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Soil pH, Soil Organic Matter, and Crop Yields in Winter Wheat–Summer Fallow Systems

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ABSTRACT

Soil acidification has become a major environmental challenge for crop production in the inland Pacific Northwest (iPNW). We evaluated the effects of tillage and N-fertilizer management on soil pH, soil organic carbon (SOC), soil N, and crop yields from 1995 through 2010 in an ongoing long-term experiment in eastern Oregon. Tillage systems included moldboard plow (MP), disk plow (DP), and subsurface sweep (SW) and N-fertilizer rates were 0, 45, 90, 135, 180 kg N ha^{-1} crop^{-1} in a dryland winter wheat (*Triticum aestivum* L.)–summer fallow (WW–SF) system. Soil pH, SOC, and N were monitored in 1995 and 2010, and crop yields were monitored every other year. Soil pH was lower in the higher N rate treatments. Long-term N fertilizer application increased soil acidity in 0- to 10-cm depth by 0.3, 0.2, and 0.3 units in MP, DP, and SW, respectively, for every 1000 kg N applied through ammonical N fertilizers. Soil pH was higher in DP than MP in 10- to 20- and 20- to 30-cm depth profiles. The SOC and N concentrations in the top 30-cm depth were lower in 2010 than in 1995 across all treatments. Wheat yield increased significantly with increase in N rates from 0 to 90 kg N ha^{-1} crop^{-1}. There were no further yield increases above 90 kg N ha^{-1} crop^{-1}. Soil acidification, SOC and nutrient dynamics should be carefully monitored in cropping systems using ammonical N fertilizers, particularly under high rate of N application and reduced tillage.

Core Ideas

- Continuous addition of ammonical N fertilizer increases soil acidity.
- Soil acidification influences nutrient dynamics and crop yields.
- Soil organic C and soil N decreased over years under winter wheat–summer fallow system.
- Soil acidifcation was not related with soil organic carbon and soil N loss over years.
- Soil acidification should be carefully monitored in systems using ammonical N fertilizers.

Soil acidification has become a major environmental challenge for crop production in the U.S. iPNW (Rasmussen and Rohde, 1989; Brown et al., 2008). The iPNW represents the largest area under dryland farming with more than 2 million ha under WW–SF system (Schillinger et al., 2003; Schillinger and Papendick, 2008). Introduction of chemical N fertilizers, mechanized equipment, and crop breeding and management practices in the iPNW in 1940s improved efficiency of dryland farming in the region (Schillinger and Papendick, 2008). However, continuous use of chemical fertilizer and intensive tillage deteriorated soil quality and negatively affected agricultural sustainability through soil acidification and SOC and nutrient loss (Mahler et al., 1985; Rasmussen and Rohde, 1989; Schillinger and Papendick, 2008). In general, soils are strongly buffered by ion exchange reactions and it takes 100 to 1000 yr for soil pH to change under natural conditions (Chadwick and Chorover, 2001). Soils in some parts of eastern Oregon and Washington, however, were acidified within 30 to 40 yr of N fertilizer applications (Mahler et al., 1985), and most farmers are not taking any measures to remedy the situation. In fact, N fertilizer use in wheat production, mostly ammoniacal, has increased from an average of 69 kg N ha^{-1} in 1993 to 90 kg N ha^{-1} in 2012 (USDA-ERS, 2013). The demand for N use in North America is expected to increase by about 0.5% between 2014 and 2018, according to Food and Agricultural Organization data (FAO, 2015). To this end, soil pH will continue to decrease below optimum levels for wheat production unless changes to fertility management to slow down acidification are implemented. Meanwhile, area under reduced-tillage (e.g., subsurface sweep, disk), no-tillage, and fertility management practices is increasing to improve soil and water conservation and sustainable crop production in drylands (Schillinger and Papendick, 2008). It is not clear how these alternative tillage and fertility management practices influence soil acidity, soil quality, and crop production in dryland WW–SF systems. Available information indicated that reduced-tillage and no-tillage cropping systems concentrate fertilizer in the seed zone thereby increasing acidity in the top surface soil layers.

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Abbreviations: DP, disk plow; MP, moldboard plow; PLTEs, Pendleton long-term experiments; iPNW, inland Pacific Northwest; SOC, soil organic carbon; SW, subsurface sweep; WW–SF, winter wheat–summer fallow.

Addition of N fertilizer itself is not an acidifying process. The acidity produced from nitrification is utilized during nitrate reduction in plant tissues and soil microorganisms (Barak et al., 1997). In the process of NH_4^+ oxidation, only N not utilized in plant and microbial metabolism can lower soil pH (Tang et al., 2002). The soils in eastern Idaho and Oregon were neutral to near neutral (pH 6.5–7.2) at the time the native prairie was first broke for cultivation in the1890s and a significant change in soil pH was not observed until ammoniacal N fertilizers were introduced in the region in early 1960s (Oveson, 1966; Mahler and Harder, 1984). After several decades of N fertilizer addition, average pH in the surface soil declined from a near neutral to <5.2, the lower critical limit for wheat production (Mahler, 2002). A study in China revealed that intensive farming and high rate of N fertilizer addition caused a drop in soil pH by 0.30 to 0.80 units in 20 yr (Guo et al., 2010). In eastern Oregon, the addition of nearly 2.25 Mg N ha^{-1} over 43-yr period (1941–1984) lowered soil pH by 0.60 units (Rasmussen and Rohde, 1989). The pH scale is logarithmic and a decrease in soil pH of 0.60 corresponds to a fourfold increase in H^+ ion activity and associated changes in ion exchange activities in the soil (Guo et al., 2010). Effects of N fertilizers on soil acidification were observed in the dryland WW–SF systems of iPNW at relatively high rates of fertilizer application (Mahler et al., 1985).

Soil acidification due to N fertilizer addition can influence crop production. Studies revealed a decrease in wheat yield with an increase in acidification (Kariuki et al., 2007; Schroder et al., 2011). Acidification below pH 5.5 increased the solubility of soil Al^{3+} and Mn^{2+}, and negatively impacted winter wheat growth and yields (Ernani et al., 2002; Schroder et al., 2011). In strongly acidified soils, Al toxicity causes reduced root growth and stunted plants (Schroeder and Pumphrey, 2013). Low soil pH is also associated with low water uptake and nutrients (N, P, Mg, Mo) availability (Kemmitt et al., 2006; Kariuki et al., 2007), which negatively influences crop production and profitability.

In an effort to improve sustainability of dryland farming in the iPNW, Pendleton Long-Term Experiments (PLTEs) have facilitated the comparison of different tillage, crop residue, and N management practices on soil properties and crop production. Effects of tillage and crop residue management on SOC and N dynamics in eastern Oregon have been reported in earlier studies (e.g., Machado et al., 2006; Gollany et al., 2011; Machado, 2011; Ghimire et al., 2015; Bista et al., 2016). Studies from other regions also report potential benefits of fertilizer N addition and conservation tillage practices as they improve water and nutrient use efficiency, SOC accumulation, and soil nutrient conservation (Rasmussen and Rohde, 1988; Khan et al., 2007; Schillinger and Papendick, 2008). Decomposition of SOM occurs slowly in acidic soils than in neutral to near neutral pH and, consequently, can influence long-term SOC and nutrient dynamics (Rasmussen and Rohde, 1989; Guo et al., 2010; Schroder et al., 2011). Acidification of surface soil was faster in conservation tillage than in conventional tillage systems because N fertilizer is often banded close to seed in the top surface layers (Mahler et al., 1985; Rasmussen and Rohde, 1989; Brown et al., 2008). In the typical inversion tillage systems, on the other hand, the rate of acidification was slower because N fertilizer is mixed with a larger volume of soil determined by tillage depth (Rasmussen and Rohde, 1989). The PLTEs have several long-term studies that allow evaluation of soil acidity, SOC, soil nutrients, and crop yields in the iPNW. The tillage–fertility long-term experiment (TF-LTE) established in 1940 has a long-history of tillage and N management, and can provide critical information regarding soil properties and crop production in the semiarid regions.

The main objective of this study was to evaluate the influence of long-term tillage and N fertilizer management on profile distribution of soil acidity, SOC and N, and wheat yield in the TF-LTE, a dryland WW–SF system. Here, we compared changes in soil pH, SOC, and N in the 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 60-cm soil depths and wheat yield as influenced by tillage and N rate treatments during 1995 to 2010. We also examined the response of N-fertilizer rate on soil N concentration and relationship among total amounts of N applied in last several decades with soil pH and wheat yield.

MATERIALS AND METHODS

Study Site and Treatments

The ongoing TF-LTE is located at the Columbia Basin Agricultural Research Center (CBARC) near Pendleton, OR (45°42′ N, 118°36′ W, elevation 438 m). The research site has a semiarid climate 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°C and average annual precipitation is 421 mm. About 70% of the precipitation occurs between September and March. The soil is classified as a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) and consist of loess deposits overlying basalt (Soil Survey Staff, 2016). The soil has approximately 20% clay, 68% silt, and 12% sand in the 0- to 30-cm depth. The cation exchange capacity of the soil is 16 $cmol_c$ kg^{-1}. Average soil depth to bedrock for replication 1 is approximately 210 cm, for replication 2 is 130 cm, and for replication 3 is 110 cm. All plots are located in <3% slope (Rasmussen and Smiley, 1997).

The experiment was established as a randomized complete block design with the split-plot arrangement of three tillage systems, five N fertilizer rates, and three replications. The tillage systems (Moldboard plow, MP; disk plow, DP; subsurface sweep, SW) are the main plot factors, and N fertilizer rates (0, 45, 90, 135, 180 kg N ha^{-1} $crop^{-1}$) are the subplot factors (Table 1). The main plots are 35 by 40 m and subplots are 5.8 by 40 m size. The main plot treatments differed in tillage equipment, tillage depth, and surface residue cover at the time of seeding. The MP, DP, and SW tilled soil to a depth of approximately 23, 10, and 15 cm, and left 7, 34, and 43% residue cover, respectively, on the soil surface at the time of seeding (Camara et al., 2003). Primary tillage in the fallow plots was conducted in late March to early April on the stubble left undisturbed since the previous year's crop harvest. All plots were subsequently smoothed to a depth of 10 to 15 cm using a field cultivator and harrow and rod-weeded as needed to control weeds during the fallow period.

Nitrogen fertilizer {urea [$CO(NH_2)_2$] and ammonium nitrate [NH_4NO_3]} was added every other year (crop year) during the first week of October, approximately a week before

Table 1. History of N application since establishment of a winter wheat–summer fallow system experiment in 1940.

N rate treatment	Amount of N applied† 1941–1951 Rate	Total	1952–1961 Rate	Total	1962–1987 Rate	Total	1988–2010 Rate	Total	Grand total (1941–2010)	Ammonium + urea N (1941–2010)
	kg N ha^{-1}									
0	0	0	0	0	45	585	0	0	585	234
45	11	66	34	170	45	585	45	495	1316	841
90	11	66	34	170	90	1170	90	990	2396	1447
135	11	66	34	170	135	1755	135	1485	3476	2052
180	11	66	34	170	180	2340	180	1980	4556	2657

† Nitrogen was applied as ammonium sulfate during 1941–1961, as ammonium nitrate during 1962–1987, and as urea ammonium nitrate since 1988.

wheat seeding, in 30 cm wide bands to a depth of 10 cm using a custom build 3000 Viper Coulters (Yetter Manufacturing Inc. Colchester, IL.). The original experiment had six N rate treatments when it was established in 1940. The experiment was revised in 1952, 1962, and 1988. In the 1952–1953 revision, N rate increased from 11 kg N ha^{-1} $crop^{-1}$ to 34 kg N ha^{-1} $crop^{-1}$ in all fertilizer treatments. Ammonium sulfate [$(NH_4)_2SO_4$–21–0–0–24S)] was used as a source of N until treatments were revised in 1962. Sulfur application during 1941 to 1962 did not improve wheat yield (Camara et al., 2003). Therefore, the S application was discontinued in 1963 in all S- applied treatments. Ammonium nitrate (34–0–0) was used from 1963 to 1987 and urea ammonium nitrate (32–0–0) was used from 1988 to 2010 as sources of N. There was no difference between treatments with and without S history. Therefore, the treatment with no S history is not included in our analysis. This allows evaluation of the treatments with the same N fertility management history (Table 1).

A nearby grassland that was maintained in native vegetation since 1931 was used as the baseline for comparisons with cultivated treatments. The grassland that consisted of grasses such as blue-bunch wheatgrass (*Agropyron spicatum* Pursh) and Idaho fescue (*Festuca idahoensis* Elmer) as dominant species, received no external fertilizer. Grass biomass was recycled within the system and the biomass input was enough to maintain the SOC (Ghimire et al., 2015).

Crop Management and Yield Estimation

Winter wheat was seeded in October throughout the study, approximately 1 wk after fertilizer application, using a JD8300 drill (Deere and Company, Moline, IL) before 2002 and a Case IH 5300 disk drill (Klamath Basin Eq. Inc. Klamath Falls, OR) thereafter. Medium tall soft white winter wheat (Rex M-1) was grown from 1940 to 1962, and semi-dwarf soft white winter wheat since 1963 (Nugaines, Hyslop, Malcolm, and Stephens). Wheat variety Malcolm was grown during 1995 to 2005 and Stephens since 2007. Wheat was seeded at 72 ± 5 kg ha^{-1} and a row spacing of 25 cm. Weeds were controlled using chemical herbicides during the crop phase and by rod-weeding three to five times between April and October in the fallow year. Glyphosate [*N*-(phosphonomethyl) glycine] was applied at 1.2 L a.e. ha^{-1} in late winter or early spring to control weeds until plots were plowed in late spring. Wheat was harvested in early July using a small plot combine (Deere and Company, Moline, IL) and the land was kept fallow for the next 14 mo before planting the next wheat crop. Grain yield was obtained by harvesting a 2.1 by 40 m swath from each treatment.

Soil Sampling and Laboratory Analysis

Soil samples were collected using a tractor-mounted Giddings Hydraulic Probe (i.d. 3.6 cm) after wheat harvest in 1995 and 2010. Soil samples were collected from 0- to 10-, 10- to 20-, 20- to 30-, and 30- to 60-cm depth increments. Four soil cores were collected from each treatment and also from a nearby grassland plot (fenced off in 1931) as a baseline for comparisons with cultivated areas. All samples were composited by depth increment, thoroughly homogenized, and brought to the laboratory for soil C, N, and pH analyses. In the laboratory, all visible plant materials (roots, stems, and leaves) were removed, soils were air dried, ground by a rolling pin, and passed through a 2-mm screen. Soil pH was analyzed on 2-mm sieved 10-g samples in a 1:2 soil to 0.01M $CaCl_2$ solution using pH electrodes after a 30 min equilibration time (Thomas, 1996). This method was preferred over 1:1 or 1:2 soil water ratio because using $CaCl_2$ minimized the impact of ionic strength and biological activity on soil pH buffering (Wang et al., 2015). Soil total C and N concentrations were determined by dry combustion (Flash EA 1112 series, Thermo Finnigan, San Jose, CA). Soil pH was used to indirectly detect inorganic C in soil samples. Since all soil samples in this study had a pH less than 6.8, we considered total C from these samples as SOC.

Statistical Analysis

The analyses of the effects of tillage, N rate, and year on wheat grain yield, soil pH, SOC, and N data were conducted using the MIXED procedure of SAS (v.9.3, SAS Institute, Cary, NC). Treatment effects on soil pH, SOC, and N data were analyzed separately for each soil depth profile in 1995 and 2010. Tillage system was considered main plot factor, N rate as a first split plot factor (space), and year as a second split plot factor (time). Replication was used as a random term in the model. Depth effects were analyzed in 2010 data only, after 70 yr of treatments, to determine interactions among treatments and depth. Data for all the study variables were tested for normality of residuals and homogeneity of variance assumptions. Treatment means differing in *F* test in all analyses were separated using a Tukey test ($P \leq 0.05$) unless otherwise stated. The pH scale is logarithmic and small differences in pH that represent huge differences in H^+ concentration may not be detected from analyzing soil pH values alone. Therefore, soil pH data were converted to H^+ concentration (μmol L^{-1}) before analyses. The level of significant differences used to separate soil pH treatment means was based on analyses of H^+ concentration. Relationships between N rate and soil pH was compared using a linear regression procedure (PROC REG) in

SAS. A linear correlation procedure (PROC CORR) in SAS was used to evaluate relationships among mean SOC, mean soil N, and changes in grain yield from 1995 to 2010.

RESULTS

Soil pH at Different Depths in 1995 and 2010

Soil pH in the 0- to 10-cm depth was significantly influenced by tillage, N and year, but not by treatment interactions (Table 2). In this soil depth, soil pH significantly decreased with increase in N rates and was below 5.0 under treatments receiving 135 and 180 kg N ha^{-1} $crop^{-1}$ (Fig. 1a). Soil pH was not significantly different between treatments receiving 45 and 90 kg N ha^{-1} $crop^{-1}$ and between treatments receiving 135 and 180 kg N ha^{-1} $crop^{-1}$. Soil pH averaged for all N rate treatments in 0 to 10 cm was significantly higher under MP than under DP and SW (Fig. 2a). The pH under DP and SW was not significantly different. Comparisons between years showed that soil pH in the 0- to 10-cm depth decreased by 0.31 units from 1995 to 2010. Soil pH in the experimental area was lower than the nearby grassland that had a pH of 6.8 in the 0- to 10-cm depth.

Soil pH in 10- to 20-cm depth was significantly different among tillage systems and N rates but not between years (Table 2). There were no interactions among tillage, N rate, and year treatments on soil pH. The pH followed the same trend as in the 0- to 10-cm depth and decreased with increase in N rates (Fig. 1b). Soil pH was below 5.0 under treatments that received 135 and 180 kg N ha^{-1} $crop^{-1}$. The pH between these high N rates was not significantly different. Soil pH averaged for all N rate treatments in 10 to 20 cm was lower under MP than under DP and SW and significantly so when compared to soil pH under DP (Fig. 2b). Soil pH levels of all WW–SF treatments were lower than pH (7.3) in the nearby grassland in 10- to 20-cm depth.

Soil pH in 20- to 30-cm depth was also influenced by N rate and tillage systems, but not by year and interactions among tillage systems, N rates, and year (Table 2). Soil pH was significantly lower under treatments that received 135 to 180 kg N ha^{-1} $crop^{-1}$ than under treatments that received 0 and 45 kg N ha^{-1} $crop^{-1}$ (Fig. 1c). Soil pH in 90 kg N ha^{-1} $crop^{-1}$ treatment was intermediate of other N rate treatments. The pH was near 6.0 even in treatments receiving the highest N rates. Soil pH averaged for all N rates revealed significantly lower soil pH under MP than under DP and SW (Fig. 2c).

Soil pH in 30- to 60-cm depth was not significantly different among tillage systems, N rates, years, and their interactions (Table 2, Fig. 1d, Fig. 2d). The pH at all N rates and under all tillage treatments was above 6.5. Soil pH in nearby grassland was ≥7.6 in soil depths below 20-cm depth.

Tillage, Fertilizer, and Depth Interactions on Soil pH in 2010

Soil pH stratification is largely influenced by tillage practices, N source, and depth of soil mixing (Mahler et al., 1985; Rasmussen and Rohde, 1989; Brown et al., 2008). Data obtained in 2010, after 70 yr of N fertilizer application and tillage treatments (1941–2010), showed that there were significant interactions among tillage, N, and depth on soil pH (Table 3). Comparing soil pH among N treatments at each depth revealed that there were no significant differences in soil pH in the 0- to 10-cm depth at fertilizer rates below 90 kg N ha^{-1} $crop^{-1}$ under all tillage treatments (Table 4a). Increasing fertilizer rates above 90 kg N ha^{-1} $crop^{-1}$ significantly reduced soil pH to below 5 in this soil depth. Under MP, there were no significant differences in soil pH at all N rates below 20-cm depth. In 0- to 10-cm depth, soil pH under MP did not significantly differ at fertilizer rates up to 135 kg N ha^{-1} $crop^{-1}$ but differed significantly at 180 kg N ha^{-1} $crop^{-1}$ compared to lower N rates. In 10- to 20-cm depth, soil pH did not differ significantly at fertilizer

Table 2. Analysis of variance table for wheat yield, soil pH, soil organic carbon (SOC) and soil N as influenced by tillage, N rate, and year in a winter wheat–summer fallow system.

Variable	Depth	Tillage (T)	N rate (N)	Year (Y)	T×N	T×Y	N×Y	T×N×Y
Soil pH	0–10	0.02	<0.01	<0.01	0.26	0.36	<0.14	0.63
	10–20	<0.01	<0.01	0.82	0.46	0.36	0.99	0.82
	20–30	<0.01	<0.01	0.81	0.08	0.31	0.99	0.83
	30–60	0.78	0.10	0.94	0.97	0.36	0.89	0.06
SOC	0–10	<0.01	0.09	0.03	0.64	0.06	0.92	0.06
	10–20	0.29	0.20	0.04	0.22	0.06	0.86	0.22
	20–30	0.40	0.70	0.03	0.56	<0.01	0.49	0.18
	30–60	0.35	0.59	0.26	0.54	0.18	0.73	0.32
Soil N	0–10	0.11	0.32	0.06	0.61	0.18	0.66	0.30
	10–20	0.22	0.03	<0.01	<0.01	0.67	0.43	0.78
	20–30	0.38	0.45	<0.01	0.21	0.24	0.47	0.79
	30–60	0.44	0.47	0.29	0.69	0.20	0.27	0.79
Wheat yield	–	0.01	<0.01	<0.01	0.19	<0.01	<0.01	0.27

Table 3. Analysis of Variance table for depth distribution of soil pH, soil organic carbon (SOC) and soil N in 2010, after 70 yr of the establishment of a winter wheat–summer fallow system experiment.

Parameter	Tillage (T)	N rate (N)	Depth (D)	T×N	T×D	N×D	T×N×D
Soil pH	<0.01	<0.001	<0.001	0.65	<0.001	<0.001	0.01
SOC	0.321	0.35	<0.001	0.60	0.002	0.91	0.44
Soil N	0.495	0.17	<0.001	0.91	0.29	0.42	0.49

rates lower than 45 kg N ha^{-1} crop^{-1} but decreased significantly (<5.0) at 90 kg N ha^{-1} crop^{-1} and above. In 0- to 10-cm depth, soil pH under DP and SW significantly decreased below 5.0 at treatments receiving 135 and 180 kg N ha^{-1} crop^{-1}. Soil pH at all depths was not significantly different between DP and SW, which was significantly lower than MP (Table 5).

In general, soil pH under all tillage systems was lower in the top surface layers than in deeper layers at all N rates but this was significantly so at fertilizer rates above 135 kg N ha^{-1} crop^{-1} under MP and above 90 kg N ha^{-1} crop^{-1} under DP and SW (Table 4a). Under MP, soil pH at 135 and 180 kg N ha^{-1} crop^{-1} had decreased below 5 in the 0- to 20-cm depth whereas soil pH under DP and SW significantly decreased to 5 or below at N rates above 90 kg N ha^{-1} crop^{-1} (Table 4a).

Comparisons of soil pH under different tillage systems at similar depths and N rates showed that there were no significant differences in soil pH at fertilizer rates below 45 kg N ha^{-1} crop^{-1} at each depth (Table 4b). At 90 kg N ha^{-1} crop^{-1} there were no significant differences in soil pH at each depth among all tillage systems. However, at this N rate, soil pH was significantly lower at the top 10 cm than at lower depths under DP. At 135 kg N ha^{-1} crop^{-1}, soil pH in the top 10 cm was significantly lower under SW than under MP. Below 10 cm, soil pH did not significantly differ among tillage systems at comparable depths. Under this N rate, soil pH in the top 10 cm was significantly lower than soil pH at lower depths. At 180 kg N ha^{-1} crop^{-1}, soil pH under all tillage treatments in the 0- to 10-, 20- to 30-, and 30- to 60-cm depths was not significantly different. However, in the 10- to 20-cm depth, soil pH under MP was significantly lower than soil pH under DP and SW. Averaged across all tillage treatments, soil pH in the top 20-cm depths was significantly lower than soil pH below 20-cm depths showing an increase in acidity as N rates increased (Table 5).

Regression analysis of soil pH with total amount of fertilizer N applied from 1941 through 2010 revealed a faster rate of soil pH decline in both 0- to 10- and 10- to 20-cm soil depths with greater amount of N application (Fig. 3). Although N fertilizers applied at different time periods may have influenced soil

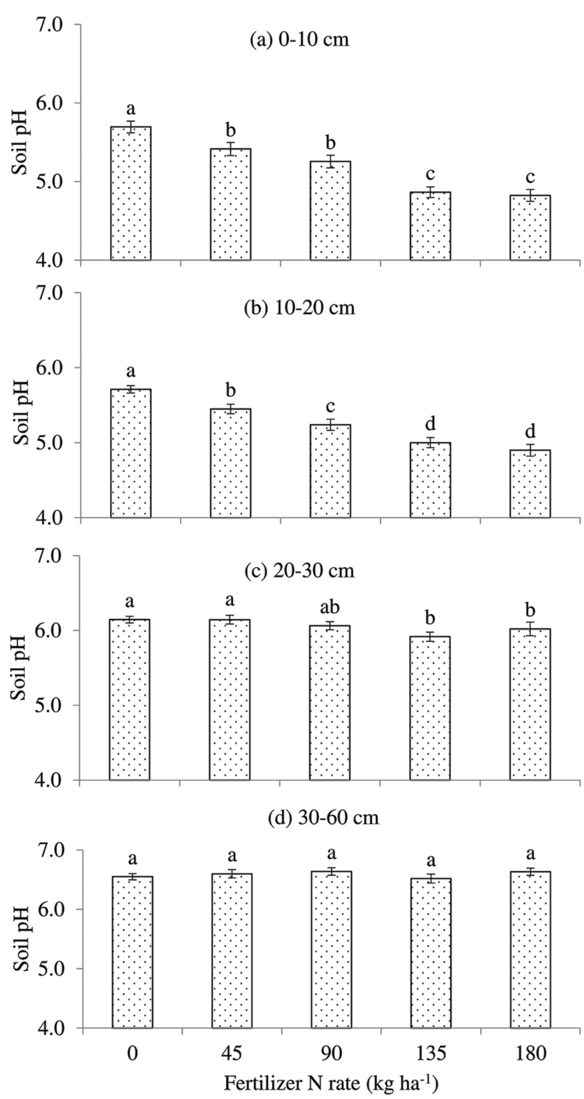

Fig. 1. Soil pH at different depths under a winter wheat–summer fallow system influenced by soil N addition. Same lowercase letters indicate no significant difference among different N rate treatments in a given soil depth ($P \leq 0.05$, Tukey test).

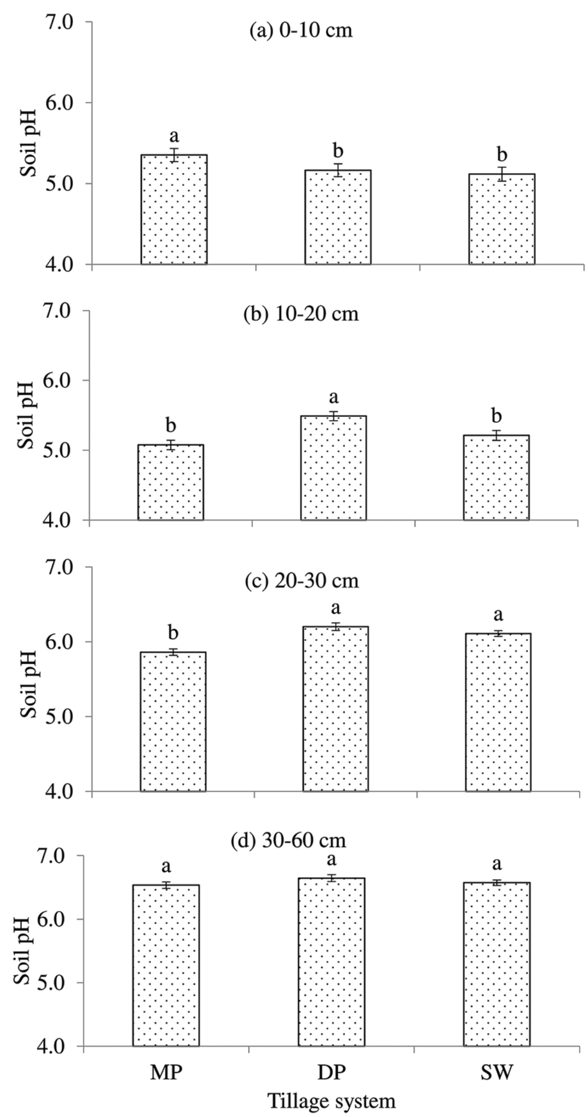

Fig. 2. Soil pH at different depths under a winter wheat–summer fallow system influenced by tillage system. Same lowercase letters indicate no significant difference among tillage treatments in a given soil depth ($P \leq 0.05$, Tukey test).

Table 4. Soil pH in 2010, after 70-yr of treatment application, as influenced by (a) interaction of sampling depth and N fertilizer rate and (b) interaction of sampling depth and tillage systems in a winter wheat– summer fallow system.

(a) Tillage system	Depth	N rate 0	45	90	135	180
		kg ha^{-1}				
MP	0–10	5.84aA†	5.41aA	5.21aA	4.98abAB	4.74bAB
	10–20	5.60aA	5.30abA	5.00abA	4.82bcB	4.61cB
	20–30	6.13aA	5.99aA	5.79aA	5.64aA	5.68aA
	30–60	6.54aA	6.70aA	6.61aA	6.33aA	6.40aA
DP	0–10	5.47aA	5.10aA	4.91abB	4.67bB	4.64bB
	10–20	5.84aA	5.59aA	5.42aAB	5.23aA	5.13aA
	20–30	6.18aA	6.17aA	6.28aAB	6.23aA	6.25aA
	30–60	6.51aA	6.60aA	6.74aA	6.78aA	6.75aA
SW	0–10	5.49aA	5.26aA	5.07aB	4.54bB	4.48bB
	10–20	5.69aA	5.49aA	5.22aB	4.97aA	4.94aAB
	20–30	6.18aA	6.26aA	6.17aA	5.97aA	6.11aA
	30–60	6.68aA	6.59aA	6.62aA	6.51aA	6.60aA

(b) N rate	Depth	Tillage system MP	DP	SW
0	0–10	5.84aA	5.47aA	5.49aA
	10–20	5.60aA	5.84aA	5.69aA
	20–30	6.13aA	6.18aA	6.18aA
	30–60	6.54aA	6.51aA	6.68aA
45	0–10	5.41aA	5.10aA	5.26aA
	10–20	5.30aA	5.59aA	5.49aA
	20–30	5.99aA	6.17aA	6.26aA
	30–60	6.70aA	6.60aA	6.59aA
90	0–10	5.21aA	4.91aB	5.07aA
	10–20	5.00aA	5.42aAB	5.22aA
	20–30	5.79aA	6.28aAB	6.17aA
	30–60	6.61aA	6.74aA	6.62aA
135	0–10	4.98aAB	4.67abB	4.54bB
	10–20	4.82aB	5.23aA	4.97aA
	20–30	5.64aA	6.23aA	5.97aA
	30–60	6.33aA	6.78aA	6.51aA
180	0–10	4.74aB	4.64aB	4.48aB
	10–20	4.61bB	5.13aAB	4.94aB
	20–30	5.68aA	6.25aA	6.11aA
	30–60	6.40aA	6.75aA	6.60aA

† Values followed by the same lowercase letter in a row indicate no significant difference between tillage systems or N rates within a soil depth and same uppercase letter in a column indicate no significant difference in pH between soil depths ($P \leq 0.05$, Tukey test). MP = moldboard plow, DP = offset disk plow, SW = subsurface sweep.

Table 5. Soil pH in 2010, after 70 yr of treatment application, as influenced by interaction of tillage systems and N fertilizer rate in a winter wheat–summer fallow system.

Depth	Tillage system† MP	DP	SW	Fertilizer N rate 0	45	90	135	180
cm				kg N ha^{-1}				
0–10	5.25aC	4.97aC	4.96aB	5.60aB	5.26abC	5.08bC	4.73cC	4.62cC
10–20	5.07bC	5.46aB	5.26abB	5.71aB	5.46abC	5.22bcC	5.01cC	4.89cC
20–30	5.87bB	6.22aA	6.13abA	6.16aA	6.14aB	6.10aB	5.94aB	6.02aB
30–60	6.53aA	6.69aA	6.59aA	6.58aA	6.63aA	6.68aA	6.54aA	6.58aA

† Values followed by the same lowercase letter in a row indicate no significant difference between tillage systems or N rates within a soil depth and same uppercase letter in a column indicate no significant difference in pH between soil depths ($P \leq 0.05$, Tukey test). MP = moldboard plow, DP = offset disk plow, SW = subsurface sweep.

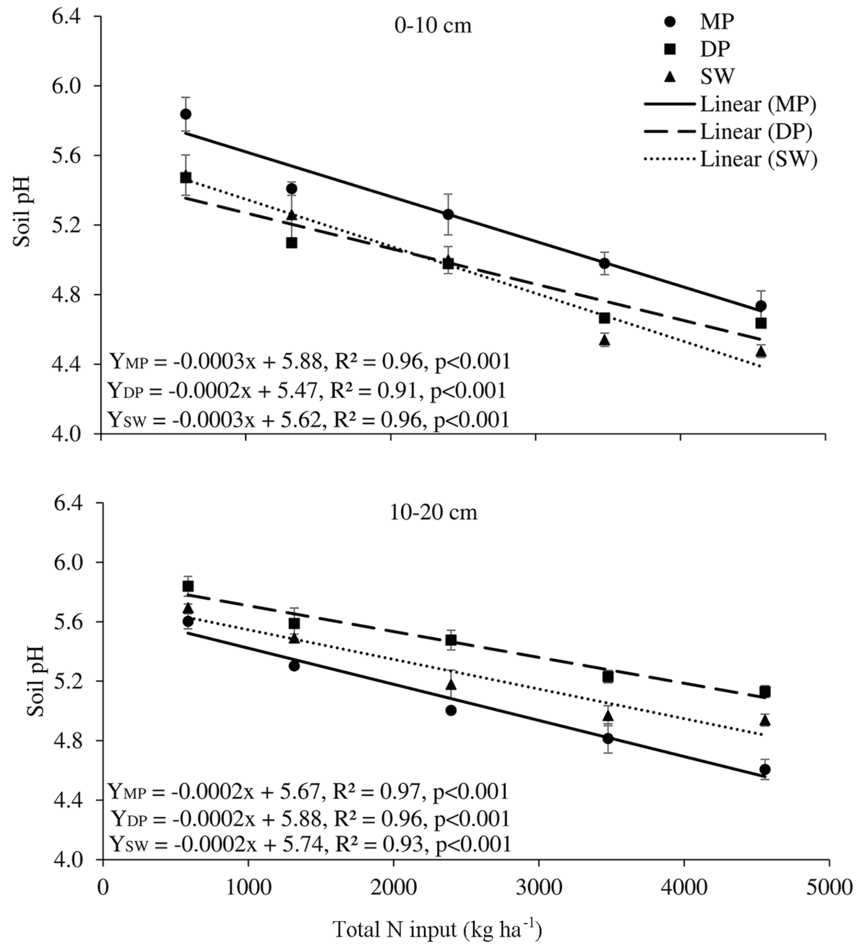

Fig. 3. Relationship between total fertilizer N input (1941–2010) and soil pH in 2010 at in (a) 0- to 10- and (b) 10- to 20-cm depths of a winter wheat–summer fallow system under different tillage management. Soil N input in horizontal axis was adapted from Table 1.

acidification to different extents, the rate of soil acidification compared after 70 yr of treatment application was higher under MP and SW (0.3 pH units per 1000 kg N ha^{-1}) than under DP (0.2 pH units per 1000 kg N ha^{-1}) in 0- to 10-cm soil depth. In 10- to 20-cm depth the rate of acidification was similar for all tillage systems (0.2 pH units per 1000 kg N ha^{-1}). The 1000 kg N applied during 1941 to 2010 was equivalent to 572 kg ammonium + urea N.

Soil Organic Carbon and Nitrogen

Soil organic C concentration was significantly influenced by tillage and year in 0- to 10-cm depth (Table 2). The SOC concentration of 11.0 g kg^{-1} in MP was significantly lower than 13.3 g kg^{-1} in DP and 12.8 g kg^{-1} in SW. In addition, SOC concentration was 7.03% less in 2010 than in 1995 in 0 to 10 cm (Table 6). The SOC concentration in 10- to 20-cm and 20- to 30-cm depths were 9.09 and 6.60% less, respectively, in 2010 than in 1995 and were not influenced by tillage and N rate. In 20- to 30-cm depth, SOC concentration was also influenced by interaction of tillage and year (Table 2). In this depth, there were no significant differences in SOC in 1995 and 2010 under MP. However, SOC was significantly lower in 2010 than in 1995 under both DP and SW (Fig. 4). The SOC concentration in 30- to 60-cm depth was not influenced by tillage, N rate, year or interactions among all treatment variables. The loss of SOC was greater in the 0- to 10-cm depth (7.03%) and 10- to 20-cm depth (9.1%) than in the 20- to 30-cm (6.6%) and 30- to 60-cm (5.3%) depths.

Table 6. Soil organic carbon (SOC) and N in different soil depths during 1995 to 2010 in a winter wheat– summer fallow system.

	SOC				Soil N			
Depth	1995	2010	ΔSOC		1995	2010	ΔN	
cm	g kg^{-1}†		%	mg kg^{-1} yr^{-1}	g kg^{-1}		%	mg kg^{-1} yr^{-1}
0–10	12.8(1.23)a	11.9(1.23)bA	−7.03	−60.0	1.11(0.02)a	1.00(0.01)aA	−9.48	−6.99
10–20	11.0(0.53)a	10.0(0.91)bB	−9.09	−66.7	0.98(0.01)a	0.90(0.01)bB	−8.60	−5.65
20–30	8.49(0.65)a	7.93(0.72)bC	−6.60	−37.3	0.90(0.01)a	0.83(0.01)bC	−7.44	−4.45
30–60	6.06(0.63)a	5.74(0.85)aD	−5.28	−21.3	0.71(0.01)a	0.67(0.01)aD	−5.28	−2.49

† Values in parenthesis indicate standard error (n = 45). Values followed by the same lowercase letter in a column indicate no significant difference between years and same uppercase letters indicate significant difference between depths ($P \leq 0.05$, Tukey test).

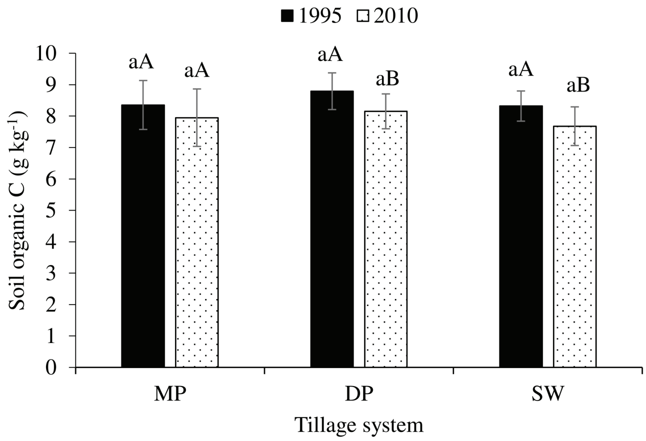

Fig. 4. Soil organic carbon (SOC) in 20- to 30-cm depth as influenced by tillage and year interaction in a winter wheat–summer fallow system. Same lowercase letters indicate no significant difference between tillage systems within a year and same uppercase letters indicate no significant difference between years within a tillage system ($P \leq 0.05$, Tukey test).

Table 7. Soil organic carbon (SOC) in 2010 as influenced by interaction of tillage and soil depth in a winter wheat–summer fallow system.

	Tillage systems		
Depth	MP	DP	SW
cm		g kg^{-1}†	
0–10	10.8bA	12.7aA	12.3aA
10–20	10.6aA	9.88aB	9.53aB
20–30	7.95aB	8.15aC	7.68aC
30–60	5.66aC	5.72aD	5.85aD

† Values followed by the same lowercase letter in a row indicate no significant difference between tillage systems within a soil depth and same uppercase letter in a column indicate no significant difference between soil depths ($P \leq 0.05$, Tukey test). MP = moldboard plow, DP = offset disk plow, SW = subsurface sweep.

Evaluation of SOC data in 2010, 70 yr after the experiment began, showed that SOC concentration was influenced by an interaction between tillage and depth (Table 3). Under MP, SOC concentration was not significantly different in the 0- to 10- and 10- to 20-cm depths (Table 7). Under DP and SW, SOC in the 0- to 10-cm depth was significantly higher than SOC in the 10- to 20-cm soil depth. The SOC in the 20- to 30-cm depth was significantly higher than SOC in the 30- to 60-cm depth under all tillage treatments. Comparing tillage practices at each depth revealed that SOC under MP was significantly lower than under DP and SW only in the 0- to 10-cm soil depth. Soil organic C was not significantly different among all tillage treatments in lower soil depths.

Soil N analyzed for each depth separately was not influenced by tillage, N, and year in 0- to 10- cm depth (Table 2). In the 10- to 20-cm depth, there were no differences in soil N among tillage treatments at 0 and 45 kg N ha^{-1} crop^{-1}. At higher N rates, soil N under DP was lower than soil N under MP and SW, and this was significantly so at the 135 kg N ha^{-1} crop^{-1} treatment (Fig. 5). When comparing tillage treatments at each N rate, soil N under MP was significantly lower at no N treatment than at N applied treatments (Fig. 5). Under DP and SW, there were no significant differences in soil N at all N rates.

Comparison between years showed that soil N concentrations in 0- to 10- and 30- to 60-cm depths were not significantly different in 2010 and in 1995 (Table 6). However, in the 10- to 20- and the 20- to 30-cm depths, soil N was significantly lower in 2010 than in 1995. In 2010, after 70 yr of experimentation, soil N was not influenced by tillage and N rate treatments but significantly decreased with increase in soil depth (Table 7).

Soil pH was negatively correlated with SOC (−0.98, $P < 0.01$) and soil N (−0.97, $P < 0.01$) in the top 10-cm depth. In the 10- to 20-cm depth, soil pH was also negatively correlated with SOC (−0.83, $P < 0.10$) and soil N (−0.97, $P < 0.01$). There were significant and positive correlations between SOC and soil N at the 0- to 10- (0.98, $P < 0.01$), 10- to 20- (0.93, $P < 0.05$), 20- to 30- (0.94, $P < 0.05$), and 30- to 60- (0.91, $P < 0.05$) cm depth profiles.

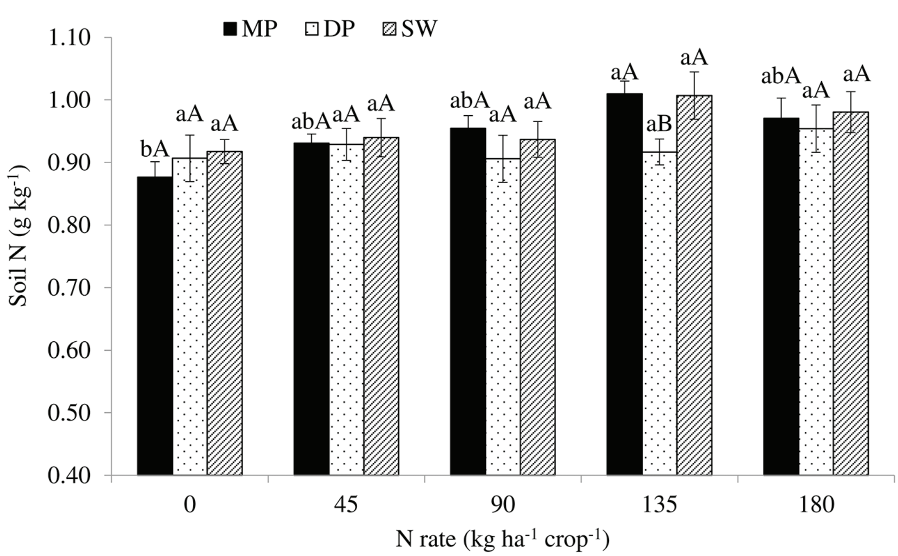

Fig. 5. Soil N in 10- to 20-cm depth of different tillage and N management treatments. Same lowercase letters indicate no significant difference between different N rate treatments within a tillage system and same uppercase letter indicate no significant difference between different tillage systems within a N rate treatment ($P \leq 0.05$, Tukey test).

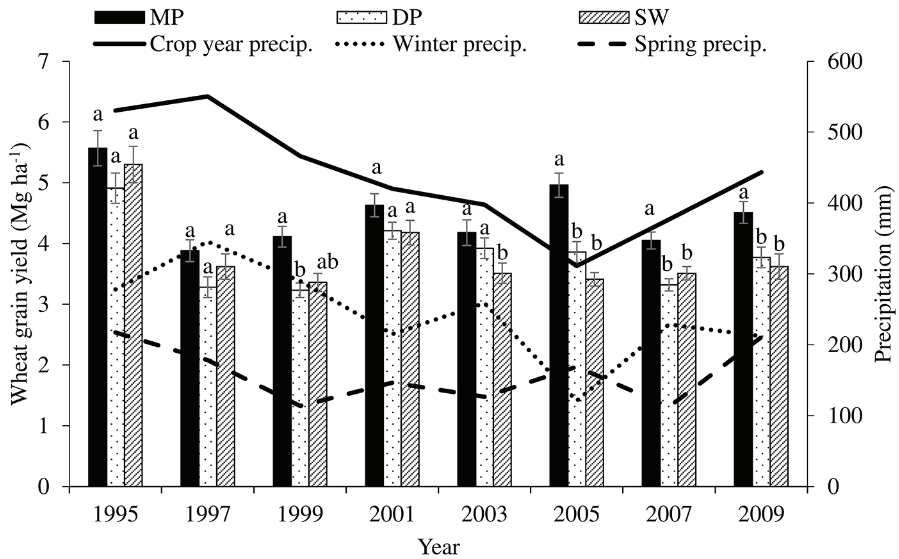

Fig. 6. Wheat yield (Mg ha^{-1}) influenced by interaction of tillage and year in a winter wheat– summer fallow system. MP = moldboard plow, DP = offset disk plow, and SW = subsurface sweep tillage. Values followed by the same lowercase letter within a year indicate no significant difference between tillage systems ($P \leq 0.05$, Tukey test).

Winter Wheat Yield

Wheat yield was not significantly influenced by total, winter, and spring precipitation of the crop year (Fig. 6). However, variation in grain yield followed more closely the trends of spring precipitation than winter or total precipitation (Fig. 6). Wheat yield was significantly influenced by tillage and N rate interactions with year (Table 2). Among tillage systems, grain yield under MP was the highest throughout the study and was significantly higher than grain yield under DP and SW in 1999 and 2005 through 2009 (Fig. 6). Grain yield in MP was significantly higher than in SW only in 2003. Among N rate treatments, wheat grain yield significantly increased with increase in N rates in all years (Fig. 7). However, yield response to N addition was observed only up to 90 kg N ha^{-1} crop^{-1} during 1995 to 1999 and only up to 45 kg N ha^{-1} crop^{-1} thereafter. Among years, wheat yield was higher in 1995 than in other years at all N rates. The reduction in yield from 1995 to 2010 was greater in treatments with high N rates and low pH than treatments with lower N rates and higher soil pH. Low soil pH at high N rates was positively correlated with greater reductions in grain yield in 0- to 10-cm ($r = 0.81$; $P < 0.09$) and 10- to 20-cm ($r = 0.87$; $P < 0.06$) depths. The decreasing trend in soil pH with N addition, mainly in 0- to 20-cm soil depth, probably decreased or stagnated wheat yield when soil pH was less than 5.0 (Fig. 8). No significant correlations were observed between changes in grain yield with SOC or soil N at all depths.

DISCUSSION

Seventy years of synthetic N fertilizer application has significantly acidified soils under WW–SF systems in the iPNW. Acidification was more evident in top 20 cm, the zone of tillage influence, than in lower soil depths. Results of this study corroborate with previous studies (Rasmussen and Rohde, 1989; Bouman et al., 1995; Schroder et al., 2011) that revealed soil acidification in the tillage zone with N fertilizer addition. Mahler et al. (1985) reported soil acidification with addition of ≥100 kg N ha^{-1} yr^{-1} of ammonium-based fertilizer. The present study revealed that continuous application of even a

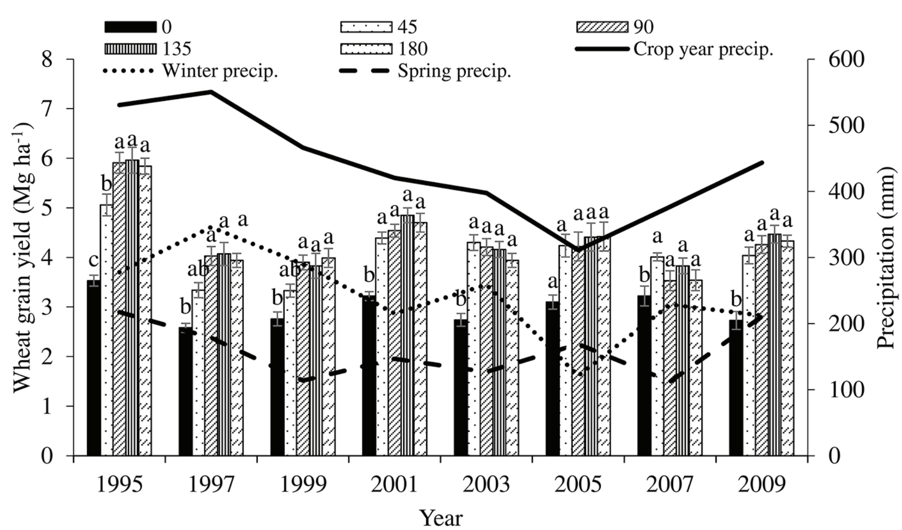

Fig. 7. Wheat grain yield (Mg ha^{-1}) as influenced by interaction of fertilizer N rate and year in a winter wheat–summer fallow system. Values followed by the same lowercase letters in a year indicate no significant difference between N rates ($P \leq 0.05$, Tukey test).

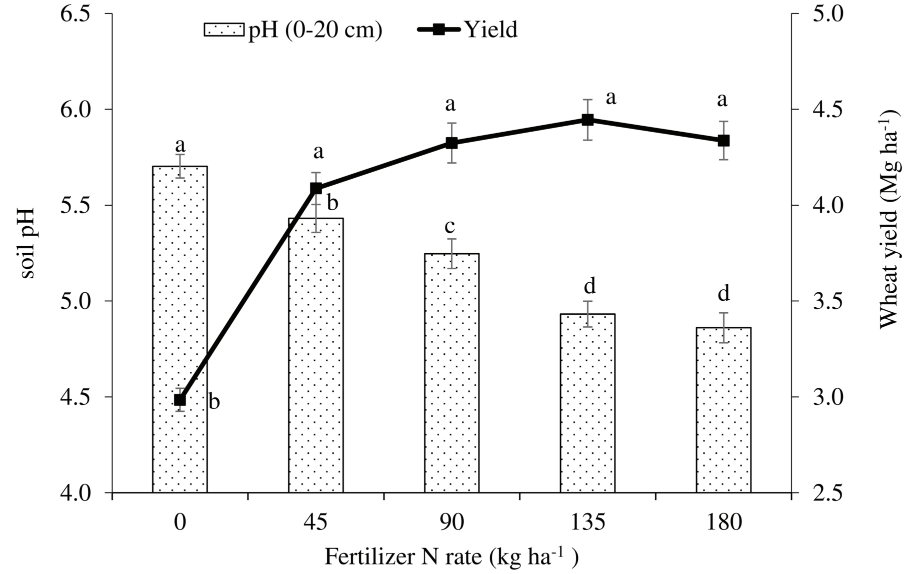

Fig. 8. Wheat grain yield response to soil pH in 0- to 20-cm soil depth and N rate treatments. Same letter for different pH or grain yield values indicate no significant difference (*P* ≤ 0.05, Tukey test). Soil pH and wheat yield data were averaged for 1995–2010.

smaller amount of N fertilizer (i.e., 45 kg N ha^{-1} $crop^{-1}$) for several years can acidify soils. The study by Mahler et al. (1985) was based on 40 yr of data. Here, we evaluated soil acidity after 70 yr of ammonical N fertilizer application. The N fertilizer used in different time periods varied on the N composition and thereby influenced soil acidification to different degree. Relative influence of nitrate and ammonical fertilizers in soil acidification was not compared in this study. All treatments received N as ammonium sulfate during 1941 to 1961, as ammonium nitrate during 1962 to 1987, and as urea ammonium nitrate since 1988. Relatively higher rate of acidification than we expected, however, may suggest low cation exchange capacity and pH buffering of Walla Walla silt loam than some other soil types in the iPNW region. The soils at the experimental site has cation exchange capacity of 12.5 $cmol_c$ per kg soil and 75% base saturation (Soil Survey Staff, 2016).

In drylands, nitrification-derived acidity barely moves to lower soil depths and acidification is concentrated in the zone of fertilizer application (Mahler and Harder, 1984). Soil acidification is exacerbated under reduced- and no-tillage systems where N fertilizer is applied just beneath the soil surface compared to conventional tillage system where N is incorporated deeper (Robbins and Voss, 1989). In this study, N fertilizer and crop residues were mixed to the depth of 23 cm in MP system. In DP and SW systems, N fertilizer and more than 80% of crop residues were mixed to a depth of 10 to 15 cm. Therefore, the amount of soils in which N fertilizer was mixed under MP, SW, and DP systems were 2967, 1935, and 1290 Mg ha^{-1}, respectively. Consequently, concentration of acidity in the surface soil resulted in stronger vertical gradient of soil pH under DP and SW than MP, which may have limited crop production in the reduced-tillage systems (Limousin and Tessier, 2007). Various fertilizers used in different time periods may have influenced soil acidity differently; however, the same fertilizer was applied across tillage systems in each time period. This allowed us to compare the soil acidity with respect to total N input. Greater soil disturbance, deeper crop residue burial, and soil mixing caused greater loss of SOC and N in MP than in DP and SW, and reduced nutrient holding capacity, lowering of the buffering capacity, and negatively influenced crop production (Machado et al., 2006; Bista et al., 2016).

We expected that soil acidification would lower SOC and N loss because the decomposition rate and plant and microbial uptake of N is expected to decrease in acidic soils (Motavalli et al., 1995). Instead, we observed a decrease in SOC and N across all treatments during 1995 to 2010 as acidification increased. No differences in SOC and N storage with N addition or adoption of reduced-tillage systems may suggest no or limited contribution of N fertilizer addition to soil C and N cycling in acidified soils. Studies revealed that SOC and N storage in the dryland soils are strongly influenced by the biomass C and N inputs and their quality (Machado, 2011; Brown and Huggins, 2012; Wuest and Gollany, 2013; Ghimire et al., 2015). In nonagricultural systems, soil acidification increased the recalcitrance of the litter and slowed down the rate of decomposition. However, there is no evidence that such shifts occur in nonwoody species such as winter wheat that contributes to SOC accumulation (Kemmitt et al., 2006; Brown et al., 2008). Crop residue production in the dryland WW–SF system is considerably lower than the biomass input required to maintain SOC in the soil profile (Machado 2011), which may have caused the continuous decline in SOC storage.

Low or no response of N addition in wheat yield could be explained by soil acidification and SOC and N loss from a WW–SF system. Other studies suggested that soil acidification influenced crop yield by its effects on N mineralization, soil microbial activity, and root growth (Curtin et al., 1998; Umiker et al., 2009; Haling et al., 2011). These soil properties were not measured in this study. However, low or no yield response in high N-rate treatments, specifically >90 kg N ha^{-1} $crop^{-1}$, suggested negative impacts of acidification on nutrient uptake. This study also showed a negative correlation between soil pH with SOC and soil N. Soil acidification may also have limited wheat root growth. Soil pH below 5.2 is detrimental for wheat production in iPNW (Mahler et al., 1985; Mahler and McDole, 1987). In this study, soil pH was <5.0 under treatments receiving ≥90 kg N ha^{-1} $crop^{-1}$, which was well below the critical limit for wheat growth. Besides, Al toxicity increases at pH levels below 5.00 (Schroder et al., 2011), which can have a greater influence in wheat yield than soil pH itself (Kariuki et al., 2007). In another ongoing long-term experiment with less acidity at the same study site, wheat yield was as high as 6.8 Mg ha^{-1} under 120 kg N ha^{-1} crop^{-1} treatment, which is considerably greater than wheat yields in treatments receiving 90 kg N ha^{-1} crop^{-1} or more observed in this study during the 1995 to 2010 period (unpublished data, 2016). In northern Idaho, up to 30% reduction in yields of winter wheat, spring wheat, barley (*Hordeum vulgaris* L.), lentil (*Lens esculanta* L.), and pea (*Pisum sativum* L.) were reported under acidified soils (Mahler and McDole, 1987). Several other studies revealed increase in N mineralization as well as crop yield after reducing soil acidity through liming (Brown et al., 2008; Umiker et al., 2009; Schroder et al., 2011). An average of 199 kg ha^{-1} winter wheat grain yield increase was observed in eastern Washington after incorporation of 2680 kg lime ha^{-1} using conventional tillage or subsoil ridge tillage (Bezdicek et al., 1998). All these studies indicated that crop yield response to N addition can be improved by reducing soil acidity.

Soil acidification occurs slowly in the natural condition and can be caused by processes such as organic matter decay and cation leaching under excessive rain (Guo et al., 2010). Acidification in drylands, however, is accelerated by agricultural practices particularly N fertilization. Soil acidification observed in this study was not only limited to WW–SF systems receiving N but also to the treatment that did not receive N fertilizer (0 N). When compared to the nearby grassland that was fenced off in 1931 and with a pH close to neutral in the 0- to 30-cm depth profile, there was considerable acidification in the 0 N treatment of this long-term experiment. For example, grassland soil pH in 0- to 10-cm depth was about 1.2 units above the 0 N treatment indicating that acidification under this treatment was attributable more to other factors than natural causes. These factors could include the continuous loss of base-forming cations and buffering capacity of soil associated with continuous removal of cations in harvested grain and loss of SOC from the soil profile. Continuous harvest of grain and residues in agricultural soils results in net export of alkalinity leaving residual hydrogen ions that contributed to soil acidity (Gazey and Ryan, 2016). In the grassland no external fertilizer was added and biomass was retained.

In most WW–SF systems in iPNW, SOC and N have decreased over time resulting in reduced soil water retention, soil fertility, and pH buffering capacity (Schillinger and Papendick, 2008; Wang et al., 2015; Bista et al., 2016). Cropping systems that reduced or eliminated tillage and increased biomass production, on the other hand, have been found to build SOC and improve sustainability of cropping system (Machado, 2011). Further studies will determine how SOC, N, and soil pH interact and influence crop production in dryland cereal regions of iPNW. Use of high rates of N may not be profitable for iPNW WW–SF as the rate of yield increase was negative at N rates above 90 kg N ha^{-1} crop^{-1} due to increased soil acidity. Agricultural practices that reduce the rate of soil acidification as well as SOC and N losses should be developed to improve the sustainability of wheat production in iPNW and similar agroecosystems.

CONCLUSIONS

Evaluation of the influence of long-term tillage and N fertilizer application on soil pH, SOC, soil N, and wheat yield in a long-term tillage and N experiment revealed that continuous application of N fertilizer increased soil acidification that may have negatively impacted SOC, soil N, and wheat yield. Nitrogen rates above 90 kg N ha^{-1} crop^{-1} reduced soil pH to levels below the critical level of wheat (5.2) that were detrimental to wheat production in WW–SF systems of iPNW. Furthermore, SOC and N concentration decreased over time irrespective of the tillage system or N application rate probably because of inadequate biomass production under the WW–SF system. Soil acidification was more rapid in surface 20-cm soil depth than lower soil depths, potentially influencing nutrient dynamics and wheat growth, development, and yield. Reduced-tillage practices such as disc and sweep plowing resulted in more acidification in the top 10 cm than conventional moldboard plow tillage. Besides, the continuous loss of SOC and soil N exacerbated the effects of soil acidification in the topsoil leading to a poor wheat yield response particularly at high N rate treatments. This study demonstrated the negative impacts of ammoniacal fertilizers on soil pH and the need to monitor soil acidification and develop agronomic strategies to increase soil pH and sustainability of wheat production in iPNW.

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