



Crop Yield Limitation by Soil Organic Matter Decline: A Case Study from the US Pacific Northwest

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Abstract

Soil degradation has become a significant challenge for agricultural and environmental sustainability. Continuous depletion in soil organic carbon (SOC) and nitrogen (N) in the past century has considerably affected agricultural productivity and sustainability in semiarid drylands of the inland Pacific Northwest (IPNW) of the USA. This chapter discusses linkages between soil organic matter depletion and yield decline in a winter wheat-summer fallow (WW-SF) system in the IPNW based on data obtained from a long-term study (>80 y). Studies conducted in dryland winter wheat-summer fallow (WW-SF) systems revealed a decrease in SOC and N storage in the profile. Specifically, SOC content decreased by $280 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in the top 30 cm soil depth with fall burning of crop residue (FB), while it was decreased by $226 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in no burning of crop residue (NB). The decline in yield was

observed with a decrease in SOC and N stocks over the years, mainly due to long fallow periods between wheat crops, crop residue burning, insufficient residue returns, and intensive tillage practices. The only treatment that maintained SOC in the top 30 cm depth was manure (MN) treatment, indicating that SOC and N, added in larger amounts under this treatment, play a crucial role in SOC maintenance, crop production, and sustainability of WW-SF systems. Results of the long-term studies show a continued declining trend in SOC and nutrients under the WW-SF system, thus negatively impacting soil health, further reducing crop yield in dryland cropping in the IPNW. A decrease in SOC and N in the soil profile leads to soil degradation, affecting the sustainability of dryland WW-SF systems in the IPNW and similar agroecosystems worldwide. Cropping system intensification, residue addition, or organic amendment additions can maintain SOC and support sustainable crop production.

Keywords

Drylands · Soil degradation · Soil organic carbon · Sustainability · Wheat-fallow system

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27.1 Introduction

Feeding 9.1 billion people by 2050 while minimizing environmental degradation is the greatest challenge currently facing humankind. The soil is a foundational resource for sustainable agriculture and environmental quality. Therefore, soil degradation, a decline in soil health with associated reductions in ecosystem functioning and services, significantly impact global food production and human nutrition. Semiarid drylands in the IPNW region of the USA face challenges in sustainably increasing crop yields due to a decrease in soil health, specifically, the continuous decline in soil organic matter (SOM) and nutrients in soil profiles (Machado et al. 2006; Brown and Huggins 2012). Farmers in this region typically burn or remove residues after crop harvest in the fall, till soils, and fallow land for 13–14 months after harvest (Schillinger et al. 2003; Schillinger and Papendick 2008). Long-fallow periods, repeated tillage, and crop residue removal lead to a rapid depletion in SOM and nutrients, ultimately reducing soil health and crop yields.

Soil organic matter is a key component for improving soil health because SOM controls many soil properties and processes important for sustainable crop production. Long-term studies have consistently demonstrated the value of increasing carbon (C) inputs to maintain soil fertility and combat land degradation. Studies at the Pendleton Long-term Experiments (PLTES) revealed that dryland cropping systems that include long fallow periods and intensive tillage had lost 50–70% of the SOC, a proxy of SOM, storage in the last 80 years (Ghimire et al. 2015). In the same period, about 37–70 kg N ha⁻¹ was lost in grain harvest each crop year, leading to continuous depletion in soil N reservoir and decline in crop production. Management systems that increase SOC and N, proxies of SOM accrual, are pertinent to sustainable crop production and environmental quality improvement. For example, green manuring, compost and biosolids application, and crop residue recycling increase SOC compared to farming practices that

do not add organic matter (Rasmussen and Parton 1994; Wuest and Gollany 2013; Chatterjee et al. 2017; Kumar et al. 2020; Li et al. 2020). Dryland producers in the IPNW still rely on soil management strategies that do not produce enough C inputs or add external inputs to support crop production, leading to the downward spiral of soil health degradation over the years.

Long-term studies that evaluate SOC and nutrients for several decades have significantly contributed to our understanding of how management systems affect SOC sequestration, nutrient cycling, and associated ecosystem services. Long-term studies are specifically important in semiarid regions where soil responses to management practices on SOC and nutrient accumulation are very slow (Rasmussen and Parton 1994; Machado 2011). Pendleton long-term experiments (PLTEs), the oldest long-term experiments in the western US with more than 80 years of cropping history, provide valuable information on how changes in SOC and nutrient dynamics over time have affected agroecosystems services in the semiarid drylands. Here, we present the case study that compares the long-term trend of SOC and N and their relationship with winter wheat yield in a WW-SF system.

27.2 Experimental Site and Treatments

Assessment of yield decline as a function of SOM depletion was studied in the Crop Residue Long-term experiment (CR-LTE), one of the WW-SF studies conducted at the Columbia Basin Agricultural Research Center (CBARC) at Pendleton, OR (45°42'N, 118°36'W, 438 m elev.). The soil at the study site had a silt loam texture with low to medium fertility status. The site had a Mediterranean climate. Detail of the treatments and experimental design was presented in Ghimire et al. (2015, 2018). In brief, this case study evaluated SOC, N, and crop yield under FB, NB, MN, and pea vine (PV) treatments in the CR-LTE (Table 27.1). Winter wheat residues were removed by burning in FB

Table 27.1 Soil carbon (C) and nitrogen (N) inputs and rate of change during 1931–2010 in 0–30 cm depth of selected treatments in the crop residue long-term experiment

Trt†	Annualized C input			dC/dt	Annualized N input			dN/dt
	Crop residue	Other sources	Total		Crop residue	Other amendments	Total	
	Mg ha ⁻¹ yr ⁻¹				Kg ha ⁻¹ yr ⁻¹			
FB	0.46	–	0.46	–0.26	5.64	–	5.64	–0.015
NB	1.51	–	1.51	–0.21	18.5	–	18.29	–0.016
PV	2.13	0.41	2.54	–0.10	26.0	18.5	44.5	–0.004
MN	2.83	0.85	3.68	+0.02	35.0	70.0	105.0	+0.003

†FB and NB indicate fall burning and no burning of crop residues, PV is pea vine incorporation, and MN is manure application.

treatment throughout the study period (1931–2010), while residues were retained in the NB treatment. Additional residue/amendment was supplied through the cattle manure and pea vines in MN and PV treatments. The study was established in 1931, and a medium-tall variety (Rex M-1) of winter wheat was grown until 1966. Multiple semi-dwarf varieties have been grown since then across the treatments compared in this case study (Ghimire et al., 2015).

Fall burning of wheat residue in FB treatment was conducted in late September after wheat harvest (Fig. 27.1), followed by the rod weeding of the field in the spring to control weeds. Primary tillage in late spring of the fallow year incorporated crop residues to a depth of 20 cm in PV, MN, and NB treatments. Pea vine residues from a nearby farm-field added 0.41 Mg C ha⁻¹ yr⁻¹ and 18.5 kg N ha⁻¹ yr⁻¹. Similarly, steer manure from a nearby cattle operation added 0.85 Mg C ha⁻¹ yr⁻¹ and 70 kg N ha⁻¹ yr⁻¹ in addition to above- and belowground biomass C and nutrients from wheat residues. Wheat residues added annual C input equivalent to 2.13 Mg ha⁻¹ and 2.83 Mg ha⁻¹ in PV and MN treatments. Wheat residue added 1.51 Mg ha⁻¹ yr⁻¹ and 18.5 kg ha⁻¹ yr⁻¹ C and N inputs in NB, and 0.46 Mg ha⁻¹ yr⁻¹ and 5.64 kg ha⁻¹ yr⁻¹ C and N inputs in FB.

Winter wheat was planted in mid-October and harvested in mid-July of the following year. The

field was left fallow for the 14 months after wheat harvest and before planting the next wheat crop in the following year. Tillage practices included cultivation with moldboard plow in the fall and using cultivator and harrow in the spring. Until 2002, wheat was planted at 90 kg ha⁻¹ in rows 17.3 cm apart using a John Deere no-till drill and after that at 92 kg ha⁻¹ in rows 16.5 cm apart using Great Plains International Disc Drill. Wheat yield was estimated at approximately 9–12% grain moisture by harvesting a center portion of a plot.

Giddings hydraulic probe was used to collect soil samples from 0–30 cm and 30–60 cm depths after wheat harvest (Fig. 27.2). Hand probes was used for collecting soil samples in earlier years. After all visible crop residues, including roots, stems, and leaves, were removed, soil samples were sieved to pass through a 2-mm screen. Then, approximately 10-g subsamples were oven-dried at 60 °C for 72 h, finely ground (0.05 mm) on a Shatter Box 8530 ball mill, and SOC and N were analyzed in a dry combustion CN analyzer. This method of soil sampling and analysis was used in 1995, 2005, and 2010 samplings. The SOC analysis method for samples collected during 1931–1986 varied based on the analyzers available (Rasmussen and Parton, 1994). The SOC and N content (kg ha⁻¹) were calculated by using SOC and N concentrations (g kg⁻¹) and soil bulk density (BD) data collected at



Fig. 27.1 Winter wheat-summer fallow system typical to the inland Pacific Northwest of USA (a) and fallow field after fall burning of wheat residues (b) at Pendleton, OR, USA

different periods of the experiment (Ghimire et al. 2015).

Treatment averages were used for long-term trend analysis of wheat yield (1931–2010), SOC, and N. After 1967, semi-dwarf varieties replaced the medium-tall variety (Rex M-1) planted from

1931 to 1967. Hence, for the time-periods 1931–1966 and 1967–2010, wheat yield trends under different treatments were analyzed separately using a linear or quadratic autoregression procedure (PROC AUTOREG) in SAS. Furthermore, suitable (linear or quadratic)



Fig. 27.2 Soil sample collection from long-term experiments at Pendleton OR, USA

autoregression models were used for the trend analysis of SOC and TN (1931–2010). The yield trend from 1931 to 2010 was also analyzed using an autoregressive integrated moving average (ARIMA) model (Brocklebank and Dickey, 2003), a time-series forecasting approach to understand long-term trends.

$$[(1 - B)Y]_t = \mu + \left(\frac{\theta(B)}{\phi(B)} \right) \times a_t \quad (27.1)$$

where, Y is the response variable, B is the backshift operator, t is time (year), and the backshift operation $BX_t = X_{t-1}$, μ is a mean term; $\theta(B)$ is the moving-average operator, $\phi(B)$ is the autoregressive operator, and $a_t =$ random error. Pearson correlation quantified the relationship between SOC, TN, and wheat yield. Results from

statistical analyses were deemed significant when $p < 0.05$.

27.3 Results and Discussion

27.3.1 Changes in Soil Organic Carbon and Nitrogen

The SOC and TN in the drylands of IPNW have significantly depleted due to the continuous use of WW-SF system. The long-term trend of SOC from 1931–2010 showed a linear decrease over time. The SOC declined at the rate of $116 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in PV, $280 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in FB, and $226 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in NB treatments in 0–30 cm depth (Fig. 27.3). The rapid decrease in SOC was associated with low biomass C input and

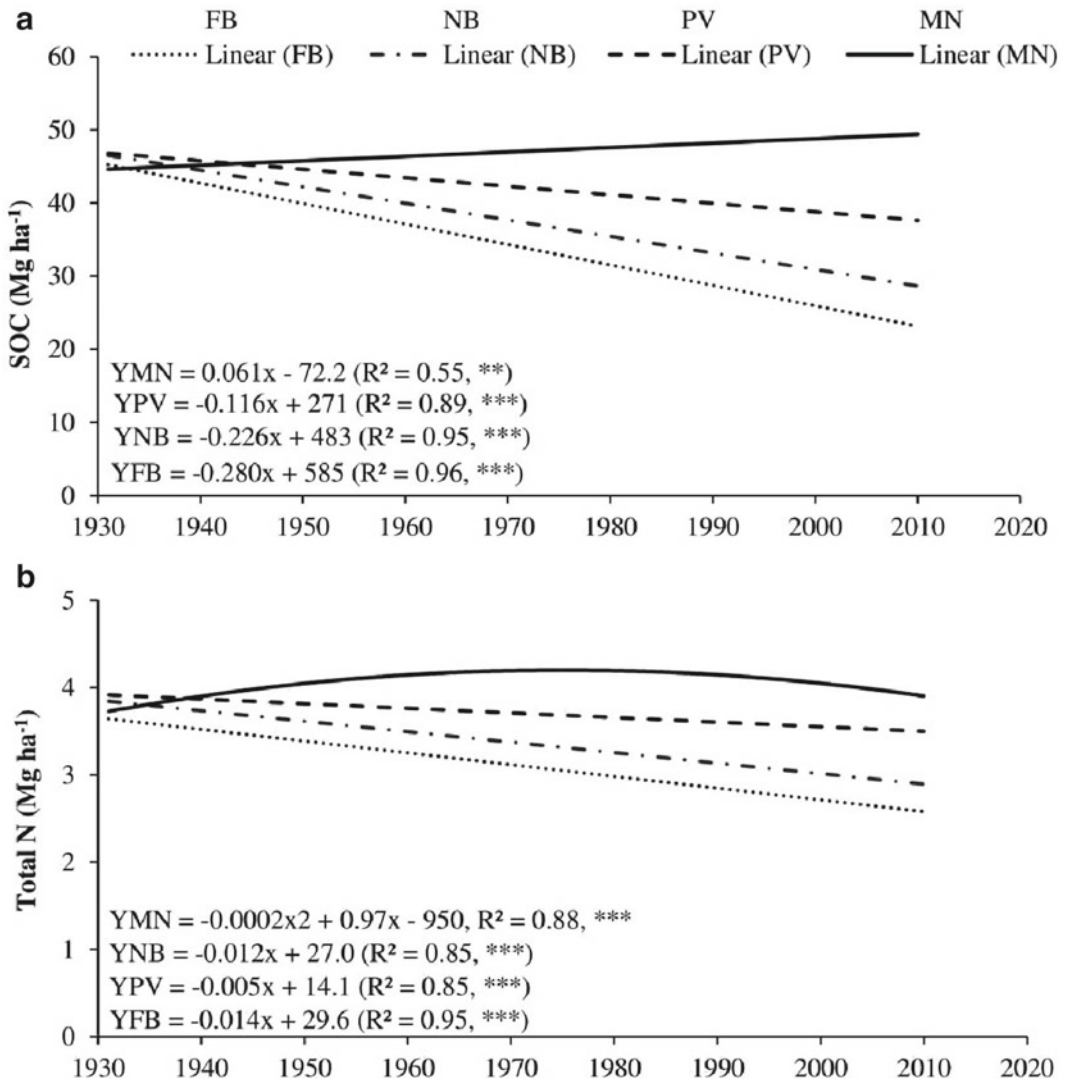


Fig. 27.3 The trend of soil organic carbon (a) and total N (b) in 0–30 cm depth of crop residue long-term experiment (1931–2010). FB, fall burning of wheat residue; MN, manure application (22.4 Mg ha⁻¹ crop⁻¹); PV, pea vine incorporation (2.24 Mg ha⁻¹ crop⁻¹); and

NB, no burning of wheat residue. Stars ** and *** indicate that trends are statistically significant at $p < 0.01$ and $p < 0.001$, respectively. Recent unpublished data for 2010–2020 show a continued declining trend in SOC and N

SOC loss during soil microbial respiration. Our unpublished data show that trend of SOC has not been changed during 2010–2020 as well. The SOC maintenance in agroecosystems depends on C input from crop residues, amendments, and soil microbial biomass and loss through decay or erosion (Huggins et al. 1998; Smith 2008; He et al. 2020; Wiesmeier et al. 2020). A previous study in the CR-LTE revealed

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 in the IPNW drylands (Machado 2011). Considering root biomass C as 45% of aboveground biomass C, the annual return of above- and belowground residue C was insufficient in PV, NB, and FB treatments. In addition, more than half of the residue C was lost due to burning in the FB treatment of this

experiment. Biomass C input was up to 72% and 33% lower in FB and NB, respectively, than the required C input to maintain the SOC in these systems. Insufficient organic inputs likely caused the continuous depletion in SOC content. The average SOC content increased in MN treatment at $61 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in 0–30 cm soil depth. In this case, C input was enough to maintain the SOC level suggesting that manure addition could be one of the ways to revert soil degradation in semiarid drylands where crop residue C is not enough to maintain SOC.

Variation in decay rates of organic residues affects SOC equilibrium in agroecosystems (Huggins et al. 1998). A higher decay rate (dC/dT ; dN/dT) would be expected with the larger input of organic residues, but studies at CBARC showed a lower SOC decay rate in PV and FB treatments (Table 27.1). It appears pea vine and fall burning lowered SOC decay rate while manure application did not affect SOC decay. Therefore, manure-derived C was accumulated in surface soil. In contrast, residue burning removed the labile fraction of biomass C, leaving more recalcitrant materials in the soil with a low decay rate (Neff et al. 2005).

We speculated 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. The C:N ratio for different treatments was as follows: manure (12.1), pea vines (22.2), and wheat residue (81.8). Huggins et al. (1998) showed that low C:N ratio residues minimizes SOC depletion and contribute to SOM building. On the other hand, a lower decay rate in FB compared to NB

treatment is probably attributed to the loss of readily decomposable organic compounds during residue burning. The limited amount of recalcitrant SOC was not enough for maintaining SOC. The labile SOC also has a high decay rate making it more susceptible to loss. More research toward understanding the biochemical composition of residues and the SOC decay rate will help our understanding of how a change in residue quality after burning influences SOC and N dynamics in agroecosystems.

The trend of TN in 0–30 cm depth of MN treatment followed a polynomial curve indicating that soil N increased slightly during the 1931–1995 period and decreased afterward (Fig. 27.3). In PV, NB, and FB treatments, soil TN decreased linearly from 1931–2010. The rate of TN loss was $5 \text{ kg ha}^{-1} \text{ yr}^{-1}$, $12 \text{ kg ha}^{-1} \text{ yr}^{-1}$, and $14 \text{ kg ha}^{-1} \text{ yr}^{-1}$ and in PV, NB, and FB treatments, respectively. It appears soil N content also has a threshold to maintain soil profile N and support sustainable crop production. Similarly, a related PLTEs study by Ghimire et al. (2017) showed that to maintain crop yield in a WW-SF system in the IPNW, the addition of $90 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ ($45 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) is required.

27.3.2 Wheat Yield Trends

We observed a linear decrease in the yield of medium-tall variety (Rex M-1) in all treatments during 1931–1966, with a significant loss in wheat production in NB and FB treatments. The rate of yield decline was 9 kg ha^{-1} in MN, 18 kg ha^{-1} in PV, 30 kg ha^{-1} in NB, and

Table 27.2 Summary statistics of a long-term trend in crop yield in medium-tall (1931–1966) and short wheat varieties (1967–2010) using the best fitting Autoregressive models

Trt	1931–1966		1967–2010	
	Model	Significance	Model	Significance
FB	$CY_{(FB)t} = -0.036t + 73.3$	***	$CY_{(FB)t} = -0.02t + 43.9$	***
NB	$CY_{(NB)t} = -0.030t + 60.8$	***	$CY_{(NB)t} = -0.02t + 42.4$	**
PV	$CY_{(PV)t} = -0.018t + 37.0$	ns	$CY_{(PV)t} = -0.002t^2 + 6.61t - 6552$	*
MN	$CY_{(MN)t} = -0.009t + 21.1$	ns	$CY_{(MN)t} = -0.004t^2 + 14.0t - 13921$	**

† $CY_{(x)t}$ = Crop yield in treatment X, where X include FB, NB, PV, MN; FB = fall burning of crop residue; NB = no burning of crop residue; PV = pea vine incorporation; MN = manure addition; t = time (year).

36 kg ha⁻¹ in FB treatments per year during this period (Table 27.2). However, the yield trend of semi-dwarf varieties (1967–2010) followed a polynomial trend in MN and PV treatments and a linear trend in yield in FB and NB treatments with the loss of 20 kg ha⁻¹ yr⁻¹. Moreover, wheat yields were not significantly different between FB and NB treatments despite some differences in SOC and N loss. Throughout the study period, both treatments did not receive any organic amendments or fertilizers.

The overall trend of wheat yield from 1931–2010 was analyzed using ARIMA models (Fig. 27.4). The ARIMA models use a combination of autoregressive (AR), integration (I), and moving average (MA) functions. An ARIMA model represents the autoregressive components (p), the number of differencing operators (d), and the moving average term to generate outcomes. Since we had a difference in wheat varieties over time, this was the best approach to evaluate the overall trend. Wheat yield increased across all treatments after introducing semi-dwarf wheat varieties in 1967, but within a few years, it started to decrease again,

specifically in FB and NB treatments. The high yield of semi-dwarf wheat varieties sustained for several years in PV and MN before the decreasing trend started in the 1990s. Our recent unpublished data show that the declining trend has continued even during 2010–2020.

27.3.3 Soil Organic Carbon and Nitrogen Loss Affect Wheat Yield

High SOC and N content are often associated with good soil aggregation (Six et al. 2002; Zhou et al 2020), high microbial biomass, activity, and diversity (Ghimire et al. 2014), high root biomass (Qin et al. 2004), and improved water storage (Sherrod et al. 2005). These improvements in soil quality indicators are often associated with high crop yields and quality. In contrast, insufficient organic inputs, repeated tillage, erosion, or other forms of soil degradation (Fig. 27.5) negatively impact crop production. For example, low organic C and N input likely caused continuous depletion in SOC and N contents and reduced

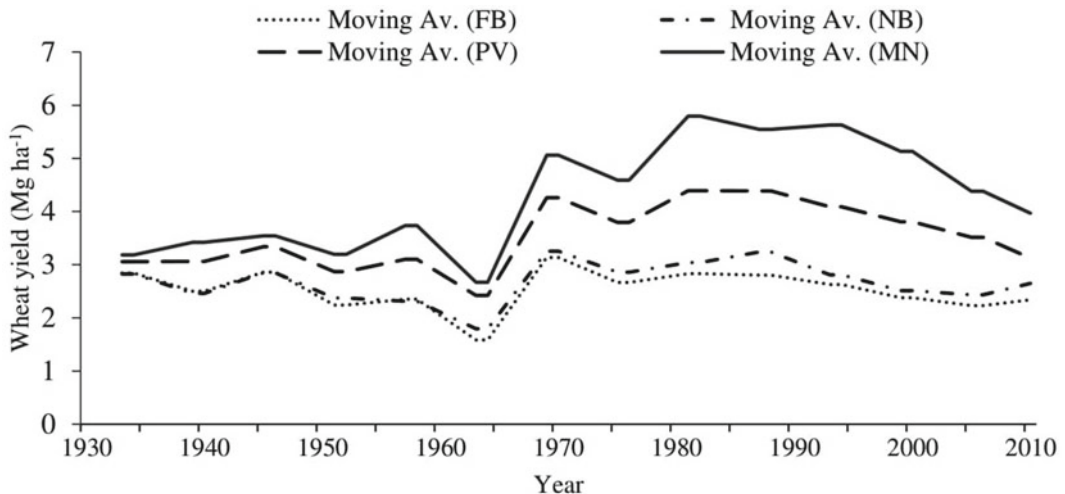


Fig. 27.4 Crop yield trend during 1931–2010 in the selected treatment of crop residue long-term experiment using autoregressive integrated moving average (ARIMA) model. FB, fall burning of wheat residue; MN, manure

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



Fig. 27.5 Wind erosion in the conventionally tilled wheat field in eastern Oregon, USA

Table 27.3 Soil carbon and nitrogen at 0–30 cm soil depth was highly correlated with crop yield in selected treatments of the crop residue long-term experiment

Period	SOC†		TN	
	Correlation	Significant	Correlation	Significance
1931–1966	0.79	***	0.86	***
1967–2010	0.87	***	0.92	***
1931–2010	0.56	***	0.65	***

†Correlation analysis between annual winter wheat yield, soil organic carbon (SOC), and total nitrogen (TN) data for the given period of time.

wheat yield in the WW-SF systems (Table 27.3). Specifically, no external input of N was supplied through mineral fertilizer or legumes to the FB and NB treatments for > 80 years. These treatments were highly N limited for much of the study period, while 37–70 kg N ha⁻¹ was lost in grain harvest each year (Rasmussen and Parton 1994).

Grain N data from 1986–2004 showed MN treatment was the only treatment that maintained a positive N balance (Ghimire et al., 2018). Insufficient N from residues and continuous depletion of N stock from the soil profile caused all other treatments to have a net negative N balance. The MN and PV treatments appeared to have maintained a positive N balance for several years, at least in the surface soil. This positive N

balance helped in maintaining crop yields in MN treatments, but ultimately yield decline was observed starting 1990s. Since TN mineralization was the only source of available N for the crop in FB and NB treatments, irrespective of the crop variety changes over time, the continuous depletion of TN was observed in these treatments, leading to greater decline in crop yields.

It is often argued that N addition can minimize crop yield decline in the WW-SF system. The previous study on these plots demonstrated the addition of 90 kg N ha⁻¹ crop⁻¹ is needed to maintain crop yield in a WW-SF system (Ghimire et al., 2017). However, further increase in N input did not increase wheat yield, rather decreased SOC and TN stock and increased soil acidity (Fig. 27.6). Similarly, the addition of

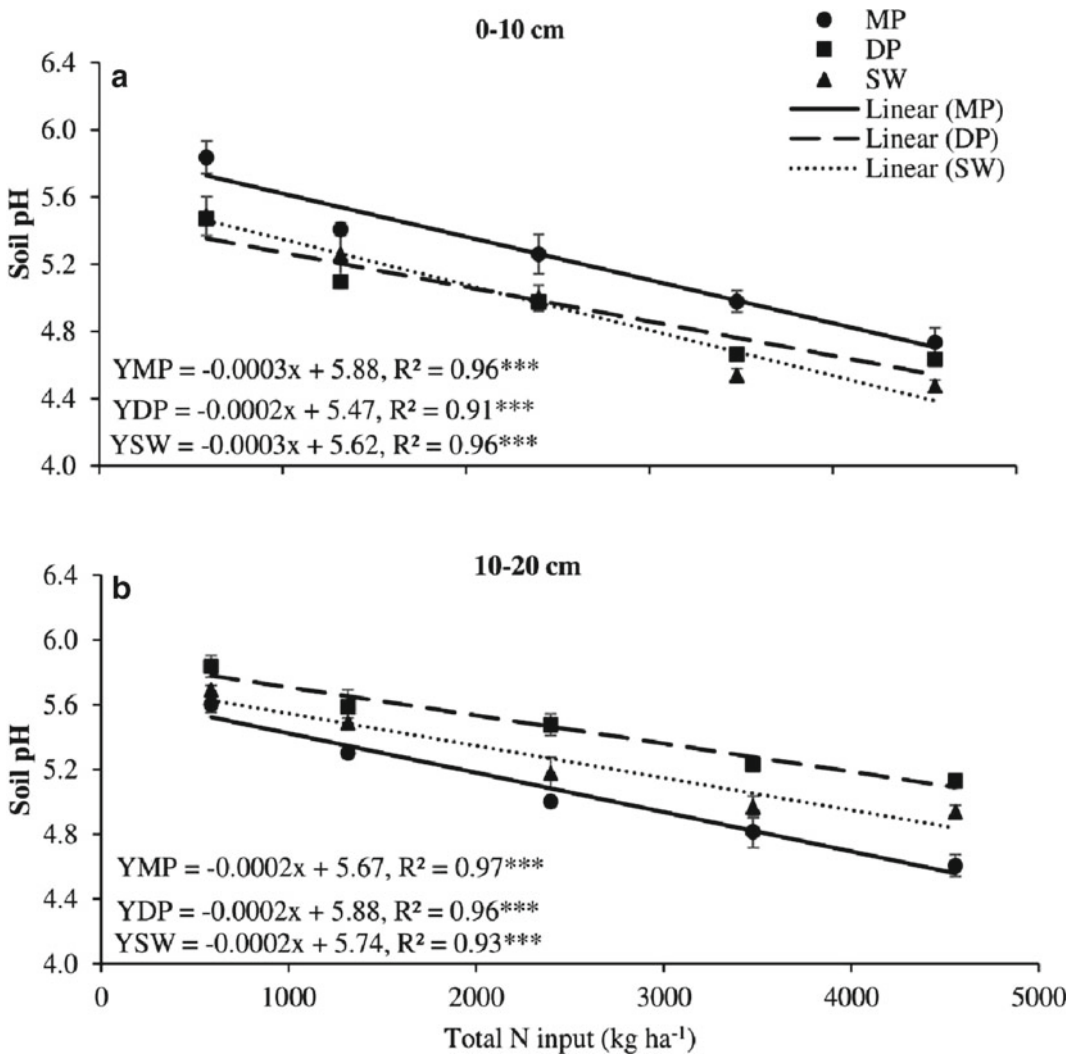


Fig. 27.6 The relationship between total fertilizer N input (1941–2010) and soil pH in 2010 in (a) 0–10 and (b) 10–20 cm depths of a winter wheat–summer fallow

system under moldboard plow (MP), disc plow (DP), and sweep (SW) tillage management

180 kg N ha⁻¹ every other year (annual rate of 90 kg N ha⁻¹ yr⁻¹) in a long-term WW-SF experiment did not stop the depletion of SOC and N. The N input on manure treatment was 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 and beyond, potentially due to loss of SOC and N reservoir from below 30 cm soil depth (Ghimire et al. 2018). Furthermore, the decline rate in SOC was more rapid after 1986, possibly due to

a change in wheat from tall to semi-dwarf varieties (Ghimire et al. 2015). The biomass C supply controls SOC levels in agroecosystems. Semi-dwarf varieties produce smaller biomass compared to tall varieties, reducing biomass C and N inputs.

27.3.4 Importance of Subsoil Fertility to Maintain Wheat Yield

The nutrients and SOC in the top 20–30 cm soil depth from the surface have been extensively studied. However, very few studies report changes in subsoil fertility and their potential impacts on soil processes because the response of deeper soil to management changes usually takes several

decades. Long-term experiments, such as CR-LTE, can be an excellent resource for understanding the role of subsoil C and nutrients on crop yield and sustainability. Although SOC was maintained in surface 0–30 cm depth in MN treatment of the CR-LTE, its level in 30–60 cm decreased consistently across all treatments (Fig. 27.7) at a rate of 175–200 kg ha⁻¹ yr⁻¹. Loss of the soil functions associated with

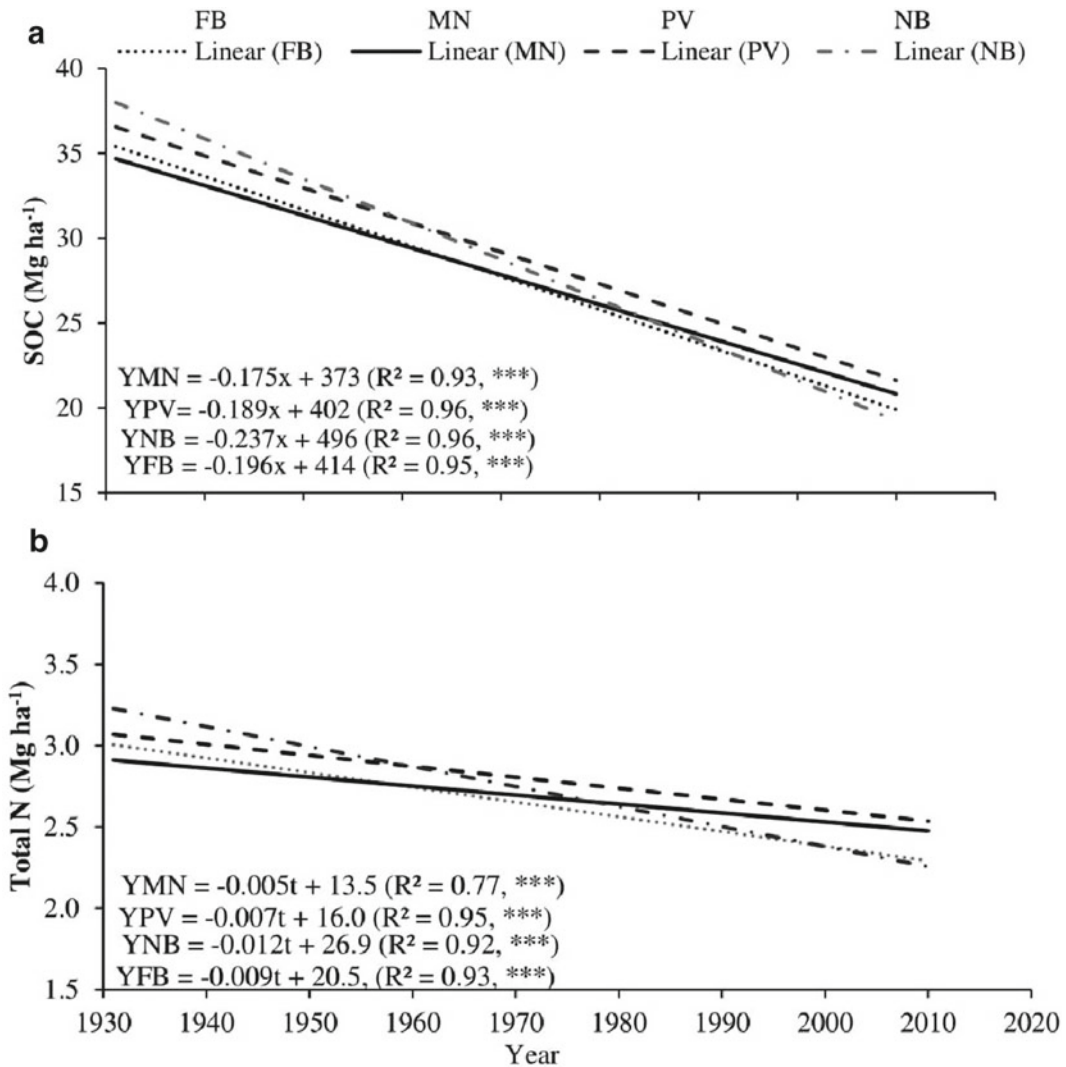


Fig. 27.7 The trend of soil organic carbon (a) and total N (b) in subsoil (30–60 cm) depths of crop residue long-term experiment (1931–2010). FB, fall burning of wheat residue; MN, manure application @22.4 Mg ha⁻¹ crop⁻¹;

PV, pea vine incorporation (2.24 Mg ha⁻¹ crop⁻¹); and NB, no burning of wheat residue (Modified from Ghimire et al. 2018)

depletion in SOC and N has significantly reduced crop yield and SOM turnover (Huggins et al. 1998; Sherrod et al. 2005). The SOC loss from the lower depth may have contributed substantially to low soil nutrient and water storage, thereby decreasing wheat yields.

27.4 Conclusion

The study of SOC, N, and winter wheat yield trends over >80 demonstrated the crucial role of long-term field experiments for understanding management impacts on soil health and possible site degradation risks. Our study shows the adverse effects of current soil management practices on soil health, resulting in SOM depletion and crop yield decline. The only treatment that maintained SOC in the top 30 cm soil was manured (MN) treatment. Larger amounts of organic matter input under this treatment played a pivotal role in maintaining SOC and sustaining crop production in the WW-SF system. Nevertheless, decrease in SOM under the WW-SF system will continue to negatively impact soil health and reduce crop yields in the drylands of the IPNW. Imbedding long-term analytical data into Agroecosystem Models and other innovative experiments could help in finding sustainable management practices for cropping systems in the IPNW region of the US and semiarid agroecosystems facing soil degradation. The SOC and N in soil profiles play a crucial role in improving the sustainability of dryland farming in semiarid environments.

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