Long-Term Crop Residue and Nitrogen Management Effects on Soil Profile Carbon and Nitrogen in Wheat – Fallow Systems

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ABSTRACT

Intensive cultivation of native grassland for dryland agriculture continuously depleted soil organic carbon (SOC) and nutrients. In 2010, we evaluated the influence of 80 years of crop residue and nutrient management practices on SOC and nitrogen (N) in 0-60 cm soil depth profiles in conventionally tilled winter wheat (*Triticum aestivum* L.) – summer fallow (WW-SF) system. Residue and N treatments, no N addition with fall burning (FB0), spring burning (SB0), and no burning (NB0), 45 kg N ha^{-1} with SB (SB45) and NB (NB45), 90 kg N ha^{-1} with SB (SB90) and NB (NB90), manure (MN, 5.32 Mg dry mass ha^{-1} yr^{-1}), and pea vines (PV, 0.99 Mg dry mass ha^{-1}yr^{-1}), were in ordered arrangement, and a grassland (GP) was used as a reference. All WW-SF treatments had less SOC and N stocks than GP. The SOC stocks were lowest under FB0 with 50% less SOC than GP. The WW-SF treatments have depleted up to 63% and 26% of SOC and N from surface soil since 1931 when the experiment was initiated. For example, FB0 and MN depleted SOC at rates of 0.64 and 0.17 Mg ha^{-1}yr^{-1}, respectively. Nitrogen stocks decreased at a rate of 0.02 Mg ha^{-1}yr^{-1} in FB, SB, and NB treatments, and 0.01 Mg ha^{-1}yr^{-1} in PV treatment. The MN treatment maintained soil N at 6.63 Mg ha^{-1}. Reduction in tillage, application

of low C:N ratio residues, and elimination of burning can improve sustainability of winter wheat production in the summer fallow region of the PNW.

Abbreviations: C, Carbon; CR-LTE, Crop residue long-term experiment; DM, Dry matter; FB, Fall burning; GP, undisturbed grassland; N, Nitrogen; NB, No burning; PLTEs, Pendleton long-term experiments; PNW, Pacific Northwest; SB, Spring burning; SOC, Soil organic carbon; TN, Total nitrogen; WW-SF, Winter wheat – summer fallow.

INTRODUCTION

Interest in soil health, in particular soil organic carbon (SOC) and nitrogen (N) storage, has greatly increased in the last few years mainly due to increasing awareness of the continuous decline in SOC and nutrients in cultivated soils. The decline in soil health could not be more evident than in the inland Pacific Northwest (PNW), where traditional winter wheat (*Triticum aestivum* L.) – summer fallow (WW-SF) rotation is practiced on more than 2 million ha and intensive tillage is utilized to conserve soil water and nutrients mineralized during the fallow period (Schillinger et al., 2003; Schillinger and Papendick, 2008). Repeated tillage along with burning or removal of crop residue has depleted more than 60% of SOC from topsoil in the last century (Brown and Huggins, 2012). Producers burn or remove crop residues to minimize possible yield loss due to poor plant establishment (Wuest et al., 2000) and insect-pests and diseases (Rasmussen and Parton, 1994; Machado, 2011). Crop residue burning or removal is also preferred to mitigate poor seed drill performance, low spring soil temperature, poor seedling growth, and low wheat yield when surface residue cover exceeds 2.1 – 3.7 Mg ha^{-1} (Rasmussen et al., 1997; Siemens and Wilkins, 2006). In recent years, crop residues have been removed for bioethanol production, mushroom cultivation, and as a bedding material for farm animals (Lemke et al., 2010; Machado, 2011). Soil organic C loss due to repeated tillage along with crop residue removal for alternative uses demands management strategies that conserve SOC and improve sustainability of dryland cropping in the PNW (Rasmussen and Smiley, 1997; Machado, 2011; Brown and Huggins, 2012).

Long-term studies evaluating soil profile C and N have significantly contributed to our understanding of SOC and N sequestration potential, soil quality, and ecosystem services provided by cropping systems and management practices. These studies are extremely important in semiarid agroecosystems where biomass production and SOC accumulation are limited by low precipitation and WW-SF system (Schillinger et al., 2003; Gollany et al., 2011; Machado, 2011). In these environments, the effects of management practices on SOC and N often take decades to manifest (Rasmussen and Parton, 1994). Under such conditions, only long-term experiments and associated measurements can detect changes in soil biological, physical, and chemical characteristics brought about by different management practices (Rasmussen and Parton, 1994; Miles and Brown; 2011). Furthermore, long-term experiments are the only resource that can be used to validate models that predict the potential of cropping systems to sequester SOC and mitigate global climate change (Rasmussen et al., 1998; Gollany et al., 2011). Consequently, there have been increased global efforts to utilize information derived from long-term experiments to improve sustainability of agriculture (Miles and Brown; 2011; Nafziger and Dunker, 2011). The Pendleton long-term experiments (PLTEs) are now 84 years old, the oldest in the western US, and provide a great resource for studying SOC and N dynamics in the semiarid environments of the PNW.

The PLTEs facilitated an evaluation of different cropping systems and management practices such as crop residue, manure, and fertilizer incorporation on their potential to maintain SOC and increase crop production as early as the 1930s (Rasmussen and Smiley, 1997). Previous studies on the PLTEs revealed that crop residue burning or removal had depleted SOC content (Rasmussen and Parton, 1994; Rasmussen and Smiley, 1997; Machado 2011). For example, Rasmussen and Parton (1994) highlighted changes in SOC and N in the crop residue long-term experiment (CR-LTE) during 1931-1986, and other studies highlighted the possibilities and negative impacts of crop residue removal from dryland WW-SF for biofuel production using data from 1931-2005 (Gollany et al., 2011; Machado 2011). These studies reported that SOC content was decreasing in CR-LTE. Using 1931-1986 data from the CR-LTE plots, Parton and Rasmussen (1994) predicted that it would take about 35 years for SOC to reach a steady state. The SOC loss was attributed mainly to long fallow period between crops and insufficient carbon inputs (Rasmussen et al. 1998; Machado 2011). Studies in other long-term experiments such as Morrow plots and Sanborn field experiments also revealed positive relationship between biomass C input and SOC content (Miles and Brown; 2011; Nafziger and Dunker, 2011). Incorporating crop residue after crop harvest returned significant amount of biomass C to the soil and increased SOC storage (Hooker et al., 2005). A 12-year study on residue production and SOC storage in dryland wheat production systems in the central Great Plains showed little or no response of crop residue on SOC accrual (Halvorson et al., 2002). Fertilizer N addition increased crop production and soil biological activity (Peacock et al., 2001; Camara et al., 2003). Nutrient management through organic sources such as green manure, compost, and biosolids application increased SOC compared with a control treatment that involved no organic residue addition (Rasmussen and Parton, 1994; Wuest and Gollany, 2013).

Although the influence of management changes on SOC and N is not restricted to the tillage depth in agricultural soils, many studies report changes in quantity and properties of SOC and nutrients in the plow layer (West and Post, 2002; VandenBygaart et al., 2003; Baker et al., 2007). For example, only six among 276 paired comparisons of conventional and no-tillage systems in the West and Post (2002) study were from sampling depths deeper than 30 cm. Baker et al. (2007) in their review also reported a limited number of studies comparing SOC in deeper soil profiles. Those studies that compared profile C and nutrients revealed differences in the distribution of SOC and nutrients in soil depths under different tillage and fertility management practices (Baker et al. 2007; Varvel and Wilhelm, 2011). Soil nutrients (mainly N) are expected to follow a similar trend to SOC. However, information regarding responses of management systems on deep soil profile N are less frequently studied than soil profile C (Baker et al., 2007). Evaluating and understanding how crop residue inputs and nutrients influence SOC and N contents in different soil depths can facilitate the development of management practices needed to improve sustainability of dryland cropping systems in the PNW (Schillinger and Papendick, 2008; Machado 2011).

In this paper, we present the status of SOC and N distribution in the 0- to 60-cm soil depth profile of different crop residue and nutrient management practices in the CR-LTE after 80 years (1931-2010). Machado (2011) examined CR-LTE, and Tillage-Fertility and Wheat-Pea experiments of the PLTE and reported SOC changes from 1976-2005. This study reports SOC and N changes from 1931-2010 only in the CR-LTE. For the first time, the SOC and N status in the WW-SF system is reported in relation to the adjacent grassland that has been undisturbed since 1931. We also evaluated SOC and N loss with reference to SOC and N status in 1986, and examined the relationship between C and N inputs and SOC and N stocks to elucidate how quantity and quality of organic inputs influence SOC and N stocks in the semi-arid environment of eastern Oregon. Such information is necessary for designing sustainable cropping systems and is critical for the formulation of science-based agricultural policies.

MATERIALS AND METHODS

Site description

The ongoing CR-LTE and nearby grassland (GP) are located on the Columbia Basin Agricultural Research Center (CBARC) near Pendleton, OR (45º42'N, 118º36'W, Elev. 438 m). The climate is semiarid with cool wet winters and hot dry summers. The 81 yr (1932-2012) average annual maximum and minimum temperatures are 17.4 and 3.06^{o}C, and annual precipitation is 421 mm. About 70% of precipitation occurs between September and March. The soil is classified as a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls), generally well drained, and consist of loess deposits overlying basalt (Soil Survey Staff, 2014).

Experimental design and treatments

The experiment was established as an ordered block of two series of nine treatments, each series representing a wheat or a fallow phase of the WW-SF system. The two series are identical in soil properties and offset by one year to facilitate collection of wheat yield and biomass data each year. All treatments were replicated two times and individual plots were 11.6 m × 40.2 m in size. In addition, treatments were revised as needed to accommodate changes in crop varieties, soil fertility, and management practices over time (Rasmussen and Smiley, 1997; Machado, 2011). Two major revisions were made in 1966-67 and 1979-80 (Table 1). A single medium-tall WW variety (Rex M-1) was grown from 1931 to 1966 and semi-dwarf varieties have been grown since then (Nugaines 1967-1973; Hyslop 1974-1978; Stephens 1979-1991; Malcolm 1992-1995, Stephens 1996-2005, ORCF102 2006-2010).

“[Table 1 here]”

The CR-LTE has crop residue and fertility management treatments that includes fall burning (FB0), spring burning (SB0), and no burning (NB0) of crop residue with no N addition, SB and NB with 45 kg N ha^{-1} (SB45, NB45) and 90 kg N ha^{-1} (SB90, NB90), and NB with manure, and pea vine incorporation. Fall burning of crop residue (FB0) was conducted in late-September and spring burning (SB0, SB45, and SB90) in late March – early April (1931-1994) and late April – early May (1994-2010) of the fallow year. In NB treatments (NB0, NB45, and NB90), wheat stubble was incorporated by moldboard plow (0-20 cm) in late spring of the fallow year. Nitrogen fertilizer was applied one week before seeding wheat in SB and NB treatments. Steer manure, at a rate of 11.2 Mg ha^{-1} yr^{-1} (DM 47.5%, 0.85 Mg C ha^{-1}, and 70 kg N ha^{-1} yr^{-1}), and pea vines, at a rate of 1.12 Mg ha^{-1} yr^{-1} (DM 87.8%, 0.41 Mg C ha^{-1} yr^{-1}, and 18.5 kg N ha^{-1} yr^{-1}), were applied at the time of spring tillage during the fallow year. Manure was obtained from surrounding livestock ranches and pea vines from nearby green pea fields.

Winter wheat was planted in mid-October and harvested in mid-July of the following year. The land was fallowed for the next 14 months before planting the next wheat crop. All wheat – fallow plots were moldboard plowed and smoothed with a cultivator or harrowed within three days of spring burning of crop residues. Wheat was planted at 90 kg ha^{-1} in 17.3-cm wide rows using a John Deere (JD8300) drill prior to 2002 and at 92 kg ha^{-1} in 16.5-cm wide rows using a Case IH 5300 disc drill thereafter. Weeds were controlled using tillage (5-7 passes with a rod weeder) during the fallow phase and with herbicides during the crop phase. Delayed spring tillage was implemented starting in 1994. Glyphosate (N-[Phosphonomethyl] glycine) was applied at 1.2 L a.i. ha^{-1} in late winter or early spring to control weeds until plots were plowed in late spring. This early spring herbicide application permitted weed control, eliminated two to four fallow tillage operations, and more importantly avoided tillage when the ground was wet.

The grassland (GP) that has been maintained in native vegetation since 1931 and in close proximity to the CR-LTE was used as an uncultivated reference for comparison of SOC and N. The GP plot was 46 m x 109 m with native grasses such as blue-bunch wheatgrass (*Agropyron spicatum* Pursh) and Idaho fescue (*Festuca idahoensis* Elmer) as dominant species. The GP received occasional controlled light grazing until 1985 and has not been grazed since. The GP has received no external fertilizer or biomass inputs. Vegetation was sometimes clipped after summer to allow plant regrowth in the following season.

Soil sampling and laboratory analysis

Soil cores were collected from the CR-LTE and the GP using a truck-mounted Giddings Hydraulic Probe (Giddings Machine Company, Inc., Windsor, CO) and steel sampling tube (i.d. 3.6 cm) after wheat harvest in 2010. Cores were taken from 0-60 cm depth of each treatment, and partitioned into 0-10, 10-20, 20-30, and 30-60 cm depth increments. Four soil cores were collected in each plot, composited by depth increment, thoroughly homogenized, and brought to the laboratory for bulk density, SOC and N analyses.

In the laboratory, all visible plant materials (roots, stems, and leaves) and crop residues were removed, and the soil was sieved using a 2-mm sieve. Approximately 10-g subsamples were oven dried at 60°C for 72 h, and finely ground (<0.05 mm) in Shatter Box 8530 ball mill (Spex Sample Prep., Metuchen, NJ) for 2 min. Total C and N contents in the 10-g samples were determined by dry combustion analysis (Flash EA 1112 series, Thermo Finnigan, San Jose, CA). Soil pH was measured on all samples to indirectly detect inorganic C. All soil samples had a pH less than 6.7 and were considered to contain only SOC. Studies show that total C in soils with pH <7.4 is mostly SOC (Schumacher, 2002). Soil bulk density was determined using mass of oven–dried soil (105°C, 24 h) and total soil volume for a given soil depth (Blake and Hartge, 1986). Analysis of bulk density measurements revealed that the soil mass at individual soil depths as well as the entire soil profile (0-60 cm) was not significantly different among treatments (Table 2). Our analysis was not sensitive enough to capture the different bulk density values that were observed at some depths. However, this result did not affect SOC and N content determinations because differences between treatments for SOC and N on concentration basis (g kg^{-1}) were similar to the SOC and N on mass basis (Mg ha^{-1}). Therefore, SOC and N content at each individual soil depth are reported as mass per area and SOC and N stock in soil profile was calculated by summing SOC content in individual soil depths (Batjes, 2014).

$$\text{SOC stock} = \sum_{i=1}^{j} \text{BD}_i \times [\text{C or N}] \times \text{D}_j \times [1 - \text{S}_j] \ldots\ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where, SOC stock indicates the total amount of organic C (Mg ha^{-1}) in 0-60 cm, j indicates the number of soil layers, BD_i indicates bulk density of the soil (Mg m^{-3}), D_j indicates the soil thickness (m), [C] indicates the carbon concentration in ‘i’th layer (g C g^{-1}), and S_j represents the volume of coarse fragments (>2 mm). Soil N content was calculated using the same method.

[Table 2 here]

Biomass C and N inputs from wheat residue were derived from average straw dry matter yield during 1976-2004 divided by 2.38 (Table 1). Carbon and N contents of wheat residue, pea vine, steer manure, and grass dry matter were determined by dry combustion as described above for soil samples. The factor 2.38 was used for biomass C input because wheat straw from the PLTE plots contained approximately 420 g C kg^{-1} biomass during 1976-2004 (Rasmussen and Parton, 1994; Machado 2011). To calculate soil C input in spring and fall burn systems, biomass C inputs were reduced to 45% and 33% of C content in the biomass harvested because Rasmussen and Parton (1994) reported loss of biomass C by 55 and 67% during spring and fall burning of crop residues. Pea vines and manure dry mass as well as biomass C and N were calculated by averaging biomass C and N input during 1976 – 2004 in accordance with Machado (2011). Carbon content and C:N ratio of manure were 160 g kg^{-1} of dry mass and 12.1, and that of pea vine were 415 g kg^{-1} and 22.2. Grassland biomass production was not monitored in earlier years. Therefore, biomass C and N inputs for the grassland were calculated based on biomass harvest during summer 2004 – 2010. Grass biomass samples were collected at maximum growth stage of grasses before flowering. Biomass C content in grass was 412 g kg^{-1} dry mass and C:N ratio was 41.6.

Statistical analysis and calculations

Data for SOC, N and bulk density were tested for normality and homogeneity of variance, and analyzed using a MIXED procedure of SAS for randomized block experiments (v.9.3, SAS Institute, Cary, NC). This model considered treatment as a fixed factor and replication as a random term in the model. Data were analyzed separately for each soil depth and for the entire soil profile (0-60 cm). Soil bulk density, SOC, and N values for soils sampled from plots of the two series did not differ significantly at any of the sampling depths ($P > 0.1$). Therefore, SOC, N, and bulk density data from the two series were combined to get a more robust estimate. The GP consisted of one large unreplicated plot and data were obtained from four random subplots. We created dummy variables of GP data to conform to CR design for statistical comparisons. Treatment means differing in F test were separated using the LSMEAN function in PLM procedure of SAS. Relationships between C and N inputs and soil properties (SOC and N) were compared using a multiple linear regression procedure (PROC REG) in SAS. This analysis used annualized biomass C and N as input variables (X) and SOC or N as response (Y) variables. Annualized biomass C and N input was calculated for WW-SF treatments to facilitate comparison with GP samples. Statistical significance was evaluated at $P<0.05$ unless otherwise stated.

RESULTS

Aboveground biomass in GP contributed 2.87 Mg C ha^{-1} yr^{-1} and 69 kg C ha^{-1} yr^{-1} (Table 1). Carbon and N inputs from wheat residue were highest in MN treatment of the WW-SF system. Pea vines and manure contributed an additional 0.41 and 0.85 Mg C ha^{-1} yr^{-1}, respectively. Biomass C:N ratio decreased in order of wheat (81.8), native grasses (41.6), and pea vines (22.2). Carbon to N ratio in manure applied in MN treatment was 12.1. Total biomass production as well as biomass C and N inputs influenced SOC and N as described below.

Soil organic C contents significantly differed among management systems in 0-10 cm and 10-20 cm soil depths (Table 3). In 0-10 cm depth, SOC content under GP and MN treatments were comparable and significantly greater than SOC content in all other treatments. Soil organic C content was greater under PV (13.9 Mg ha^{-1}) than under FB0, NB0, and all SB treatments. We observed similar results in the 10-20 cm depth, but with less distinct differences among treatments. In the 10-20 cm depth, SOC content under MN and GP was not significantly different whereas SOC under PV was 28% less than under GP. Soil organic C content among 0, 45, 90 kg N ha^{-1} treatments were also not significantly different under SB as well as NB. Soil organic C was consistent between FB0 and SB0 in 10-20 cm depth. In 20-30 and 30-60 cm soil depths, SOC content was not influenced by crop residue and N management treatments under WW-SF system.

"[Table 3 here]"

Soil organic C stock in the whole 0-60 cm soil depth profile was highest under GP (87.4 Mg ha^{-1}), and significantly more than SOC stocks under all WW-SF treatments (Fig. 1). Among WW-SF treatments, SOC stock in MN was more than the SOC stock in SB, NB, PV, and FB0 treatments. Soil organic C stock under PV, SB90 and all NB treatments was not significantly different (Fig. 1). Fertilizer N application rate (0, 45, 90 kg N ha^{-1}) under both SB and NB treatments did not influence SOC stocks. Similarly, SOC stock was not significantly different between FB0 and SB0 treatments.

[Fig. 1 here]

Soil N in all WW-SF treatments was significantly lower than soil N under GP in 0-10 cm as well as in 10-20 cm depths (Table 4). Among WW-SF systems, soil N content in MN treatment (1.41 Mg ha^{-1}) was greater than soil N content in FB, SB and NB treatments in 0-10 cm soil depth. Soil N under PV (1.19 Mg ha^{-1}) was not significantly different from soil N under all WW-SF treatments. The MN treatment had more soil N than FB0 and all SB treatments in 10-20 cm depth. Soil N was not significantly different among PV, MN, and NB90 treatments. In the 10-20 cm depths, soil N content was not influenced by N rates under NB treatments, but increased with increasing N rates under SB treatments. Soil N content was not significantly different among all treatments in 20-30 cm depth. In 30-60 cm depth, soil N under GP was higher than soil N under all WW-SF treatments. At this depth profile, soil N in MN and PV treatments was not significantly different to soil N in other WW-SF treatments. There was more soil N under NB90 than NB0 in the 30-60 cm depth. Similar results were observed under SB treatments but the increase in soil N with increasing N rates was not significant.

“[Table 4 here]”

Soil N stock in the 0-60 cm soil depth profile was the highest under GP (8.22 Mg ha^{-1}) and was significantly greater than soil N under all WW-SF treatments (Fig. 1). Among WW-SF treatments, soil N stock under MN (6.40 Mg ha^{-1}) was more than soil N stock under other treatments. Soil N stock under PV was more than soil N under FB0, SB0, NB0, SB45, and NB45. Soil N stock was not significantly influenced by N rates under SB and NB treatments.

Carbon to nitrogen (C:N) ratio was influenced by management systems at 0-10 cm depth (Fig. 2). The C:N ratio was significantly greater under MN (15.0) than under all other treatments followed by C:N ratios under PV and GP treatments. The PV C:N ratio was higher than FB0, SB, and NB C:N ratios, but was not significantly different from the ratio under GP. Nitrogen application rates did not influence C:N ratios under both SB and NB treatments. Below 10-cm soil depth, C:N ratios averaged 10.2, 8.39, and 9.04 in the 10-20, 20-30, 30-60 cm soil depths, respectively, and were not significantly different among all treatments.

“[Fig. 2 here]”

Multiple linear regression analyses of SOC content with C and N inputs revealed that SOC stocks were positively influenced by C and N inputs in 0-10 (R^2=0.70) and 10-20 cm (R^2=0.83) soil depths, and so was the SOC stock in the whole 0-60 cm (R^2=0.63) soil depth profile (Table 5). The SOC stock was significantly influenced by carbon input alone in 10-20 cm depth, but model prediction significantly increased across all soil depths when C input was combined with N input. The C and N input required to accumulate SOC was the highest for 0-10 cm depth (5.09 units for C and 0.007 units for N) than at lower depths. Similarly, soil N content was also influenced by biomass C and N inputs particularly in 0-10 (R^2=0.92) and 10-20 (R^2=0.95) soil depth profiles, and in the 0-60 cm (R^2=0.92) depth profile as a whole.

“[Table 5 here]”

Overtime, starting in 1931, all treatments including MN depleted SOC and N stocks in the 0-60 cm depth profile (Table 6). Soil analyses results in 1986, 56 years after the start of the experiment, showed that most treatments had lost more than 20% of the original SOC stocks at rates of more than 0.30 Mg $ha^{-1}yr^{-1}$. At this time, MN had lost only 10% of the original SOC stocks at a rate of 0.10 Mg $ha^{-1}yr^{-1}$, while PV and NB90 had lost 18 and 19% of the original SOC stocks, but at rates of 0.28 Mg $ha^{-1}yr^{-1}$and 0.29 Mg $ha^{-1}yr^{-1}$, respectively. Most treatments had lost more than 50% of the original SOC stocks by 2010, 80 years later. The NB90, PV and MN treatments had lower SOC losses with MN having the lowest reductions in SOC stocks in 0-60 cm soil depth profile after 80 years. Depletion of SOC was faster in the period from 1986 to 2010 than from 1931 to 1986. For example, FB0 lost SOC at the rate of 0.38 Mg $ha^{-1}yr^{-1}$ from 1931 to 1986 and at 1.21 Mg $ha^{-1}yr^{-1}$ from 1986 to 2010. The effect of WW-SF treatments on N stocks after 56 and 80 years was similar to that of SOC (Table 7). The lowest loss in N stock was observed under MN (3%) while N loses of more than 20% were observed under all burn treatments and NB0 and NB45 treatments. Loses in N stock under PV were similar to loses under NB90. The rate of N loss per year was similar between the two periods (1931-1986 and 1986-2010) evaluated in this study.

“[Table 6 here]”

“[Table 7 here]”

DISCUSSION

Cultivation of virgin land inevitably precipitates the depletion of original SOC and N stocks (Guo and Gifford, 2002; Wei et al., 2014). Studies show that soils around the Pendleton, OR area lost approximately 35% SOC in the first 50 years since the native prairie was broken for cultivation in 1881 (Rasmussen et al., 1998). Eighty years later, our study revealed that some WW-SF systems have lost up to 63% and 26% of SOC and N. On the other hand, soil C stocks increased when land reverted to grassland (Guo and Gifford, 2002). It was no surprise then that the highest content of SOC and N at all soil depths as well as in the whole 0-60 cm profile were observed under the GP treatment that had reverted to native grassland vegetation in 1931. In 60 years after conversion from cropland to perennial grasses (1931-1991), GP recovered more than half of SOC and N lost through 50 years of cultivation (Rasmussen et al., 1998). Now, nearly after 80 years under perennial grasses, GP approximates near-virgin grassland and serves as an undisturbed reference system for determining SOC loss in other long-term experimens at Pendleton. The GP sequestered the most C through high biomass C production. The aboveground biomass measured under the GP treatment in this study was not removed. Although the GP plot was occasionally and lightly grazed until 1985, that practice was not likely to reduce SOC build up. Ingram et al. (2008) reported that occasional light grazing for more than 21 years did not reduce SOC and N contents compared with undisturbed reference. It has been also reported that perennial grasses contributed significant amounts of C and N to soil through their deep and dense root systems (Schuman et al., 1999; Wuest and Gollany, 2013; Ghimire et al., 2014). Although belowground biomass was not measured in this study, other studies demonstrated positive correlation between root biomass and aboveground biomass production (Bolinder et al., 2007). More than 18.5% of the total root biomass in soil profile (0-60 cm) was observed below 15 cm depth in a rangeland study indicating the potential of grass roots to contribute to deep profile carbon storage in grasslands (Schuman et al., 1999). Greater SOC content in soil depth profile under GP than under WW-SF treatments in this study may be attributable to greater aboveground and belowground biomass production of perennial grasses than wheat.

Lower SOC and N stocks in the 0-60 cm soil depth profile of all crop residue and nutrient management treatments under WW-SF compared with GP may be attributed to smaller biomass C and N inputs, long fallow period (14 months) between wheat crops, and soil disturbance (5-7 tillage passes a year). The least depletion of SOC in the 0-20 cm soil depth profile was observed under the MN treatment that received C inputs of about 3.68 Mg $ha^{-1}yr^{-1}$. However, this amount was not enough to maintain SOC below 20 cm, a region where root biomass from GP may have contributed to more SOC accrual than wheat under the WW-SF treatments. We observed at least 20% less SOC under MN than under GP when the whole 0-60 cm profile was considered. With an input of 2.54 Mg C ha^{-1} yr^{-1}, SOC under PV was 32% less than under GP. Our observations corroborate previous studies showing that the decline in SOC and N in deeper soil layers was influenced more by belowground biomass production than by aboveground C and N inputs (e.g. Rasmussen and Parton, 1994; Rasmussen et al., 1998). It follows that low SOC and N stocks under all WW-SF treatments was likely due to lower root biomass than the GP treatment.

Increasing SOC in the deeper soil profile is important in dryland systems of the PNW for increasing soil moisture holding capacity. Unlike the Great Plains, which receive approximately 70% of precipitation during summer (Schuman et al., 1999; Ghimire et al., 2014), the PNW receives about 30% of the total precipitation during the same period (April 1 – August 31) when crops are actively growing. As a consequence, crops in the PNW rely more on soil moisture and nutrients stored deep in soil profile than crops in the Great Plains (Rasmussen et al., 1998). We did not study rooting depths and root characteristics of wheat under WW-SF. However, based on SOC and N distributions observed in this study, and difference in yield and biomass production under different treatments, wheat under WW-SF is likely producing less root biomass than the grass under GP and roots are more concentrated in shallower depth. Studying profile distribution of roots and their influence on SOC and N in deeper depth may elucidate C and N dynamics in soil profile and their impact on dryland cropping systems. Such information is important in designing sustainable cropping systems in PNW.

Regression analysis of combined C and N inputs with SOC and N stocks indicated that both biomass C and its quality are important for SOC and N accrual. Neither biomass C nor N input was significantly related to SOC and TN when regressed independently. The increase in SOC, mainly in 0-20 cm depth, was more robust and highly significant when biomass C and N inputs were combined suggesting the importance of quality as well as quantity of biomass input in SOC and N accrual. Quality of organic residues as indicated by low C:N ratio can improve long-term SOC storage (Kirkby et al., 2013). Soil microbial efficiency of organic matter decomposition and nutrient mineralization often decreases with increasing C:N ratio (Scott and Binkley, 1997). Greater SOC and N accumulation under PV, MN and GP compared with FB, SB, and NB treatments could be attributed to both quantity as well as quality of organic residues. The lower C:N ratio in manure, pea vine and grass inputs than in wheat residue contributed to increased SOC accretion in the MN, PV, and GP treatments.

We did not observe significant differences in SOC and N accumulation due to different N rates under both SB and NB treatments. The lack of SOC and N content response to N application is in agreement with previous studies, which revealed differences in crop yield and biomass production (Camara et al., 2003), but no difference in SOC content with N addition in WW-SF system (Rasmussen and Parton, 1994; Halvorson et al., 2002; Lugato et al., 2006; Machado et al., 2006). Apparently, the amount of C from crop residues was insufficient to add measurably to SOC. The high biomass produced at high N rates was rapidly decomposed when residues were incorporated into soil (Rasmussen and Parton, 1994; Rasmussen et al., 1998; Ghimire et al., 2012) as was the case in this study. Only about 18% of added C was incorporated into SOC under WW-SF system in the PLTEs (Rasmussen et al., 1998). Rapid decomposition of residues coupled with a 14-month fallow period where no residues were returned to the soil contributed to the depletion of SOC.

Fall and spring burning of crop residue (FB and SB) that had 50% less SOC content in the 0-60 cm compared with GP were less efficient in conserving SOC and N in this study. Wheat residue burning was commonly practiced in the PNW until the 1990s to reduce straw level that hampers planting and control weeds (Rasmussen et al., 1980; Machado, 2011). Both fall and spring burning of crop residue caused significant loss of residue C and N compounds to the atmosphere. Rasmussen and Parton (1994) reported 55% residue C loss in spring burn and 67% loss in fall burn systems. In a controlled burning experiments in China, 38% wheat residue C was lost to the atmosphere as particulate organic C, elemental C, and CO_2-C (Cao et al., 2008). Significant losses in SOC content under SB and FB systems in this study, along with previous studies, revealed that crop residue burning is not a desired practice for both soil and environmental health.

Over time, we observed a continuous decrease in SOC and N stocks under all treatments with the exception of the MN treatment. Rasmussen and Parton (1994) observed a significant decrease in SOC in the same treatments in 1986 compared with SOC levels in 1931. More than 60% of SOC stock under some of the WW-SF systems in this study has been lost since 1931. Lugato et al. (2006) reported reaching a steady state in SOC stocks under annual cropping in about 20 years. Using 1931-1986 data from the CR-LTE plots, Parton and Rasmussen (1994) predicted that it would take about 35 years for SOC to reach steady state, but this was not the case in this study. The rate of loss in SOC in the CR-LTE increased after 1986 with no sign of reaching equilibrium. Disturbance of natural vegetation upsets SOC equilibrium established in that ecosystem until another equilibrium is attained. A cropping system with annual additions of

C inputs (Lugato et al., 2006) is likely to reach the new equilibrium faster than a WW-SF system with insufficient residue returns. Machado (2011), using 1976-2005 data, suggested that about 3.27 Mg C ha^{-1} yr^{-1} is required to maintain SOC in CR-LTE. We envisage that SOC will continue to decline until the rate of depletion equals the conversion efficiency. The rapid decline in SOC after 1986 may be attributed to change in C inputs after cultivars were changed from tall to dwarf types. The change from tall to semi-dwarf cultivars occurred in the 1970s and the lag between the change of cultivar and the drop in SOC would be expected. The continuous decline in SOC stocks will inevitably threaten sustainability through negative impacts on ecosystem services necessary for sustained crop production. Cropping systems that increase crop residue return and reduce or eliminate tillage have been found to build SOC and improve crop productivity (Machado, 2011).

Results from this study underscore the importance of long-term experiments. Short-experiments do not have the capacity to detect subtle changes and results can lead to premature conclusions and recommendations. As the oldest long-term experiments in the western U.S., the PLTEs are a useful source of information for improving sustainability of dryland farming and formulating agricultural policies in the PNW, particularly under changing climatic conditions. The CR-LTE and other PLTEs are still ongoing and continue to elucidate impacts of crop residue and nutrient management practices on soil properties and crop yields.

CONCLUSION

Cultivation in the WW-SF system depletes SOC and N and threatens the sustainability of dryland wheat production in the PNW. Our study revealed that some of the WW-SF systems evaluated in this study have depleted up to 63% and 26% of the SOC and N in 0-60 cm depth since 1931, when the experiment was initiated. The rate of SOC depletion was even greater in last 35 years. High SOC levels in GP may be attributable to both high aboveground and below ground biomass production. Therefore, the buildup of SOC under cropping systems can benefit most from crops with deep and dense root systems such as perennial grasses and reduced fallow periods. Residue quality and quantity were equally important in SOC and N accretion. Application of low C:N ratio organic residues and amendments such as pea vine and manure application can minimize SOC and N depletion, mainly from surface soils. Crop residue burning exacerbated SOC and N depletion and therefore we do not recommend this practice for any WW-SF system in PNW region with similar soils and climate. This practice, although not as common as in the 1800s and early 1900s, is still practiced in eastern Oregon.

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List of Figures

Fig. 1. Soil organic carbon (SOC) and nitrogen (TN) stock (0-60 cm) under different crop residue and nitrogen management treatments in WW-SF system and undisturbed grassland at Pendleton long-term experiments. FB = fall burn, SB = spring burn, NB = no burn, MN = manure application, PV = pea vine, and GP = undisturbed grassland. 0, 45, 90 accompanied with FB, SB, and NB indicate amount of N (kg ha^{-1}) applied from chemical fertilizer. Different letters across SOC and N contents indicate significant differences between treatments ($p<0.05$).

Fig. 2. Soil organic carbon to nitrogen ratio (C:N ratio) at 0-10 cm soil depth under different crop residue and nitrogen management treatments in WW-SF system and undisturbed grassland at Pendleton long-term experiments. FB = fall burn, SB = spring burn, NB = no burn, MN = manure application, PV = pea vine, and GP = undisturbed grassland. 0, 45, 90 accompanied with FB, SB, and NB indicate amount of N (kg ha^{-1}) applied from chemical fertilizer. Different letters across columns indicate significant differences between treatments ($p<0.05$).

Table 1. Treatment history and carbon (C) and nitrogen (N) inputs under different residue and nitrogen management treatments in WW-SF system and undisturbed grassland in Pendleton long-term experiments.

T. No.	Treatment†	Organic residue addition‡	Residue management			Nitrogen management			Annualized biomass input‡			Annualized total C input	Annualized total N input
			1931-1966	1967-1978	1979-2010	1931-1966	1967-1978	1979-2010	residue	other	total		
						kg ha^{-1} crop^{-1}			Mg ha^{-1} yr^{-1}				kg ha^{-1} yr^{-1}
6	FB0	-	FB	FB	FB	0	0	0	3.33	-	3.33	0.46	5.64
7	SB0	-	SB	SB	SB	0	0	0	3.35	-	3.35	0.63	7.73
2	SB45	-	FD	NB	SB	0	45	45	4.89	-	4.89	0.93	33.8
3	SB90	-	SD	NB	SB	0	90	90	5.52	-	5.52	1.04	57.8
1	NB0	-	NB	NB	NB	0	0	0	3.60	-	3.60	1.51	18.5
4	NB45	-	NB	NB	NB	34	45	45	5.06	-	5.06	2.12	48.5
5	NB90	-	NB	NB	NB	34	90	90	5.54	-	5.54	2.33	73.5
8	MN	MN	NB	NB	NB	0	0	0	6.75	5.32	12.1	3.68	105
9	PV	PV	NB	NB	NB	0	0	0	5.07	0.99	6.06	2.54	44.5
	GP	-	-	-	-	-	-	-	6.97	-	6.97	2.87	69.0

† FB = fall burn, FD = fall disk, SB = spring burn, SD = spring disk, NB = no burn, PV = pea vine, MN = manure, GP = undisturbed grassland.

‡Wheat residue, pea vines and manure dry mass as well as biomass C and N was determined by averaging dry matter mass of crop residues and manure during 1987-2004 period. Grass biomass, biomass C and N inputs were calculated based on biomass harvest during 2004-2010 period.

Table 2. Soil bulk density in different soil depths under crop residue and nitrogen management treatments in WW-SF system and undisturbed grassland at Pendleton long-term experiments.

Depth	Treatment†‡									
	FB0	SB0	SB45	SB90	NB0	NB45	NB90	MN	PV	GP
	Mg m^{-3}									
0-10	1.29(0.02)	1.23(0.03)	1.23(0.04)	1.23(0.01)	1.31(0.02)	1.23(0.03)	1.28(0.03)	1.24(0.03)	1.24(0.03)	1.28(0.00)
10-20	1.25(0.01)	1.11(0.02)	1.25(0.02)	1.21(0.02)	1.38(0.03)	1.23(0.04)	1.29(0.01)	1.18(0.04)	1.25(0.04)	1.42(0.01)
20-30	1.33(0.01)	1.41(0.02)	1.31(0.01)	1.34(0.01)	1.26(0.03)	1.29(0.05)	1.19(0.03)	1.30(0.03)	1.37(0.02)	1.24(0.02)
30-60	1.28(0.04)	1.16(0.00)	1.17(0.01)	1.16(0.01)	1.13(0.05)	1.14(0.01)	1.20(0.03)	1.19(0.02)	1.21(0.01)	1.29(0.02)

†FB = fall burn, SB = spring burn, NB = no burn, MN = manure application, PV = pea vine, and GP = undisturbed grassland. 0, 45, 90 accompanied with FB, SB, and NB indicate amount of N applied from chemical fertilizer.

‡Soil bulk density was not significantly different among treatments ($p < 0.05$) at any soil depth. Numbers in parenthesis indicates standard error (n = 4).

Table 3. Soil profile organic carbon (SOC) in different soil depths under crop residue and nitrogen management treatments in WW-SF system and undisturbed grassland in Pendleton long-term experiments.

Depth	Treatments†‡									
(cm)	FB0	SB0	SB45	SB90	NB0	NB45	NB90	MN	PV	GP
	Mg ha^{-1}									
0-10	8.70d(0.36)	9.17cd(0.46)	8.66d(0.20)	9.81cd(0.18)	10.6cd(0.31)	11.4bc(0.29)	11.8bc(0.20)	24.8a(1.15)	13.9b(0.68)	27.0a(0.23)
10-20	7.92d(0.19)	8.15d(0.53)	9.19cd(0.07)	10.5cd(0.26)	9.97cd(0.34)	10.8cd(0.33)	13.3bc(0.61)	16.7ab(1.78)	13.7bc(1.28)	18.9a(0.32)
20-30	6.77a(0.32)	8.65a(0.56)	9.11a(0.16)	7.81a(0.30)	8.47a(0.15)	8.44a(0.19)	7.84a(0.56)	8.12a(0.27)	10.1a(0.74)	11.7a(0.09)
30-60	20.7a(1.45)	20.2a(1.16)	19.4a(1.31)	20.5a(0.39)	19.8a(0.70)	17.7a(0.51)	24.1a(1.86)	20.7a(0.44)	21.3a(0.79)	29.8a(0.94)

†FB = fall burn, SB = spring burn, NB = no burn, MN = manure application, PV = pea vine and GP = undisturbed grassland. 0, 45, 90 accompanied with FB, SB, and NB indicate amount of N (kg ha-1) applied from chemical fertilizer.

‡Within a row, values followed by the same letter are not significantly different at $p<0.05$. Numbers in parenthesis indicates standard error (n = 4).

Table 4. Soil profile nitrogen (N) in different soil depths under crop residue and nitrogen management treatments in WW-SF system and undisturbed grassland in Pendleton long-term experiments.

Depth	Treatments									
(cm)	FB0	SB0	SB45	SB90	NB0	NB45	NB90	MN	PV	GP
	Mg ha^{-1}									
0-10	0.99c(0.03)	0.98c(0.04)	0.96c(0.02)	1.03c(0.01)	1.10c(0.02)	1.12c(0.02)	1.13c(0.01)	1.41b(0.07)	1.15bc(0.04)	2.34a(0.01)
10-20	0.91ef(0.01)	0.87f(0.03)	0.98def(0.01)	1.07cde(0.03)	1.16bc(0.03)	1.09cd(0.04)	1.18bc(0.05)	1.30b(0.04)	1.19bc(0.06)	1.75a(0.03)
20-30	0.91a(0.01)	1.09a(0.04)	1.08a(0.01)	1.08a(0.02)	0.99a(0.05)	1.11a(0.07)	0.96a(0.03)	1.2a(0.09)	1.15a(0.03)	1.18a(0.01)
30-60	2.52bc(0.13)	2.24bc(0.08)	2.38bc(0.08)	2.55bc(0.05)	2.20c(0.08)	2.32bc(0.04)	2.58b(0.11)	2.49bc(0.14)	2.52bc(0.08)	2.95a(0.07)

†FB = fall burn, FD = fall disk, SB = spring burn, SD = spring disk, NB = no burn, MN = manure application, PV = pea vine and GP = undisturbed grassland. 0, 45, 90 accompanied with uppercase letters indicate amount of N (kg ha^{-1}) applied from chemical fertilizer.

‡ Within a row, values followed by the same letter are not significantly different at $p<0.05$. Numbers in parenthesis indicates standard error (n = 4).

Table 5. Relationship between carbon (C) and (N) inputs and average soil organic carbon (SOC) and total N (TN) contents at each sampling depth and whole soil profile (n =10) in Pendleton long-term experiments.

Parameter	Depth	Regression equation	R2	PCI	PNI	Model p value
SOC	0-10	YSOC = 5.09CI + 0.007NI + 4.03	0.70	0.08	0.94	0.01
	10-20	YSOC = 2.69CI + 0.018NI + 6.23	0.83	0.04	0.63	<0.01
	20-30	YSOC = 1.24CI – 0.027NI + 7.71	0.29	0.16	0.35	0.30
	30-60	YSOC = 1.09CI + 0.007NI + 19.1	0.17	0.62	0.92	0.53
	0-60	YSOC = 10.1CI + 0.005NI + 37.1	0.63	0.12	0.98	0.03
TN	0-10	YTN = 0.29CI - 0.003NI + 0.75	0.92	<0.01	0.15	<0.01
	10-20	YTN = 0.16CI + 0.000NI + 0.83	0.95	<0.01	0.92	<0.01
	20-30	YTN = 0.02CI + 0.001NI + 0.98	0.39	0.37	0.45	0.18
	30-60	YTN = 0.01CI + 0.001NI + 2.26	0.54	0.08	0.86	0.06
	0-60	YTN = 0.57CI - 0.002NI + 4.82	0.92	<0.01	0.69	<0.01

†CI indicate carbon input (Mg ha^{-1} yr^{-1}) coefficient, NI indicate nitrogen input (Mg ha^{-1} yr^{-1}) coefficient, and Y indicate response variable (SOC or and TN Mg ha^{-1} yr^{-1}), PCI indicate significant probability of CI and PNI indicate significant probability of NI to contribute SOC or TN.

Table 6. Soil organic carbon (SOC) stock loss over time as influenced by crop residue and nitrogen management treatments in the crop residue long-term experiment.

Treatment†	SOC in 1931‡	SOC in 1986	SOC loss (1931-1986)		SOC 2010	SOC loss (1986-2010)		SOC loss (1931-2010)	
	Mg ha^{-1}	Mg ha^{-1}	%	Mg ha^{-1}yr^{-1}	Mg ha^{-1}	%	Mg ha^{-1}yr^{-1}	%	Mg ha^{-1}yr^{-1}
FB0	82.18	61.0	-26	-0.38	30.8	-49	-1.21	-63	-0.64
SB0	82.58	63.0	-24	-0.35	34.9	-45	-1.13	-58	-0.60
SB45	84.11	63.3	-25	-0.37	33.9	-46	-1.17	-60	-0.63
SB90	85.01	64.7	-24	-0.36	37.2	-43	-1.10	-56	-0.60
NB0	86.88	64.8	-25	-0.39	35.9	-45	-1.16	-59	-0.64
NB45	86.02	67.5	-22	-0.33	38.0	-44	-1.18	-56	-0.60
NB90	84.24	68.2	-19	-0.29	50.6	-26	-0.70	-40	-0.42
MN	82.34	74.4	-10	-0.14	69.0	-7	-0.21	-16	-0.17
PV	86.03	70.5	-18	-0.28	53.1	-25	-0.70	-38	-0.41

†FB = fall burn, SB = spring burn, NB = no burn, MN = manure application, PV = pea vine and GP = undisturbed grassland. 0, 45, 90 accompanied with uppercase letters indicate amount of N (kg ha^{-1}) applied from chemical fertilizer.

‡SOC content in 1931 and 1986 were adapted from Rasmussen and Parton (1994).

Table 7. Soil total nitrogen (TN) stock loss over time as influenced by crop residue and nitrogen management treatments in the crop residue long-term experiment.

Treatment†	TN in 1931‡	TN in 1986	TN loss (1931-1986)		TN 2010	TN loss (1986-2010)		TN loss (1931-2010)	
	Mg ha^{-1}	Mg ha^{-1}	%	Mg ha^{-1}yr^{-1}	Mg ha^{-1}	%	Mg ha^{-1}yr^{-1}	%	Mg ha^{-1}yr^{-1}
FB0	6.59	5.37	-19	-0.02	5.04	-6	-0.01	-24	-0.02
SB0	6.62	5.77	-13	-0.02	4.97	-14	-0.03	-25	-0.02
SB45	6.74	5.81	-14	-0.02	5.18	-11	-0.03	-23	-0.02
SB90	6.82	5.85	-14	-0.02	5.55	-5	-0.01	-19	-0.02
NB0	6.98	5.84	-16	-0.02	5.15	-12	-0.03	-26	-0.02
NB45	6.91	6.11	-12	-0.01	5.47	-10	-0.03	-21	-0.02
NB90	6.75	6.19	-8	-0.01	5.77	-7	-0.02	-15	-0.01
MN	6.63	6.80	3	0.00	6.41	-6	-0.02	-3	0.00
PV	6.91	6.29	-9	-0.01	5.92	-6	-0.01	-14	-0.01

†FB = fall burn, SB = spring burn, NB = no burn, MN = manure application, PV = pea vine and GP = undisturbed grassland. 0, 45, 90 accompanied with uppercase letters indicate amount of N (kg ha^{-1}) applied from chemical fertilizer.

‡Soil TN content in 1931 and 1986 were adapted from Rasmussen and Parton (1994).