have influenced dryland wheat production trends in WW-SF systems of the IPNW. Previous studies revealed changes in SOC and N (Rasmussen and Parton 1994), residue input required to maintain SOC in surface soil (Machado 2011), and profile distribution of SOC and N after several decades of treatments in CR-LTE (Ghimire et al. 2015) and other PLTEs (Machado et al. 2006). The present study attempts to evaluate the relationship between changes in SOC and N from 1931 to 2010 and the trend of winter wheat productivity in the CR-LTE.

The aim of this study was to evaluate the effects of long-term crop residue and nutrient management in selected treatments of CR-LTE on crop yield, SOC, and N in last 15 years (1995–2010) as well as to analyze the trends of SOC, N and crop yield from 1931 to 2010.. We were also interested in evaluating SOC stabilization under long-term application of crop residue and manure management practices.

Materials and methods

Study site and treatments

The CR-LTE was established in 1931 at the Columbia Basin Agricultural Research Center (CBARC) near Pendleton, OR (45°42′N, 118°36′W, 438 m elev.). The CR-LTE is one of the oldest replicated and most comprehensive long-term experiments in the western US. The study site has a Mediterranean type climate with cool, wet winters and hot, dry summers. Eighty-year (1932–2012) annual average maximum and minimum temperatures and precipitation, monitored at a weather station within 500 m of CR-LTE, were 17.4 °C, 3.06 °C, and 395 mm, respectively (Western Regional Climate Center 2014). Approximately 70% of annual precipitation occurred between September and March. Growing

degree day (GDD) and crop year (October – July) precipitation were calculated from data collected from the weather station. Cumulative growing degree days (GDD) for a crop year were calculated from daily average temperature from planting to harvesting of the wheat crop. The soil at the study site was Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls) derived from loess deposits overlaying basalt (Soil Survey Staff 2014).

The experiment has an ordered arrangement of treatments consisting of two series of plots, so both phases of the experiment were present each year. All treatments were replicated two times. Individual plots were 11.6 m wide × 40.2 m long. A single medium-tall variety (Rex M-1) was grown from 1931 to 1966 and multiple semi-dwarf varieties have been grown since then (Nugaines 1967–1973, Hyslop 1974–1978, Stephens 1979–1991 and 1996–2005, Malcolm 1992–1995, and ORCF102 since 2006). The CR-LTE has nine treatments that consists of diverse residue management (Fall burn-FB, Spring burn- SB, and no burn - NB) and soil fertility management practices (0, 45 and 90 kg N ha^{-1} crop^{-1}, manure - MN, and pea vine - PV). Details of each treatment were described in Ghimire et al. (2015). This study focuses on crop yield, SOC and N under FB, NB, PV and MN treatments with no N addition. Fall burning of wheat stubble was conducted in late September after crop harvest. Crop residues were incorporated to a depth of 20 cm during primary tillage in late spring of the fallow year in NB, MN, and PV treatments. Pea vines (1.12 Mg ha^{-1} yr.$^{-1}$, DM 87.8%, biomass C 0.41 Mg ha^{-1} yr.$^{-1}$, and N 18.5 kg ha^{-1} yr.$^{-1}$) and steer manure (11.2 Mg ha^{-1} yr.$^{-1}$, DM 47.5% and C 0.85 Mg ha^{-1} yr.$^{-1}$, N 70 kg ha^{-1} yr.$^{-1}$) were also added during spring tillage of the crop year (every other year) in PV and MN treatments, respectively. Besides, crop residues with annual C and N inputs equivalent to 2.13 Mg ha^{-1} and 26 kg ha^{-1} in PV, and 2.83 Mg ha^{-1} and 35 kg ha^{-1} in MN, respectively, were returned to the soil. Pea vine from 1931 to 1950 included seed with pods and vines, but additions after 1951 did not include seeds. FB and NB did not receive any additional fertilizer or organic residue inputs. Biomass C and N inputs from wheat residues were 0.46 Mg ha^{-1} yr.$^{-1}$ and 5.64 kg ha^{-1} yr.$^{-1}$ in FB, and 1.51 Mg ha^{-1} yr.$^{-1}$ and 18.5 kg ha^{-1} yr.$^{-1}$ in NB, respectively.

Fall burning of crop residue was implemented by tilling a 1-m boarder around each plot and starting a backfire on the lee side of the plot. Soil surface was not disturbed between burning in fall and plowing in the spring. Spring tillage occurred in late March-early April during 1931–1994 and late April-early May during 1994–2010. Herbicides were applied in late winter or early spring (February/March) to control weeds until plots were plowed in late spring (April/May). This early spring herbicide application permitted weed control, eliminated two to four tillage operations during fallow, and more importantly avoided tillage when the ground was wet. Partially dried steer manure applied to the MN plots was obtained from nearby feedlots since 1931. The dry matter content, organic C, and nutrients in manure and pea vine has been analyzed since1976.

Winter wheat was planted in mid-October, harvested in mid-July of the following year, and the land fallowed for the next 14 months before planting of the next wheat crop. All wheat – fallow plots were moldboard plowed and smoothed with cultivator or harrow in the spring. Wheat was planted at 90 kg ha^{-1} in rows 17.3 cm apart using JD8300 drill (https://www.deere.com) until 2002 and at 92 kg ha^{-1} in rows 16.5 cm apart using an International disc drill since (Great Plains Manufacturing, Salina KS). Wheat yield was determined by combine harvesting a center portion of a plot at approximately 9–12% grain moisture. A 10.1- × 40.2-m plot was harvested during 1931–1950, two 3.6- × 40.2-m swathes during 1951–1966, one 2.1- × 40.2-m swath during 1967–1980, and two 2.1- × 20.1-m swathes since 1981. We also calculated precipitation use efficiency (PUE) by dividing wheat yield by total effective precipitation, calculated by adding 24% of fallow year precipitation with crop year precipitation (Schillinger 2001).

Soil sampling and laboratory analysis

Soil samples were collected from 0 to 30 and 30–60 cm depths. Details of soil sampling and laboratory SOC and N analyses for the period before 1986 were described by Rasmussen and Parton (1994). Soil sampling intensity for the 1931–1964 is not known. Soil samples were collected from randomly selected 8–16 places within a plot using a hand probe during 1964, 1976, and 1986. Soil samples were collected from four places using a truck-mounted Giddings Hydraulic Probe (i.d. 3.6 cm, Giddings Machine Company, Inc., Windsor, CO) since 1986. The samples collected from each plot were composited by each depth increment, thoroughly

homogenized, and brought to the laboratory for SOC and N analysis.

In the laboratory, all visible crop residues (roots, stems, and leaves) were removed and the soil was sieved to pass through a 2-mm sieve. Approximately 10-g subsamples were oven dried at 60 °C for 72 h and finely ground on a Shatter Box 8530 ball mill (Spex Sample Prep., Metuchen, NJ). The SOC and N were analyzed using a Thermo Finnigan N and C analyzer (Flash EA 1112 series, Thermo Finnigan, San Jose, CA). This method was used for soil samples collected in 1995, 2005, and 2010. The method for SOC analysis for samples collected during 1931–1986 was described by Rasmussen and Parton (1994). In brief, SOC content was analyzed using the loss on ignition method for 1931 and 1941 samples. No method of SOC analysis was reported for 1951 and 1964 samples. Total C content was determined by dry combustion using a LECO CN analyzer (LECO Corp. St. Joseph, MI) in 1976 and 1986. Soil total N in soil samples collected during 1931–1986 were analyzed using a standard macro-Kjeldahl procedure. The SOC and N concentrations (g kg^{-1}) were converted to SOC and N content (kg ha^{-1}) using soil bulk density (BD).

The BD was 1.17 g cm^{-3} in 1931 at the time of establishment of the long-term plots (Pendleton Experiment Station, 1931, unpublished annual report). It was measured by using a core method in 1991 and 2010 (Blake and Hartge 1986). The BD was not significantly different between treatments in 1991 and averaged 1.22 g cm^{-3}. Bulk density was also not significantly different among management systems in 2010 (Ghimire et al. 2015). The BD measured in 1991 was used for SOC and N contents in 1986 and 1995 and BD measured in 2010 was used for calculating SOC and N contents in 2005 and 2010. The BD values of 1.18, 1.19, 1.20, and 1.21 g cm^{-3} were used for 1941, 1951, 1964, and 1976 soil samples, respectively (Rasmussen and Parton 1994).

Relationships between SOC inputs and decomposition under different treatments in 2010 were estimated assuming first-order kinetics as suggested by Huggins et al. (1998), i.e.,

$$dCs/dt = hA - kCs \qquad (1)$$

Where, Cs is the SOC, t is time, A is biomass carbon addition to soil per unit time, h is humification coefficient, and k is the SOC decay rate per unit time. Turnover time was calculated as 1/k and SOC at equilibrium (SOCe) as hA/k. Crop residue and manure C inputs were calculated based on published data from CR-LTE (Ghimire et al. 2015; Machado 2011; Rasmussen and Parton 1994). Plant biomass C and N on wheat residues as well as wheat grain N during 1976–2004 were analyzed on a LECO CN analyzer as explained earlier for soil samples. Humification coefficient (h) of 0.2 for cultivated systems was used based on reported determinations and assumed to be constant across treatments (Buyanovsky et al. 1987). Nitrogen balance was calculated based on N input from crop residues, pea vine, and manure and grain N export in each treatment at harvest.

Statistical analysis and calculations

Crop yield, SOC, and N data for 1995 to 2010 were analyzed using a MIXED procedure of SAS v9.3 (Littell et al. 2002). In this analysis, treatments and years were considered fixed effects and replications as random effects. Treatment means in F test ($P < 0.05$) were separated by using a LSMEAN procedure in SAS (SAS Institute Inc., Cary, NC.). Only the treatments averages for SOC, N, and yield data were archived prior to 1995. Therefore, treatments averages were used for trend analysis (1931–2010). The medium-tall variety (Rex M-1) was replaced by semi-dwarf varieties in 1967. Therefore, wheat yield trends under different treatments were analyzed separately for the time-period 1931–1966 and 1967–2010 using a linear or quadratic autoregression procedure (PROC AUTOREG) in SAS. The trend of SOC and N (1931–2010) were also analyzed using suitable (linear or quadratic) autoregression models. Furthermore, yield trend from 1931 through 2010 was analyzed using autoregressive integrated moving average (ARIMA) model described by Brocklebank and Dickey (2003).

$$(1-B)Y_t = \mu + \left(\frac{\theta(B)}{\varnothing(B)} \right) a_t \qquad (2)$$

Where, 'Y' is response variable, 't' is time (year), 'B' is backshift operator, where $BX_t = X_{t-1}$, μ is a mean term; $\theta(B)$ is the moving-average operator, $\phi(B)$ is the autoregressive operator, and α_t = random error. Relationship between SOC, N, and wheat yield was analyzed using Pearson correlation analysis in SAS. All the regression and correlation analyses were performed at $p < 0.05$.

Results

Growing degree day and precipitation

Long-term average crop year GDD (1931–2010) were 2641 °C (Fig. 1). There were seven years with high (>20% of the long-term average) and low (<20% of the long-term average) crop growing period GDD. Similarly, long-term average precipitation for crop growing period was 395 mm, but it was not consistent between years. There was 17 high precipitation (>20% of the long-term average) and 13 low precipitation (<20% of the long-term average) years. Average precipitation was stable from 1931 till 1955, decreased from 1956 to 1968, remained above long-term average for several years, and decreased again during 1980s to 1994 and during 1995 to 2010. The influence of precipitation on crop production in WW-SF system is discussed below.

Wheat yield trends

The yield of medium-tall variety (Rex M-1) decreased linearly across all treatments during 1931–1966. During this period, the annual rate of yield decline was 9 kg ha^{-1}, 18 kg ha^{-1}, 30 kg ha^{-1}, and 36 kg ha^{-1} in MN, PV, NB, and FB, respectively (Fig. 2a). Yield trend of semi-dwarf varieties (1967–2010), however, revealed a polynomial response in MN and PV treatments and a linear

decrease in yield in FB and NB treatments (Fig. 2b) with the loss of 20 kg ha^{-1} yr.$^{-1}$. Further analysis of wheat yield data for the 1996–2010 period using a Mixed Model in SAS revealed that wheat yield was significantly greater in MN treatment than in other treatments (PV, NB, and FB) (Table 1). Average wheat yield in last 15 years was 104% and 56% more in MN and PV treatments, respectively, than in FB. Wheat yields were not significantly different between FB and NB treatments. Both treatments did not receive any organic amendments or fertilizer throughout the study. The PUE followed a similar trend and was significantly greater in MN than other treatments (PV, NB, and FB) for several years (Table 1). The average wheat yield long-term trend (1931–2010) was best explained by ARIMA models (Table 2, Fig. 3). Wheat yield increased across all treatments after the introduction of semi-dwarf wheat varieties in 1967, but immediately started to decrease in FB and NB treatments. The yield of semi-dwarf wheat varieties increased and sustained for several years in PV and MN before starting to decrease from the 1990s onwards.

Soil organic carbon and total nitrogen

The SOC content was significantly greater under MN than under all other treatments in 1995 as well as in

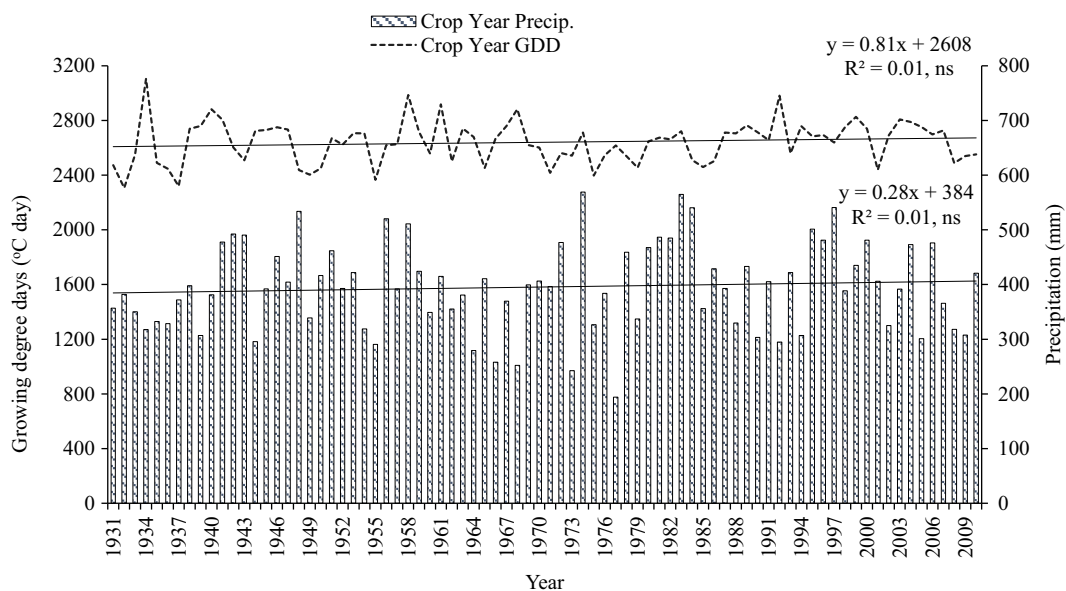Fig. 1 Growing degree days (GDD) and crop year (October-June) precipitation at the research site during 1931-2011

Fig. 2 Crop yield trend during two time periods (a. 1931–1966 and b. 1967–2010) in selected treatmetns of crop residue long-term experiment. FB = fall burning of wheat residue, MN = manure application (22.4 Mg ha^{-1} crop^{-1}), PV = pea vine incorporation (2.24 Mg ha^{-1} crop^{-1}), and NB = no burning of wheat residue
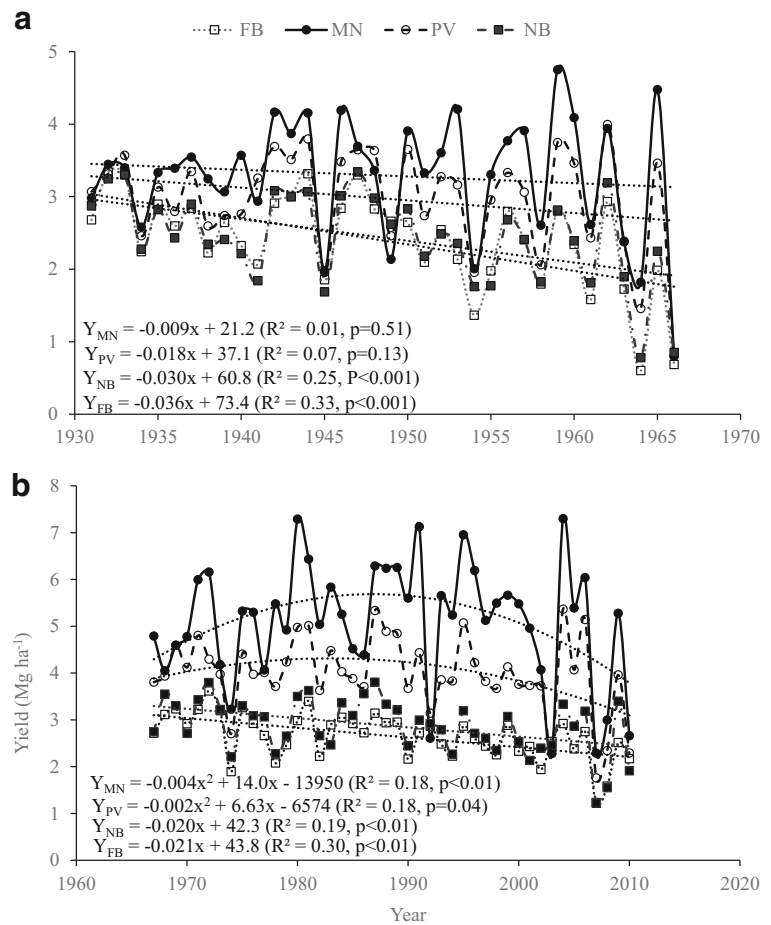
2010 in 0–30 cm depth (Table 3). The SOC in PV was also significantly more than FB and NB in both years. It was not significantly different among all treatments in 30–60 cm soil depth. The long-term average SOC trend from 1931 to 2010 revealed a significant linear decrease in SOC at a rate of 280 kg ha^{-1} yr.$^{-1}$, 226 kg ha^{-1} yr.$^{-1}$ and 116 kg ha^{-1} yr.$^{-1}$ in FB, NB, and PV treatments, respectively, in 0–30 cm soil depth (Fig. 4a). Average SOC content in MN treatment increased at 61 kg ha^{-1} yr.$^{-1}$ in 0–30 cm soil depth. Soil organic C in 30–60 cm, however, decreased consistently across all treatments with the rate of 175–200 kg ha^{-1} yr.$^{-1}$(4b).

Soil N content in 0–30 cm depth was significantly more under MN than in all other treatments in 1995 and it was not significantly different among MN, NB, and PV in 2010 (Table 3). Soil N was also not significantly different between FB and NB in 2010. In MN, soil N in 0–30 cm followed a polynomial trend, increasing slightly during the 1931–1995 and decreasing thereafter

(Fig. 5). In FB, NB, and PV treatments soil N decreased linearly throughout the 1931–2010 period. The rate of N loss was 14 kg ha^{-1} yr.$^{-1}$, 12 kg ha^{-1} yr.$^{-1}$, and 5 kg ha^{-1} yr.$^{-1}$ in FB, NB, and PV treatments, respectively. Soil N in 30–60 cm soil depth decreased linearly across all treatments and ranged from 5 to 12 kg ha^{-1} yr.$^{-1}$(5b).

Soil carbon turnover and nitrogen balance

The SOC decay rate was smaller for PV and FB treatments than for NB and MN (Table 4). Turnover time for SOC was longer for PV followed by FB than NB and MN. Despite smaller decay rate, it appears SOC continues to decrease for next 66 years in FB until it equilibrate at 6.06 Mg ha^{-1}. Similarly, SOC decay continues for next 57 years in NB and it equilibrate at 17.2 Mg ha^{-1}. The turnover time is 82 and 57 years

Table 1 Total grain yield and precipitation use efficiency of winter wheat during 1996–2010 period in selected treatments of crop residue-long term experiment

Year	Total grain yield (Mg ha^{-1})				Precipitation use efficiency (kg ha^{-1} mm$^{-1)}$)			
	FB	NB	PV	MN	FB	NB	PV	MN
1996	2.60c	2.71c	4.22b	6.19a	4.46c	4.65c	7.23b	10.6a
1997	2.44c	2.61c	3.82b	5.12a	3.82c	4.09c	5.99b	8.04a
1998	2.25c	2.34c	3.67b	5.50a	4.54c	4.73c	7.40b	11.08a
1999	2.88c	3.07c	4.13b	5.66a	5.76c	6.14c	8.25b	11.3a
2000	2.33c	2.53c	3.76b	5.48a	3.82c	4.32c	6.42b	9.36a
2001	2.43c	2.13c	3.73b	4.96a	4.96c	4.35c	7.63b	10.1a
2002	1.94d	2.40c	3.72b	4.07a	4.68c	5.78b	8.99a	9.82a
2003	2.28c	2.42b	2.46ab	2.54a	4.9a	5.23a	5.32a	5.49a
2004	2.92d	3.33c	5.36b	7.29a	5.07c	5.79c	9.31b	12.7a
2005	2.38c	2.87c	4.07b	5.39a	5.80c	6.99b	12.7a	13.2a
2006	2.75d	3.18c	5.14b	6.04a	5.07c	5.88c	9.49b	11.2a
2007	1.23c	1.22c	1.76b	2.29a	2.71c	2.69c	3.87b	5.04a
2008	1.58b	1.55b	2.34a	3.00a	3.75c	3.68c	5.56b	7.11a
2009	2.51d	3.40c	3.96b	5.28a	4.96d	6.72c	7.83b	10.4a
2010	2.17b	1.91b	2.29ab	2.66a	3.32b	3.78ab	3.98ab	4.63a

†FB = fall burning of crop residue, NB = no burning of crop residue, PV = pea vine incorporation, and MN = steer manure application. Yield data followed by different letters indicate significant difference between treatments within a year ($P < 0.05$)

for PV and MN treatments. SOC in these treatments will equilibrate at higher SOC level than previous two treatments (Table 4).

Evaluation of N balance using N input from crop residues and N loss in grain harvest revealed that MN is the only treatment that maintained positive N balance (Table 5). Total grain N export in FB, NB, and PV was 29.7 kg ha^{-1} yr.$^{-1}$, 32 kg ha^{-1} yr.$^{-1}$ and 52.6 kg ha^{-1} yr.$^{-1}$, respectively. Correlation analysis among average SOC, N, and crop yield for, 1931–1966, 1967–2010, and 1931–2010 revealed that differences in SOC

and N contents between treatments were strongly and positively correlated with decrease in crop yield (Table 6).

Discussion

The continuous use of the WW-SF system in IPNW has significantly depleted SOC, N, and crop yields. Results of this study revealed that maintenance of SOC and N in the soil profile and sustaining crop yields in a WW-SF

Table 2 Summary statistics of long-term trend in crop yield (1931–2010) using best fitting Autoregressive models

Trt.	1931–1966			1967–2010		
	Model	R^2	P	Model	R^2	P
FB	$CY_{(FB)t} = -0.036t + 73.3$	0.33	<0.001	$CY_{(FB)t} = -0.02t + 43.9$	0.30	<0.001
NB	$CY_{(NB)t} = -0.030t + 60.8$	0.25	<0.001	$CY_{(NB)t} = -0.02t + 42.4$	0.19	0.003
PV	$CY_{(PV)t} = -0.018t + 37.0$	0.07	0.13	$CY_{(PV)t} = -0.002t^2 + 6.61t - 6552$	0.18	<0.04
MN	$CY_{(FB)t} = -0.009t + 21.1$	0.01	0.51	$CY_{(MN)t} = -0.004t^2 + 14.0t - 13921$	0.18	<0.008

†$CY_{(x)t}$ = Crop yield in treatment X, where X = FB, NB, PV, and MN. FB = fall burning of crop residue, NB = no burning of crop residue, PV = pea vine incorporation, MN = manure addition; t = time (year); B = backshift operator that is $BX_t = X_{(t-1)}$; and α_t = random error

Fig. 3 Crop yield trend during 1931–2010 in selected treatmetns of crop residue long-term experiment using autoregressive integrated moving average (ARIMA) model. FB = fall burning of wheat residue, MN = manure application (22.4 Mg ha^{-1} crop^{-1}), PV = pea vine incorporation (2.24 Mg ha^{-1} crop^{-1}), and NB = no burning of wheat residue
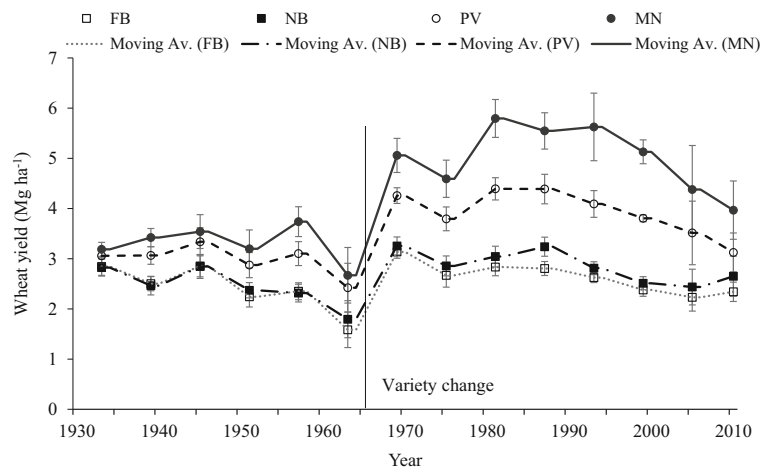
without artificial N inputs depend on the amount and quality of organic inputs. In line with this, previous studies reported that a minimum biomass C input of about 3.27 Mg ha^{-1} yr.$^{-1}$ is required to maintain SOC in a WW-SF system (Machado 2011). Considering root biomass C as 45% of aboveground biomass C and 67% residue C lost due to burning, the annual return of above and belowground residue C in FB was up to 72% lower than the required C input to maintain the SOC. Similarly, residue C input was 33% lower in NB than the amount of C required to maintain the SOC. The insufficient organic inputs likely caused continuous depletion in SOC and N contents and thereby contributed to the reduction in wheat yield in the WW-SF systems. One may argue that N

addition can offset yield loss in the WW-SF system. Our previous study showed that addition of 90 kg N ha^{-1} crop^{-1} (45 kg N ha^{-1} yr.$^{-1}$) is required to maintain crop yield in a WW-SF system (Ghimire et al. 2017). Any further increase in N input did not increase wheat yield, it rather increased soil acidity and decreased SOC and N stock. Similarly, addition of 180 kg N ha^{-1} every other year (90 kg N ha^{-1} yr.$^{-1}$ for 70 years) in another long-term WW-SF experiment at CBARC has not stopped the depletion of SOC and N (Machado 2011; Ghimire et al. 2015). The MN treatment received 105 kg N ha^{-1} yr.$^{-1}$, which was sufficient to maintain positive N balance in 0–30 cm depth, but did not offset yield loss during 1995–2010.

Table 3 Soil organic carbon and nitrogen (Mg ha^{-1}) in 1995 and 2010 in selected treatments in crop residue-long term experiment

Soil depth	Treatment	SOC†		N†	
		1995	2010	1995	2010
0–30 cm	FB	27.0c	23.4c	2.86c	2.80b
	NB	32.3c	29.1c	3.32b	3.25ab
	PV	39.9b	37.6b	3.53b	3.48a
	MN	49.8a	50.0a	4.20a	3.90a
	P value	*<0.001*	*0.01*	*0.02*	*<0.001*
30–60	FB	22.0a	21.4a	2.44a	2.52a
	NB	21.5a	20.8a	2.35a	2.20a
	PV	23.0a	22.3a	2.58a	2.52a
	MN	21.9a	21.7a	2.43a	2.49a
	P value	*0.87*	*0.94*	*0.62*	*0.71*

†FB = fall burning of crop residue, NB = no burning of crop residue, PV = pea vine incorporation, and MN = steer manure application. Data followed by different letters within a column indicate significant difference between treatments within a year within a soil depth (P < 0.05)

Fig. 4 Trend of soil organic carbon (1931–2010) in (**a**) 0–30 cm and (**b**) 30–60 cm depths of Crop Residue Long-term Experiment. FB = fall burning of wheat residue, MN = manure application (22.4 Mg ha^{-1} crop^{-1}), PV = pea vine incorporation (2.24 Mg ha^{-1} crop^{-1}), and NB = no burning of wheat residue
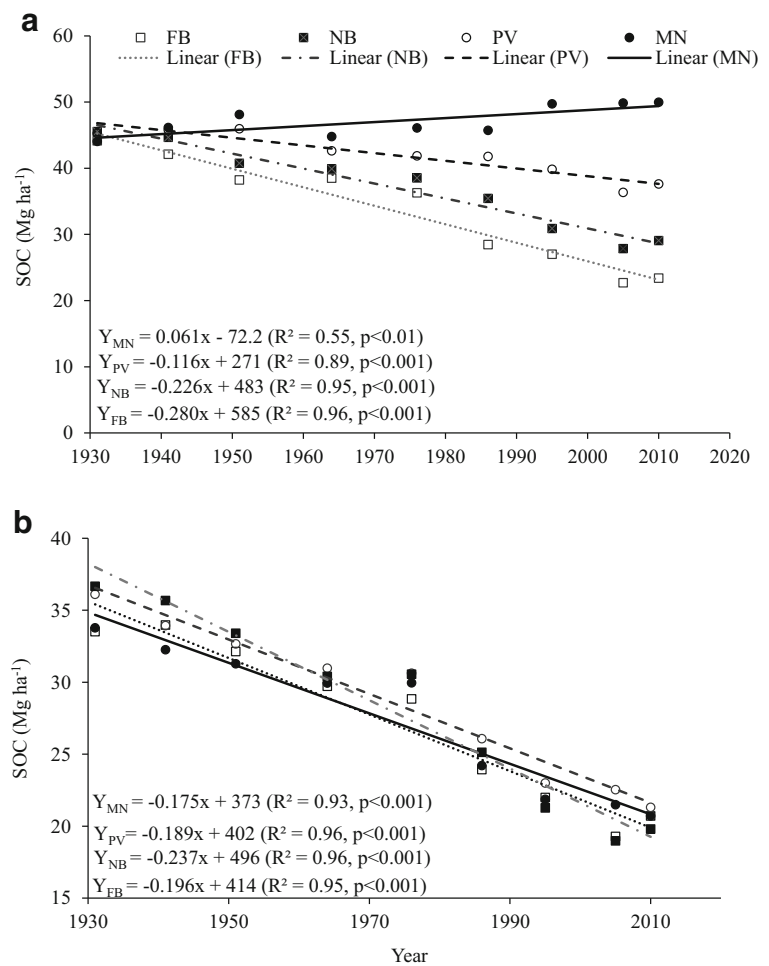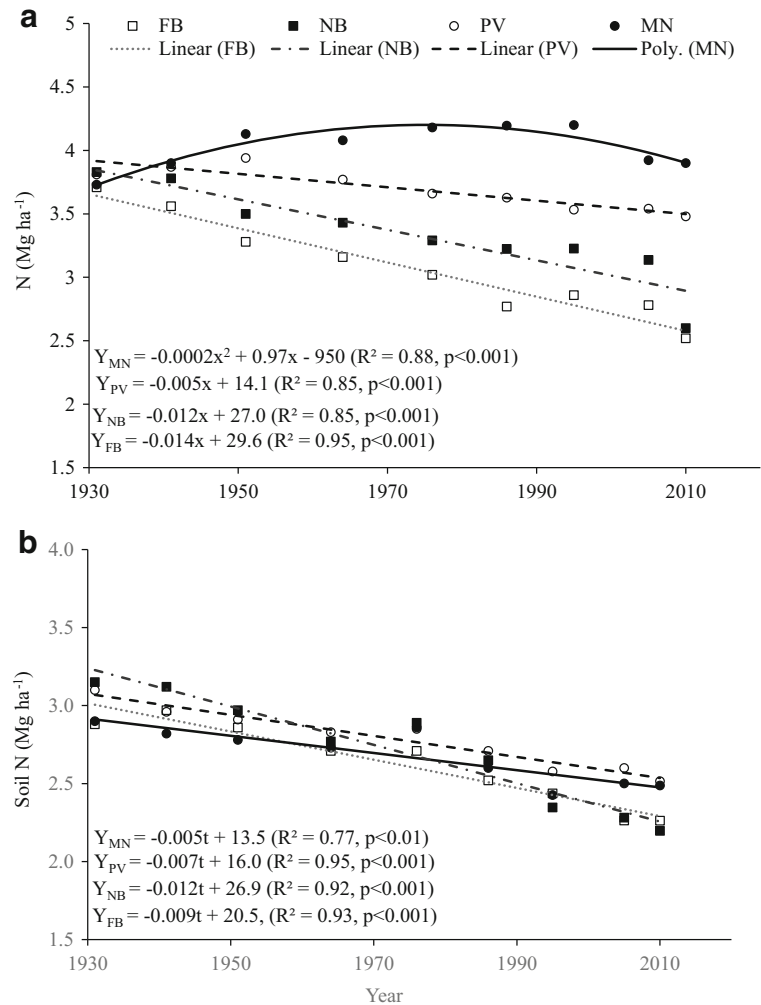

Although SOC and N was maintained at 0–30 cm depth in MN treatment, it was depleting across all treatments in 30–60 cm depth. Greater SOC and N content is often associated with greater soil aggregation (Six et al. 2002), greater microbial biomass, activity, and diversity (Ghimire et al. 2014), higher root biomass (Qin et al. 2004), improved water storage (Machado et al. 2008; Sherrod et al. 2005), and greater crop yield. However, yield response to SOC and N loss from lower soil depth has not been studied extensively. We suspect SOC loss in lower depth has significantly contributed to low soil water and nutrient storage and thereby decreasing wheat yields. Loss of the ecosystem functions associated with SOC and N loss significantly influenced crop production and SOM turnover (Huggins et al. 1998; Sherrod et al. 2005).

Maintenance of SOC and nutrients in agroecosystems also depend on the decay rate of organic residues

(Huggins et al. 1998; Smith 2008). Greater decay rate would be expected with the larger input of organic residues but our result showed lower SOC decay rate in PV and FB treatment. It is not clear how residue burning vs no burning, and pea vines and manure addition influenced the decay rate. It appears pea vine and fall burning lowered SOC decay rate while it was not influenced by manure application. Residue burning causes loss of labile C input leaving more recalcitrant material in the soil (Neff et al. 2005). We speculate high quality pea residue as indicated by its low C:N ratio helped in reducing SOC decay by reducing priming of existing organic matter in the soil (Kirkby et al. 2013; Kirkby et al. 2014). Carbon to N ratio was highest for wheat residue (81.8) followed by pea vines (22.2) and manure (12.1). Studies demonstrated that low C:N ratio residues contribute to SOM building and minimizes SOC depletion (Huggins et al. 1998). Smaller decay rate

Fig. 5 Trend of soil total nitrogen (1931–2010) in (**a**) 0–30 cm and (**b**) 30–60 cm depths of crop residue long-term experiment. FB = fall burning of wheat residue, MN = manure application (22.4 Mg ha^{-1} crop^{-1}), PV = pea vine incorporation (2.24 Mg ha^{-1} crop^{-1}), and NB = no burning of wheat residue

a

Legend: □ FB ■ NB ○ PV ● MN
····· Linear (FB) —·— Linear (NB) — — Linear (PV) —— Poly. (MN)

$Y_{MN} = -0.0002x^2 + 0.97x - 950$ (R^2 = 0.88, p<0.001)
$Y_{PV} = -0.005x + 14.1$ (R^2 = 0.85, p<0.001)
$Y_{NB} = -0.012x + 27.0$ (R^2 = 0.85, p<0.001)
$Y_{FB} = -0.014x + 29.6$ (R^2 = 0.95, p<0.001)

N (Mg ha^{-1})

b

$Y_{MN} = -0.005t + 13.5$ (R^2 = 0.77, p<0.01)
$Y_{PV} = -0.007t + 16.0$ (R^2 = 0.95, p<0.001)
$Y_{NB} = -0.012t + 26.9$ (R^2 = 0.92, p<0.001)
$Y_{FB} = -0.009t + 20.5$, (R^2 = 0.93, p<0.001)

Soil N (Mg ha^{-1})

Year

in FB compared to NB treatment, on the other hand, may have been attributed to the loss of easily decomposable organic C and N compounds during residue burning. More research will improve our understanding of how

change in residue quality after burning influence SOC and N dynamics in agroecosystems.

Given that no source of N (i.e. mineral fertilizer or legumes) was applied to the FB and NB treatments for

Table 4 Soil carbon (C) input, changes in soil organic carbon content during 1931–2010 (dSOC), decay rate (k), turnover time, and equilibrium soil organic carbon (eSOC) content in 0–30 cm depth of selected treatments in crop residue long-term experiment

Trt†	Annualized C input			dSOC/dt (Mg ha^{-1} yr.$^{-1}$)	Decay rate (k) (yr^{-1})	Turnover time (yr)	eSOC Mg ha^{-1}
Mg ha^{-1} yr.$^{-1}$	Crop residue	Other sources	Total				
FB	0.46	–	0.46	−0.26	0.015	66	6.06
NB	1.51	–	1.51	−0.21	0.018	57	17.2
PV	2.13	0.41	2.54	−0.10	0.012	82	42.0
MN	2.83	0.85	3.68	+0.02	0.018	57	41.9

†FB = fall burning of crop residue, NB = no burning of crop residue, PV = pea vine incorporation, and MN = steer manure application

Table 5 Annualized soil N input and N loss during crop harvest in selected treatments of crop residue long-term experiment

Trt†	N input			N loss in grain harvest	N balance
	Crop residue kg ha^{-1} yr.$^{-1}$	Other amendments	Total		
FB	5.64	–	5.64	29.7	−24.1
NB	18.5	–	18.5	32.6	−14.1
PV	26.0	18.5	44.5	52.6	−8.42
MN	35.0	70.0	105	78.2	+26.8

†FB = fall burning of crop residue, NB = no burning of crop residue, PV = pea vine incorporation, and MN = steer manure application

80 years, it is likely that these treatments have been highly N limited for much of the experiment. Each crop year, 37–70 kg N ha^{-1} is lost in grain harvest from CR-LTE plots (Rasmussen and Parton 1994). Evaluation of grain N data from 1986 to 2004 revealed that MN treatment was the only treatment able to maintain a positive N balance (Table 5). All other systems were net negative in N balance due to insufficient N from residues and continuous depletion of N stock from the soil profile. The MN and PV treatments appeared to have maintained a positive N balance for several years leading to reduced yield loss as compared to other two treatments. Studies suggest that limited nutrient availability can limit SOC sequestration and thereby reduce crop production (Kirkby et al. 2013; Kirkby et al. 2014). Since the only source of mineral N for the crop in FB and NB treatments would be from N mineralization, the continuous depletion of N over time ultimately reduced crop yields irrespective of the crop variety changes over time.

Interannual variability in temperature and precipitation probably caused the year to year variability in wheat yield. Although there was no statistically significant

Table 6 Correlation coefficients for soil carbon and nitrogen at 0–30 cm soil depth with crop yield in selected treatments of crop residue long-term experiments

Time period	SOC†		N	
	R	P value	R	P value
1931–1966	0.79	<0.001	0.86	<0.001
1967–2010	0.87	<0.001	0.92	<0.001
1931–2010	0.56	<0.001	0.65	<0.001

†Correlation analysis was performed on the wheat yield, soil organic carbon (SOC) and total nitrogen (N) data averaged for the given time period

trend, there was greater variability in precipitation (as indicated by high and low precipitation years) and greater GDD in last two decades than in previous decades. This may have caused higher soil water loss and changes in crop physiological processes that can affect crop yields. Our analysis revealed small increases in growing season temperature and precipitation in the last 80-years. In general, increased average growing season precipitation is expected to increase crop production (Brown and Huggins 2012; Nelson 2009) and vice versa. Smaller rate of yield decline in MN treatment compared with other treatments and no significant interaction with weather variables and crop yield suggested that SOC and N play a critical role in crop production and sustainability of WW-SF systems. Improvement in nutrient management practices in the last several decades have helped in optimizing N management (Guo et al. 2012). However, some dryland producers in the IPNW still rely on minimum inputs for crop production. Long-term experiments such as CR-LTE provide valuable information regarding long-term impacts of crop residue management on agroecosystem responses that helps in improving sustainability of WW-SF system.

Conclusions

Maintenance of SOC and N in the dryland WW-SF systems of the IPNW depend on the balance of SOC and N inputs with losses. We evaluated trends of SOC, N and crop yield from 1931 to 2010 in selected treatments of CR-LTE, and calculated SOC decay and N balance under long-term crop residue and nutrient management. Evaluation of SOC, N, and crop yield trend for last 80 years revealed an important contribution of organic residues and manure on SOC, N, and crop yield.

Gradual decrease in crop yields over the study years was associated with decrease in SOC and N contents in the soil profile. The SOC depletion continues until it reaches to the new equilibrium. However, further decrease in SOC will negatively impact sustainability of dryland cropping in the IPNW. Long-term experiments such as CR-LTE are important for understanding long-term impacts of agricultural management on agroecosystem responses, and for improving sustainability of WW-SF system. Maintenance of SOC and N in the soil profile can improve crop production and sustainability of dryland cropping systems in the IPNW and similar agroecosystems across the world.

References

Blake GR, Hartge KH (1986) Bulk density. In: Klute A (ed) Methods of soil analysis, part 1: physical and mineralogical methods, 2nd edn. American Society of Agronomy and Soil Science Society of America, Madison, pp 363–375

Brocklebank JC, Dickey DA (2003) SAS for forecasting time series. SAS Institute Inc, Cary

Brown TT, Huggins DR (2012) Soil carbon sequestration in the dryland cropping region of the Pacific northwest. J Soil Water Conserv 67:406–415

Buyanovsky GA, Kucera CL, Wagner GH (1987) Comparative analyses of carbon dynamics in native and cultivated ecosystems. Ecology 68:2023–2031

Camara KM, Payne WA, Rasmussen PE (2003) Long-term effects of tillage, nitrogen, and rainfall on winter wheat yields in the Pacific northwest. Agron J 95:828–835

Ghimire R, Norton JB, Stahl PD, Norton U (2014) Soil microbial substrate properties and microbial community responses under irrigated organic and reduced-tillage crop and forage production systems. PLoS One 9(8):e103901

Ghimire R, Machado S, Rhinhart K (2015) Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat – fallow systems. Agron J 107:2230–2240

Ghimire R, Machado S, Bista P (2017) Soil pH, soil organic matter, and crop yields in winter wheat–summer fallow systems. Agron J 109:706–717

Guo S, Wu J, Coleman K, Zhu H, Li Y, Liu W (2012) Soil organic carbon dynamics in a dryland cereal cropping system of the loess plateau under long-term nitrogen fertilizer applications. Plant Soil 353:321–332

Hooker BA, Morris TF, Peters R, Cardon ZG (2005) Long-term effects of tillage and corn stalk return on soil carbon dynamics. Soil Sci Soc Am J 69:188–196

Horner GM, Oveson MM, Baker GO, Pawson WW (1960) Effect of cropping practices on yield, SOM and erosion in the Pacific Northwest wheat region. USDA-ARS, Washington, DC 20006–1002 USA

Huggins DR, Buyanovsky GA, Wagner GH, Brown JR, Darmody RG, Peck TR, Lesoing GW, Vanotti MB, Bundy LG (1998) Soil organic C in the tallgrass prairie-derived region of the corn belt: effects of long-term crop management. Soil Tillage Res 47:219–234

Kirkby CA, Richardson AE, Wade LJ, Batten GD, Blanchard C, Kirkegaard JA (2013) Carbon-nutrient stoichiometry to increase soil carbon sequestration. Soil Biol Biochem 60:77–86

Kirkby CA, Richardson AE, Wade LJ, Passioura JB, Batten GD, Blanchard C, Kirkegaard JA (2014) Nutrient availability limits carbon sequestration in arable soils. Soil Biol Biochem 68:402–409

Lemke RL, VandenBygaart AJ, Campbell CA, Lafond GP, Grant B (2010) Crop residue removal and fertilizer N: effects on soil organic carbon in a long-term crop rotation experiment on a Udic Boroll. Agric Ecosyst Environ 135:42–51

Littell RC, Stroup WW, Freund RJ (2002) SAS for linear models. SAS Institute, Cary NC, p 466

Machado S (2011) Soil organic carbon dynamics in the Pendleton long-term experiments: implications for biofuel production in Pacific northwest. Agron J 103:253–260

Machado S, Rhinhart K, Petrie S (2006) Long-term cropping system effects on carbon sequestration in eastern Oregon. J Environ Qual 35:1548–1553

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

Miles RJ, Brown JR (2011) The Sanborn field experiment: implications for long-term soil organic carbon levels. Agron J 103:268–278

Nafziger ED, Dunker RE (2011) Soil organic carbon trends over 100 years in the morrow plots. Agron J 103:261–267

Neff JC, Harden JW, Gleixner G (2005) Fire effects on soil organic matter content, composition, and nutrients in boreal interior Alaska. Can J For Res 35:2178–2187

Nelson GC (2009) Agriculture and climate change: an agenda for negotiation in Copenhagen. International Food Policy Research Institute. 2033 K Street, NW, Washington DC 20006–1002 USA

Oveson MM (1966) Conservation of soil nitrogen in a wheat summer fallow farming practice. Agron J 58:444–447

Peacock AD, Mullen MD, Ringelberg DB, Tyler DD, Hedrick DB, Gale PM, White DC (2001) Soil microbial community responses to dairy manure or ammonium nitrate applications. Soil Biol Biochem 33:1011–1019

Qin RJ, Stamp P, Richner W (2004) Impact of tillage on root systems of winter wheat. Agron J 96:1523–1530

Rasmussen PE, Parton WJ (1994) Long-term effects of residue management in wheat-fallow .1. Inputs, yield, and soil organic matter. Soil Sci Soc Am J 58:523–530

Schillinger WF (2001) Minimum and delayed conservation tillage for wheat–fallow farming. Soil Sci Soc Am J 65:1203–1209

Schillinger WF, Papendick RI (2008) Then and now: 125 years of dryland wheat farming in the inland Pacific northwest. Agron J 100:S166–S182

Schillinger WF, Papendick RI, Guy SO, Rasmussen PE, van Kessel C (2006) Dryland cropping in the Western United States. In: Peterson GA, Unger PW, Payne WA (ed) Dryland Agriculture, Agron Monogr 23. American Society of Agronomy and Soil Science Society of America, Madison, WI p 365–393

Sherrod LA, Peterson GA, Westfall DG, Ahuja LR (2005) Soil organic carbon pools after 12 years in no-till dryland agroecosystems. Soil Sci Soc Am J 69:1600–1608

Six J, Feller C, Denef K, Ogle SM, Sa JCD, Albrecht A (2002) Soil organic matter, biota and aggregation in temperate and tropical soils - effects of no-tillage. Agronomie 22:755–775

Smith P (2008) Land use change and soil organic carbon dynamics. Nutr Cycl Agroecosyst 81:169–178

Soil Survey Staff (2014) Web Soil Survey. Available at http://websoilsurvey.nrcs.usda.gov. Natural Resources Conservation Service, United States Department of Agriculture. Accessed Oct 22, 2014

Tiessen H, Stewart JWB, Bettany JR (1982) Cultivation effects on the amounts and concentration of carbon, nitrogen, and phosphorus in grassland soils. Agron J 74:831–835

Western Regional Climate Center (2014) Oregon climatological data summaries. http://www.wrcc.dri.edu/summary/Climsmwy.html. Desert Research Institute, Reno, NV. Accessed Oct 22, 2014

Wuest SB, Gollany HT (2013) Soil organic carbon and nitrogen after application of nine organic amendments. Soil Sci Soc Am J 77:237–245