What do the long-term experiments in the dryland Pacific Northwest tell us?

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Photo: Santosh Shiwakoti

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1. Overview of cropping practices in the dryland Pacific Northwest

The dryland Pacific Northwest states of Oregon, Idaho, and Washington have a large land area under low precipitation that forms a significant winter wheat production region. Every year, around 2 million hectares of wheat are planted in the PNW, with approximately 1.6 million hectares in the low-precipitation zone getting less than 305 mm rainfall per crop year. Most of the wheat in this region is without irrigation and is produced in a wheat-fallow rotation.

In this century-old production system, wheat is grown once, for 10 months in 24 months. The 14-month fallow period between each wheat crop is vital for soil water conservation for next year's wheat, nutrient mineralization during the fallow period, and weed control. However, during these 14 fallow months (also known as summer fallow), the ground is exposed to soil erosion by wind and degradation of soil quality. Maintaining soil organic matter and available nutrients is a challenge in this kind of environment due to a less-cropped year and fewer crop residues returned to the soil.

Replacing summer fallow with dry pea in rotation offers a potential alternative to summer fallowing and is practiced in a vast area of the PNW, including dryland regions, the benefits of pea as a rotational crop include:

- Increased organic residue addition.
- Biological N fixation.
- Erosion protection.
- Reduction in the downward movement of water in the soil.
- Suppression of weeds and disease.
- Nutrient cycling.

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However, the effect of these management practices on soil nutrients often takes decades to manifest (Rasmussen and Parton, 1994). So, scientists believe that long-term experiments (LTE) can provide useful indications of whether current agricultural practices will sustain or degrade the productive capability of our soil. Although not a complete panacea, long-term experiments provide the perspective of changes and are vital for modeling change in nutrient cycling and dynamics.

The Columbia Basin Agricultural Research Center (CBARC), near Pendleton, Oregon, is an Oregon State University Agricultural Experiment Station. CBARC boasts the oldest long-term experiment of the western USA along with several classical (more than 50 years old) field cropping system experiments under dryland agriculture. The soil is Walla Walla silt loam derived from loess overlying basalt, and the average annual precipitation at the station is 400 mm, with more than 90% of that occurring during November – June. The site has a semi-arid climate with cold, wet winters and hot, dry summers.

The long-term experiments at CBARC represent some of the dominant agricultural practices in the dryland Pacific Northwest. All over the world the last few decades have seen increased interest from producers, scientists, policy-makers, and the general public in the long-term impact of farming practices, such as:

- Crop residue management.
- Tillage timing and intensities.
- Inorganic N fertilizer application rates.
- Legumes in rotation with winter wheat on soil organic matter.
- Nutrient cycling.

The knowledge gained from the long-term impacts of such agricultural practices on the status of plant essential nutrients in soil will provide insights into one of the critical aspects of soil quality, and can play a vital role in maintaining sustainable agriculture systems.

We investigated the long-term impact of the practices listed above on essential macro- and micronutrients in soil under the PNW winter wheat dryland cropping system. Specifically, we assessed the long-term effect of these agricultural practices on soil pH and the concentration of:

1. Total soil nutrients: nitrogen (N), carbon (C) and sulfur (S).
2. Mehlich III extractable (plant available) soil nutrients: phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn) and boron (B).

We used soil samples from the years 1995, 2005 and 2015 for analysis. Since we didn't observe a consistent and noticeable 20-year trend on nutrient response, we chose to discuss the results based on the comparison with the 2015 data only; that is, the recent status of soil nutrients.

Also, we compared the nutrients of soil samples from the treatments of three long-term experiments with those of an adjacent, nearly undisturbed (since 1931) grass pasture. The grass pasture plots are native perennial grasses and serve as the reference and baseline to determine the treatment-induced change in the long-term experiments at CBARC. Assessing the essential nutrients in the soil from the long-term study will help to reveal any long-term changes in soil nutrients due to management, and to correct or develop current cropping management practices for sustainable agriculture in the PNW and other regions with similar climate.

Photo courtesy: Web Soil Survey, 2020, Natural Resources Conservation Service-USDA

Aerial photo of the long-term experiments at Columbia Basin Agricultural Research Center (CBARC), Adams, OR.
1: CBARC, Oregon State University; 2: Columbia Plateau Conservation Research Center, USDA Agricultural Research Service; 3: Grass pasture; 4: Crop residue experiment plot; 5: Tillage-fertility experiment plot; and 6: Wheat-pea experiment plot.

2. Crop residue long-term experiment (CR-LTE)

The crop residue long-term experiment was established in 1931 to evaluate the effect of different residue management practices (based on farmers' practices in the 1930s) on soil and crop productivity under the winter wheat-14 months fallow (WW-F) cropping system. This long-term experiment is under conventional tillage and has nine treatments (see Figure 1). The treatments were assigned to determine the effect of organic (farmyard manure and pea vines) or synthetic (inorganic N) fertilization and crop residue management (residue burning vs. no burn) on different aspects of soil qualities.

2.1. Why these treatments?

Wheat residue burning was a standard soil management method during the 1930s in the WW-F cropping system and is still being practiced by some farmers in the PNW. Burning

a.

Symbol	Description of residue management	Nitrogen applied ($kg\ ha^{-1}$)
NB0	Wheat straw incorporated into soil	0
NB45	Wheat straw incorporated into soil	45
NB90	Wheat Straw incorporated into soil	90
SB0	Wheat straw burned in spring	0
SB45	Wheat straw burned in spring	45
SB90	Wheat straw burned in spring	90
FB0	Wheat straw burned in fall	0
FYM	wheat straw plus manure incorporated into soil	0
PV	wheat straw plus pea vine incorporated into soil	0

b.

Figure 1. (a) Treatments of crop residue long-term experiment (CR-LTE) and (b) residue burned and no residue burn plots in CR-LTE at CBARC.

crop residues is preferred for better seedling growth, less disease and pest incidence, and to mitigate low soil temperature in spring. But, over time, repeated burning decreases soil organic matter, increases carbon emissions, causes air pollution, and reduces microbial activity (Rasmussen et al., 1980).

On the other hand, relying entirely on applications of manure and pea vines for the wheat's nutrient needs was not a workable option. Therefore, CBARC pioneers assigned these treatments (Figure 1) to test the hypothesis that the application of inorganic N would alleviate detrimental effects caused by burning crop residues and also replace the use of pea vine and manure in dryland wheat production. This hypothesis assumed that inorganic N would increase crop biomass production (above and below the soil surface) and thus recharge the nutrient pool of the soil through the decomposition of an increased amount of crop residue.

2.2. Macronutrients

Overall, the results showed that after 84 years since the establishment of the crop residue-long term experiment (CR-LTE), the treatment's effect on nutrient concentration took place only in the top 10 cm soil depth. Farmyard manure applications significantly increased the concentration of soil macronutrients compared to other CR-LTE treatments (Figure 2). This is attributed to the

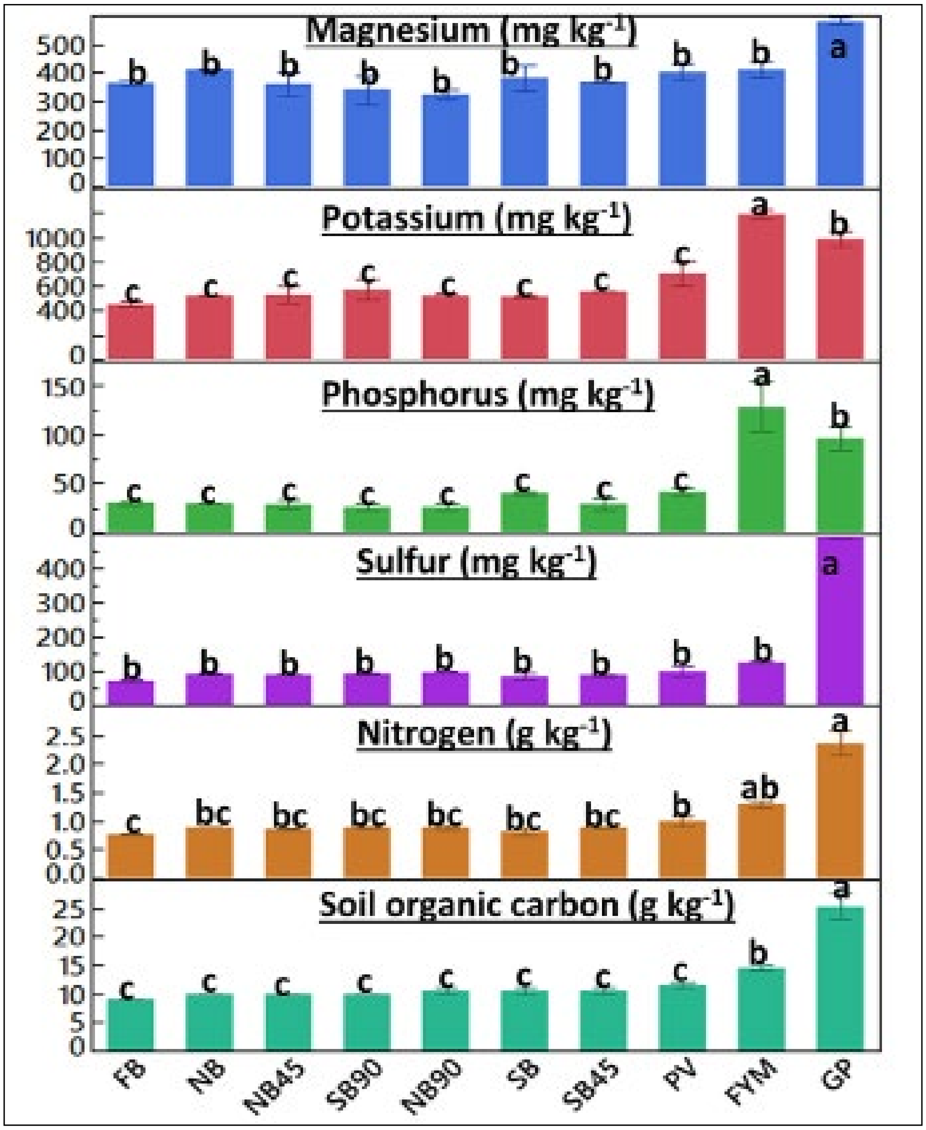

Figure 2. Macronutrients concentration in the crop residue-long term experiment and grass pasture plots at 0–10 cm soil depth in 2015 (Shiwakoti et al., 2020). Means sharing the same letter are not significantly different at 0.05 significance level. FB = fall burn; GP = grass pasture; FYM =Farmyard manure; NB, NB45 and NB90 = No burn with N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively; PV = pea vine; SB, SB45 and SB90 = spring burn with N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively.

extra supply of nutrients from the manure in the farmyard manure plots.

However, the macronutrient concentrations, except extractable P and K, were lower at the farmyard manure plots than grass pasture at the same soil depth (Figure 2). The concentrations of extractable Mg, soil organic carbon, total N, and S in the top 10 cm soil depth of the farmyard manure plots were lower than that in the grass pasture plots by 32%, 43%, 46%, and 73%, respectively. The concentrations of P and K were higher by 32% and 63%, respectively, in farmyard manure plots than at grass pasture plots at 0-20 cm depth (Figure 2).

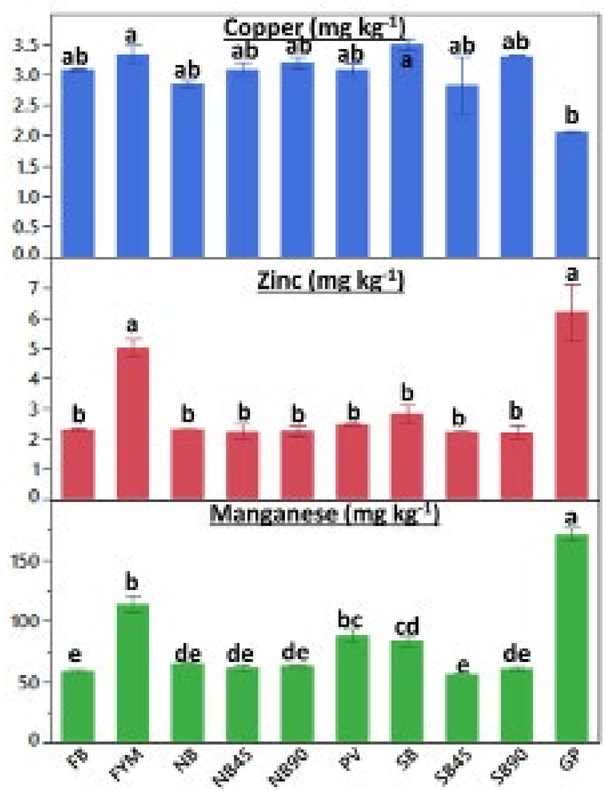

Figure 3. Micronutrients concentration in the crop residue-long term experiment and grass pasture plots at 0-10 cm soil depth in 2015 (Shiwakoti et al., 2019d). Means sharing the same letter are not significantly different at 0.05 significance level. FB = fall burn; GP = grass pasture; FYM =Farmyard manure; NB, NB45 and NB90 = No burn with N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively; PV = pea vine; SB, SB45 and SB90 = spring burn with N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively.

2.3. Micronutrients

Among the crop residue-long term experiment treatments, farmyard manure had the highest concentration of extractable Mn (114 mg kg^{-1}) and Zn (5 mg kg^{-1}) in the top 10 cm soil depth (Figure 3). The concentrations of Mn and Zn in farmyard manure were lower by 33% and 22%, respectively, than to those of grass pasture. The boron concentration was not affected by CR-LTE treatments.

Of interest was that copper (Cu) concentration did not decline even after 84 years of cultivation. In fact, grass pasture had significantly lower Cu than farmyard manure treatment (Figure 3). Copper strongly binds with organic matter in soils; however, low molecular weight fractions of soluble organocomplexes of Cu like farmyard manure improve the availability of Cu in soils and uptake by plants.

2.4. Soil pH

One of the critical factors responsible for nutrients' availability to plants is soil pH. Soil pH in the top 20 cm of soil depth was affected by the crop residue-long term experiment treatments. Plots with higher N application rates from inorganic fertilizer had lower pH than plots in the rest of the CR-LTE treatments, whereas farmyard manure sustained soil pH over time. In fact, after 84 years of cultivation, farmyard manure was modestly higher in pH than grass pasture (Figure 4).

2.5. Inferences from crop residue long-term experiment study

- Inorganic N application doesn't increase the concentration of soil macro/micronutrients over time compared to farmyard manure and cannot replace the farmyard manure application. However, pea vine application can be replaced by inorganic N application and vice-versa.

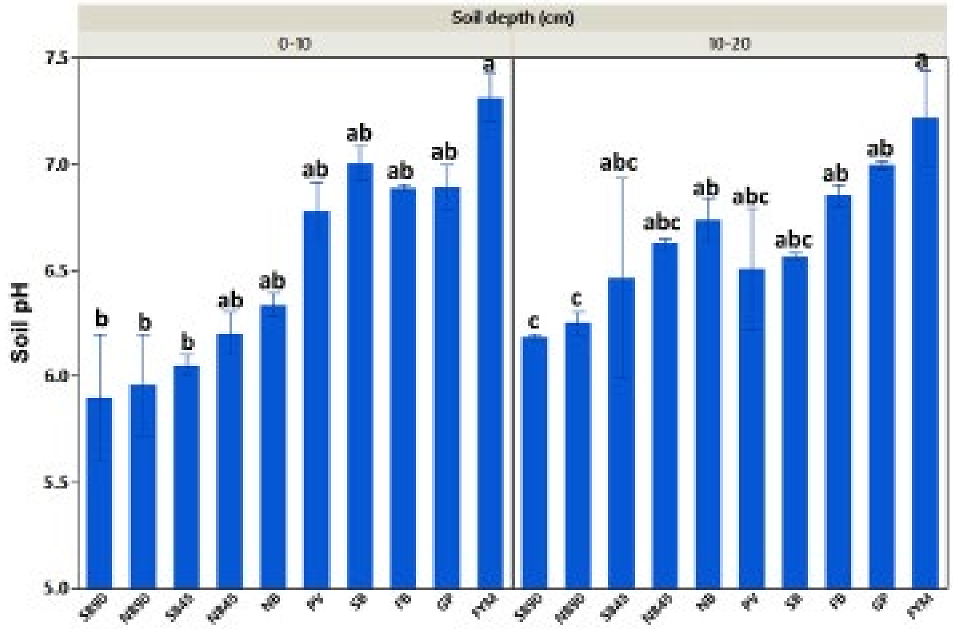

Figure 4. Soil pH in the crop residue-long term experiment and grass pasture plots in 2015 in 0-10 and 10-20 cm soil depths (Shiwakoti et al., 2018). Means sharing the same letter within the depth are not significantly different at 0.05 significance level. FB = fall burn; GP = grass pasture; FYM = farmyard manure; NB, NB45 and NB90 = No burn with N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively; PV = pea vine; SB, SB45 and SB90 = spring burn with N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively.

- Burning plant residues in spring and no-burn treatments both have similar impacts on soil nutrients over time under dryland winter wheat-14 months fallow rotation in the PNW.
- Soil acidification increases over time by the application of inorganic N, whether the N is applied to burned or unburned residue plots.
- The nutrients haven't stratified in the 0-30 cm soil depth under conventional tillage.

3. Tillage-fertility long-term experiment (TF-LTE)

The tillage-fertility long-term experiment was established in 1940 to evaluate the effect of different tillage methods and varying rates of inorganic N application on crop and soil productivity under the winter wheat-14 months fallow. This LTE has three tillage systems (disc plow, sweep and moldboard plow) and five N rates (0, 45, 90, 135, and 180 kg ha^{-1}) in a split-plot randomized block design. The tillage depths of moldboard plow, disc plow, and sweep were 23 cm, 10 cm, and 15 cm, respectively, and left 7%, 34%, and 43% soil surface covered by residue, respectively (Shiwakoti et al., 2019a).

3.1. Why these treatments?

Tillage affects soil organic matter, pH and nutrient availability. Due to reduced disturbance of soil, coupled with crop residue retention, conservation tillage such as disc tillage and sweep have shown positive effects on crop productivity and nutrient availability (Seddaiu et al., 2016). On the other hand, more traditional tillage, such as moldboard plow, enhances soil organic matter mineralization and depletes nutrients due to increased access of microbes to a larger volume of soil organic matter, a greater amount of soil disturbance, faster mineralization, and greater residue incorporation with less residue cover of the soil (Obour et al., 2017).

The other important management practice that affects soil organic matter and nutrient availability is N fertilization. The CBARC pioneers hypothesized that over time, conservation tillage (disc plow or sweep) and N fertilization would maintain or reduce the decline of soil nutrients and pH due to a lesser volume of soil aggregate disturbance and a higher percentage of residue cover left under disc plow or sweep than under moldboard plow.

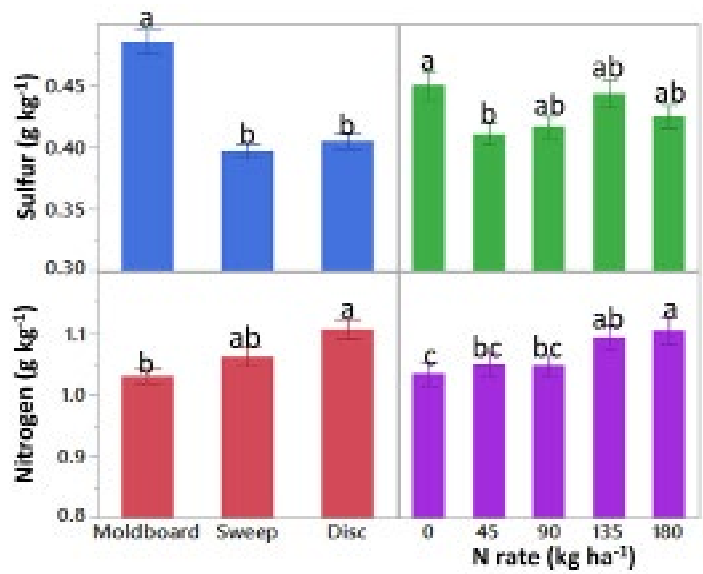

Figure 5. The long-term effect of tillage and N application rates on soil total N and total S in the winter wheat-fallow system (Shiwakoti et al., 2019a). The bars sharing the same letters within the treatments are not significantly different at 0.05 significance level.

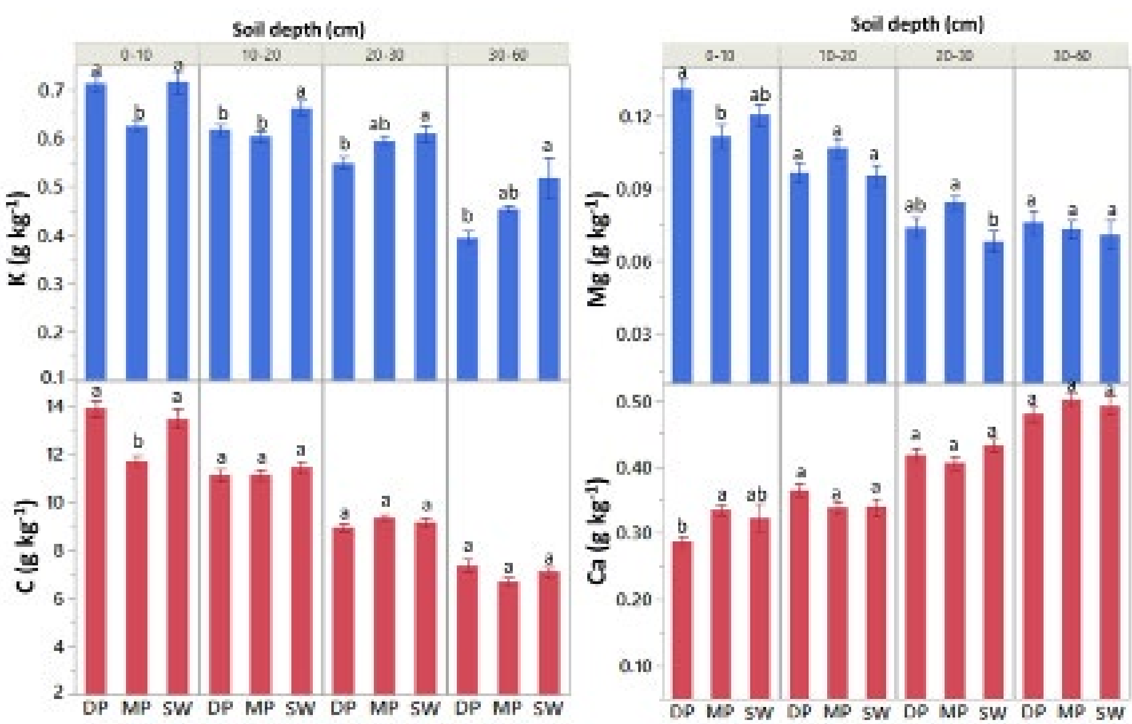

Figure 6. The long-term effect of tillage by depth (cm) on total soil organic carbon and on the Mehlich III extractable cations in the winter wheat-fallow system (Shiwakoti et al., 2019a). MP: moldboard plow; SW: sweep tillage; and DP: disc tillage. The bars sharing the same letters within each soil depth are not significantly different at 0.05 significance level.

3.2. Macronutrients

Averaged over the soil depths, the concentration of total N was much greater under the disc plow (1.10 g kg^{-1}) than under the moldboard plow (1.03 g kg^{-1}) (Figure 5). In contrast, total S concentration was greater under moldboard plow (0.48 g kg^{-1}) than under sweep (0.39 g kg^{-1}) and disc plow (0.40 g kg^{-1}. In the 0-10 cm soil depth, soil C, K and Mg were significantly higher under disc tillage or sweep than under moldboard plow; but, the concentration of extractable Ca was lower under disc tillage (0.28 g kg^{-1}) and sweep (0.32 g kg^{-1}) than moldboard plow (0.33 g kg^{-1}) (Figure 6).

The moldboard plow treatment resulted in a lower percentage of crop residue and a higher volume of disturbed soil than the disc plow and sweep treatments, which may have contributed to the higher C, N, K and Mg under disc tillage and sweep than under moldboard plow. The moldboard plow exposed more protected organic matter, increased aeration and temperature, and thereby enhanced microbial decomposition rates resulting in the release of inorganic N along with other nutrients (Rasmussen and Rhode, 1988).

The P concentration in the upper 20-cm soil depth increased with increased N rates, while Ca showed a negative response (Figure 7). Probably, the effect of increased acidity on P that resulted from high N rates was balanced by the high biomass production and increase in available N in this study (Shiwakoti et. al., 2019a). The increase in available N probably facilitated decomposition of crop residue and release of P from microbial

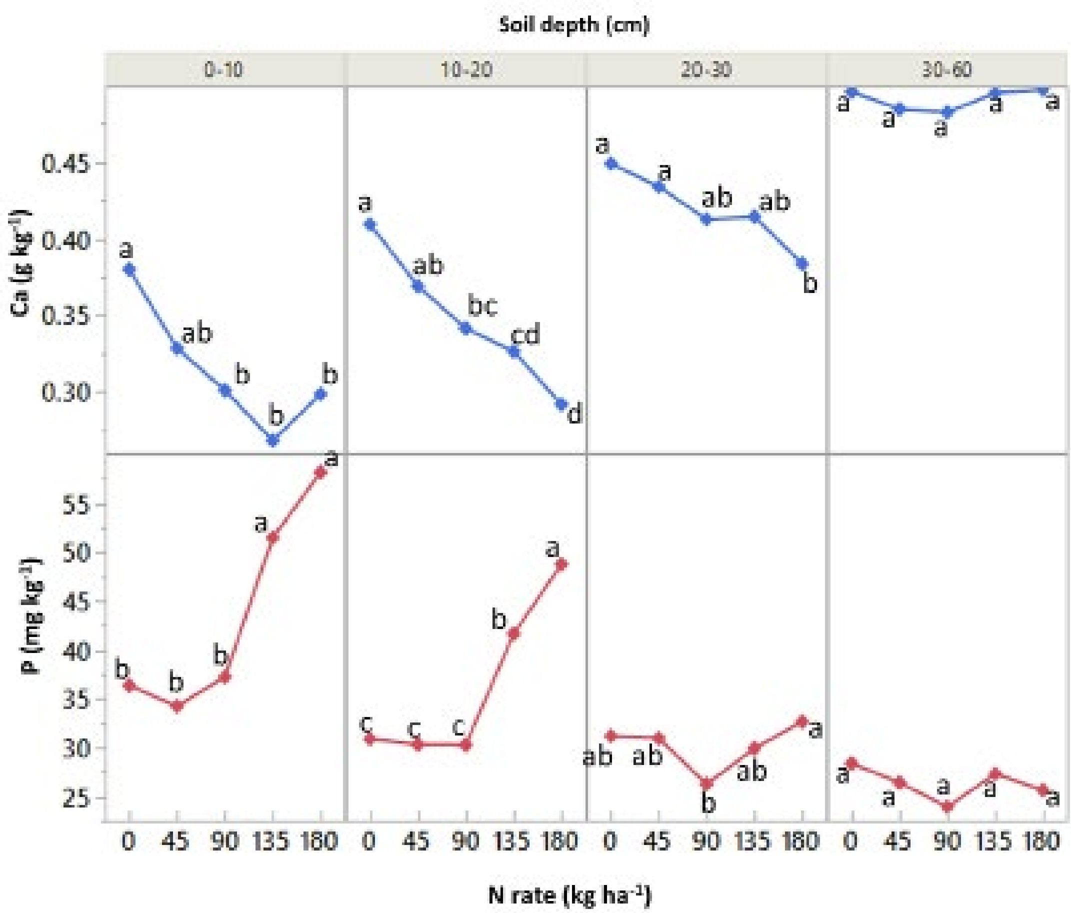

Figure 7. Soil depth distribution of Mehlich III extractable P and Ca as influenced by long-term inorganic N application rates in the winter wheat-fallow system (Shiwakoti et al., 2019a). Means sharing the same letters within each soil depth are not significantly different at 0.05 significance level.

activity. The negative response of Ca could be due to increased acidity in the upper surface.

We selected disc tillage treatment for comparison with grass pasture because disc tillage was the most desirable tillage method for most of the nutrients. A comparison of results from the disk plow with those in nearby undisturbed grass pasture revealed a decline of soil total N (14%), soil organic carbon (34%), and Mehlich III extractables P (32%), K (6%), Ca (86%) and Mg (77%) in the top 10 cm soil depth of the cultivated plots (Table 1). Loss of macronutrients in cultivated plots was mainly due to increased weathering of primary minerals with tillage and nutrient removal by high yielding crops, while in the grass pasture, aboveground biomass was not removed from the plots and sustained soil nutrient levels (Shiwakoti et al., 2019a).

Table 1. Impact of 75 years of the inorganic N application rate on the concentration of total soil C, N, and S, and extractable P, K, Ca, and Mg in the dryland winter wheat-fallow cropping system under disc tillage management compared to nearby grass pasture (GP) (Shiwakoti et al., 2019a).

Nutrients	Soil depth (cm)	N application rate (kg ha-1)						Cultivation effect[1]
	(cm)	0	45	90	135	180	GP	
Carbon (g kg-1)	0-10	13.3b	13.5b	13.8b	14.4b	14.2b	21.8a	34% ↓
	10-20	11.4ab	11.4ab	10.7ab	10.6b	11.5ab	13.6a	15% ↓
	20-30	9.1a	8.8a	9.1a	8.5a	9.1a	10.3a	12% ↓
	30-60	7.2ab	6.6b	7.9ab	6.7b	8.4ab	9.8a	14% ↓
Nitrogen (g kg-1)	0-10	1.2b	1.2b	1.2b	1.4b	1.4b	2.1a	35% ↓
	10-20	1.2ab	1.1b	1.1b	1.1b	1.2ab	1.4a	20% ↓
	20-30	1.1a	1.1a	1.0a	1.0a	1.1a	1.2a	03% ↓
	30-60	0.9a	0.9a	0.9a	0.9a	1.0a	1.1a	13% ↓
Sulfur (g kg-1)	0-10	0.4a	0.4a	0.4a	0.5a	0.4a	0.4a	07% ↓
	10-20	0.4a	0.4a	0.4a	0.4a	0.4a	0.4a	19% ↓
	20-30	0.5a	0.4ab	0.4ab	0.4ab	0.4ab	0.3b	41% ↓
	30-60	0.4a	0.4a	0.4a	0.4a	0.4a	0.3a	21% ↓
Phosphorus (mg kg-1)	0-10	34.9c	35.2c	35.7c	56.1b	61.1b	89.9a	32% ↓
	10-20	29.9b	29.8b	25.3b	37.4b	40.3b	60.6a	33% ↓
	20-30	31.3b	30.2b	26.6b	26.4b	26.4b	50.9a	39% ↓
	30-60	27.8b	25.7b	24.9b	27.9b	23.7b	46.4a	40% ↓
Potassium (g kg-1)	0-10	0.7a	0.7a	0.7a	0.7a	0.8a	0.8a	06% ↓
	10-20	0.6ab	0.5b	0.6ab	0.7ab	0.6ab	0.7a	03% ↓
	20-30	0.5a	0.5a	0.6a	0.6a	0.6a	0.6a	02% ↓
	30-60	0.4b	0.4b	0.4b	0.4b	0.4b	0.6a	31% ↓
Calcium (g kg-1)	0-10	0.3b	0.3bc	0.3bc	0.3bc	0.2c	2.4a	86% ↓
	10-20	0.4b	0.4bc	0.3bc	0.4bc	0.3c	2.4a	83% ↓
	20-30	0.4b	0.4b	0.4b	0.5b	0.4b	2.4a	81% ↓
	30-60	0.5bc	0.5bc	0.4c	0.5b	0.5bc	2.4a	78% ↓
Magnesium (g kg-1)	0-10	0.1b	0.1b	0.1b	0.1b	0.1b	0.6a	77% ↓
	10-20	0.1b	0.1b	0.1b	0.1b	0.1b	0.6a	84% ↓
	20-30	0.1b	0.1b	0.1b	0.1b	0.1b	0.6a	89% ↓
	30-60	0.1b	0.1b	0.1b	0.1b	0.1b	0.6a	85% ↓

Means sharing the same letters within the rows are not significantly different at the 0.05 significance level.

[1]Percentage obtained from the difference in the value from grass pasture and the highest value from the treatment within each soil depth. Downward arrow indicates lower values in disc tillage treatment than in the grass pasture.

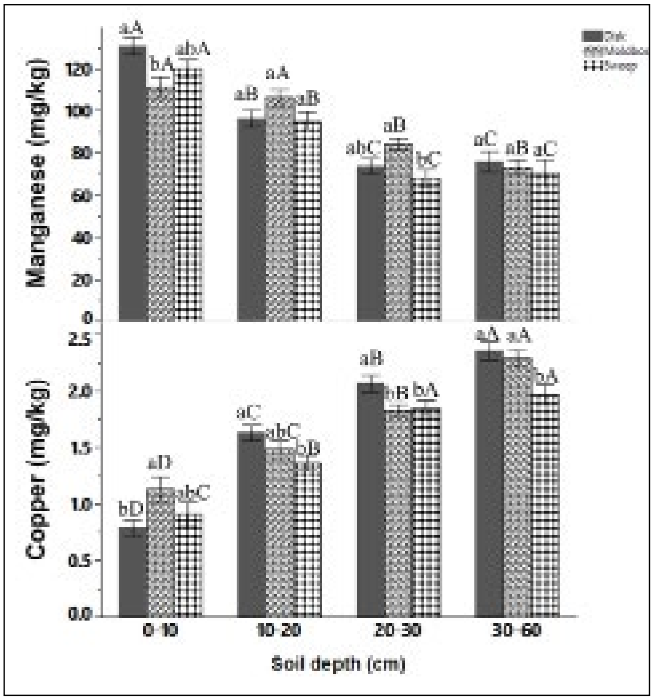

Figure 8. Mehlich III extractable manganese and copper as influenced by the interaction of tillage system and soil depth in 2015 (Shiwakoti et al., 2019b). Bars sharing the same letters are not significantly different at 0.05 significance level. Lowercase letters are a comparison of the tillage system within each soil depth, and uppercase letters are a comparison of the tillage system across the four soil depths.

3.3. Micronutrients

Over time, the concentration of extractable Mn was higher under disc tillage (131 mg kg^{-1}) than under moldboard plow (111 mg kg^{-1}), while soil Cu was more significant under moldboard plow (1.13 mg kg^{-1}) than under disc tillage (0.79 mg kg^{-1}) (Figure 8). The disc tillage also increased the Zn concentration in the tillage-fertility long-term experiment. Only Cu was found to be affected by N fertilization rates and declined with the application of N fertilizer (Figure 9).

Fertilizing with inorganic N could reduce soil Cu by decreasing soil pH and increasing Al and Fe levels in soils (Prasad and Power, 1997). The Fe and Al oxides and oxyhydroxides adsorb Cu very tightly and consequently reduce the mobility of Cu in soils (Prasad and Power, 1997). The concentration of extractable Cu, Mn and Zn had declined at the 0-10 cm soil depth in the cultivated plots compared to the ones in the undisturbed grass pasture. The cultivated plots lost at least 43% and 53% of extractable Zn and Cu, respectively, in the upper 10 cm of soil after 75 years of continuous N fertilizer and tillage (Table 2).

Table 2. Impact of 75 years of inorganic N application on the concentration of extractable Mn, Zn, Cu, and B in upper 10 cm soil depth of the dryland winter wheat-fallow cropping system under disc tillage management compared to nearby grass pasture (Shiwakoti et al., 2018).

Nutrients	**N rate (kg ha^{-1})**						
	0	**45**	**90**	**135**	**180**	**GP**	**Cultivation effect‡**
	---------------------- mg kg-1 ----------------------						
Manganese	124b†	120b	134ab	138ab	139ab	166a	16% ↓
Zinc	2.6b	1.7b	3.5b	1.8b	1.4b	6.0a	43% ↓
Copper	1.1b	0.9b	0.7b	0.6b	0.6b	2.3a	53% ↓
Boron	6.6a	6.2a	6.5a	6.7a	6.1a	0.0b	NA

‡Downward arrow indicates percent decline in the concentration of nutrients after 75 years of inorganic N application under disc tillage management compared to grass pasture (GP). The decline percentage is calculated from the concentration differences between the nutrients in the grass pasture and the best performing N rate application treatments, i.e., N rate treatments with the highest concentration. NA indicates 'Not Applicable'.

†Means sharing the same letter within the rows are not significantly different at 0.05 significance level.

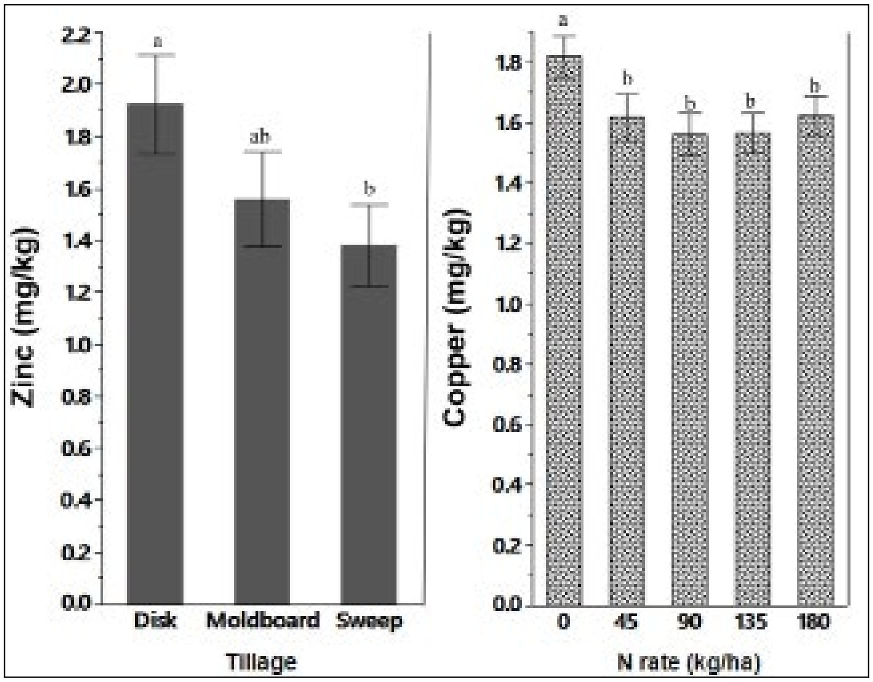

Figure 9. Mehlich III extractable zinc (left) as influenced by tillage system; and copper (right) as influenced by N application rates in 2015, respectively (Shiwakoti et al., 2019b). Bars sharing the same letters are not significantly different at 0.05 significance level.

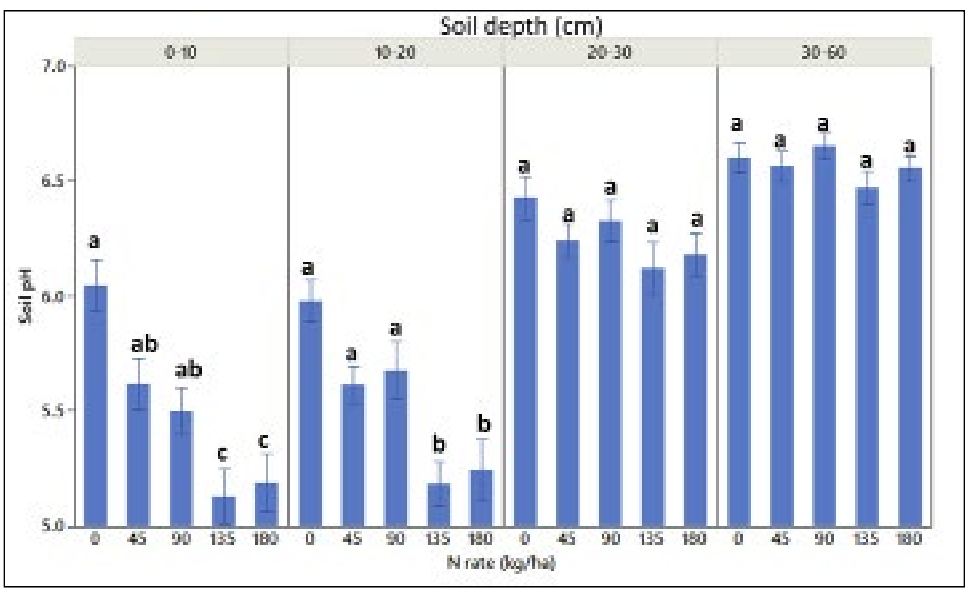

Figure 10. Average soil pH (from the years 1995, 2005, and 2015) in tillage-fertility long-term experiment plots. Means sharing the same letter are not significantly different within the soil depth at a 5% significance level.

3.4. Soil pH

Over time, inorganic N application affected soil pH in the 0-10 cm and 10-20 cm soil depths only (Figure 10). In these depths, pH was significantly lower in the 135 kg N ha^{-1} and 180 kg N ha^{-1} than in the 0 kg N ha^{-1}, 45 kg N ha^{-1}, and 90 kg N ha^{-1} application rates (Figure 10).

Among the tillage systems, moldboard tillage was the most detrimental with regard to soil pH. In the 10-20 cm and 20-30 cm soil depths, soil pH with moldboard tillage (5.35 at 10-20 cm and 6.03 at 20-30 cm) was markedly lower than the soil pH under sweep (5.52 at 10-20 cm and 6.30 at 20-30 cm) and disc tillage (5.74 at 10-20 cm and 6.43 at 20-30 cm) (Data not presented).

3.5. Inferences from TF-LTE (Tillage-fertility long-term experiment)

- Among the tillage methods of the tillage-fertility long-term experiment, disc plow is better than moldboard or sweep regarding nutrient dynamics in the dryland PNW.
- Higher nitrogen application rates decrease the soil copper levels and soil pH over time.

4. Wheat-pea long-term experiment (WP-LTE)

The wheat-pea long-term experiment was established in 1963 to evaluate the timing and severity of tillage operations on the soil, and on wheat and pea productivity (CBARC, 2018). This long-term experiment has four treatments: fall tillage, spring tillage, no-tillage, and disc/chisel tillage in a split-plot design under a winter wheat-dry pea rotation system. The no-tillage treatment was under minimum tillage until 1995, so the actual no-tillage is only 20 years old while the other treatments are 52 years old at the time of the last sampling in 2015. Detailed descriptions of the treatments are reported by Shiwakoti et al. (2019b).

4.1. Why these treatments?

Winter wheat-14 months fallow is not considered a sustainable crop rotation due to relatively small addition of organic matter, although it has been (successfully) practiced in the PNW for a long time. The conventional tillage aggravates this situation. Therefore, the pioneers at CBARC hypothesized that annual cropping using wheat and peas in rotation under reduced tillage would improve soil productivity by contributing more to the soil organic matter compared to the yearly mono-crop of wheat under conventional tillage.

The timing of tillage also affects whether nutrients are available due to the role of tillage in soil water conservation and erosion control, especially in dryland systems and on steep slopes. Understanding of tillage's role at the time led to a hypothesis that spring tillage would increase available soil moisture and increase yields compared to fall tillage.

4.2. Macronutrients

The impact of tillage methods on soil macronutrients began to show in the top 10 cm of soil after 52 years of the winter wheat-dry pea experiment (WW-P). In 2015, the concentration of soil organic carbon was higher under no tillage (18.9 g kg^{-1}) than under fall tillage (14.0 g kg^{-1}) or spring tillage (14.2 g kg^{-1}) at the top 10-cm soil surface (Figure 11). No-tillage resulted in higher concentrations of extractable P, S and K levels compared to fall tillage or spring tillage. After 52 years, the WW-P plots lost at least 28%, 67%, and 46% of soil organic carbon, S and Mg, respectively, in the top 10 cm of soil compared to the undisturbed grass pasture plots. No-tillage plots were the only plots in WW-P to maintain P (99 mg P kg^{-1}) comparable with that in the undisturbed grass pasture plots (102 mg P kg^{-1}) at the same depth (Figure 11).

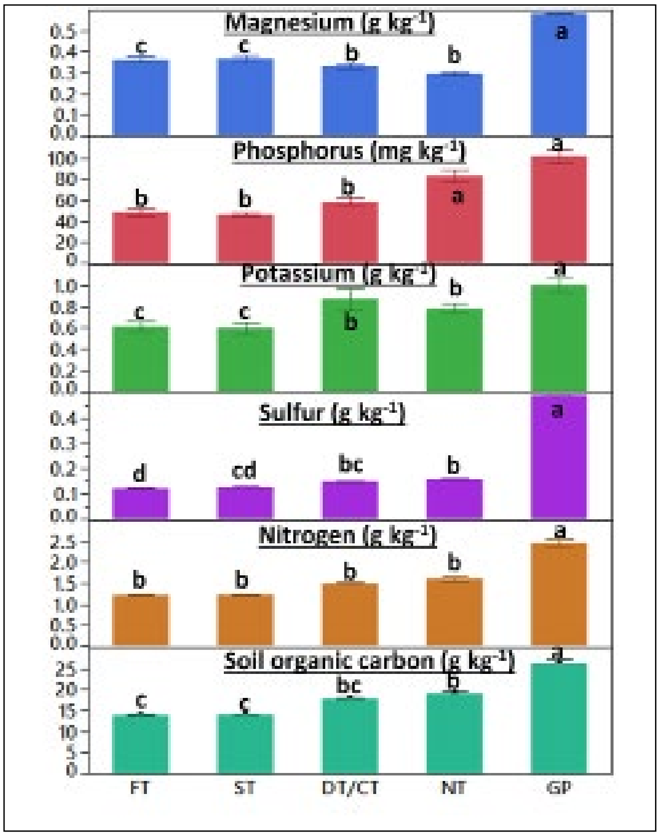

Figure 11. Concentration of macronutrients in the wheat-pea long-term experiment (WP-LTE) and grass pasture plots at 0-10 cm soil depth in 2015 (Shiwakoti et al., 2019c). FT = fall tillage; ST = spring tillage; DT/CT = disc/chisel tillage; NT = no tillage; and GP = grass pasture. Means sharing the same letter are not significantly different at a 5% significance level.

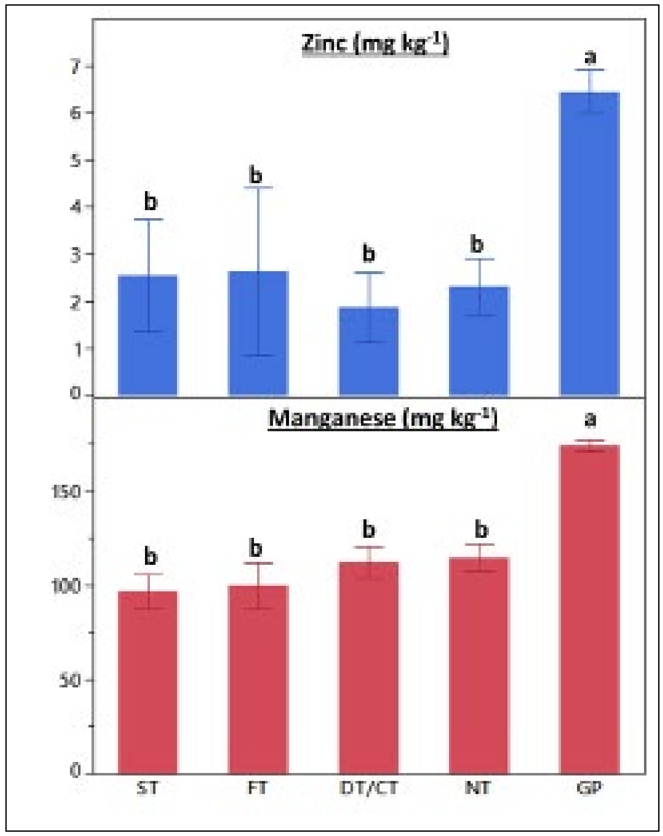

Figure 12. The concentration of zinc and manganese in the WP-LTE and grass pasture plots at 0-10 cm soil depth in 2015 (Shiwakoti et al., 2019e). ST = spring tillage; FT = fall tillage; DT/CT = disc/chisel tillage; NT = no tillage; and GP = grass pasture. Means sharing the same letter are not significantly different at 5% significance level.

4.3. Micronutrients

The concentrations of Mehlich III extractable B, Mn, Zn, Cu and Fe in soil were unaffected by the tillage methods over 20 years. However, comparison with nearby undisturbed grass pasture showed a significant decline in extractable Mn and Zn in the upper soil layer (Figure 12). After 52 years of winter wheat-dry pea (WW-P) cropping, the concentration of extractable Mn was comparable between no till (NT, 123 mg kg^{-1}) and grass pasture (175 mg kg^{-1}) in 0-10 cm soil (Figure 12). Similarly, extractable Zn was greater under grass pasture than in WW-P plots in the upper 10 cm of the soil. This study demonstrated a significant loss of extractable Mn and Zn over time in WW-P plots compared to the undisturbed grass pasture, and none of the studied tillage methods could curb the decline, except for no-tillage in the upper 10 cm soil surface.

4.4. Soil pH

Soil pH ranged from 5.65 to 6.76 and was not influenced by the tillage methods at any of the studied depths in WP-LTE treatments (Figure 13). However, soil pH under grass pasture was higher than the tillage treatments at 0-10, 10-20, 20-30, and even at 30-60 cm soil depth.

4.5. Inferences from Wheat-Pea Long Term Experiment (WP-LTE)

- No-tillage is superior to other treatments regarding available soil nutrients in the dryland PNW.
- The timing of tillage had a similar effect on available soil nutrients in the dryland PNW.

5. What have these LTEs (Long Term Experiments) told us so far?

All of the long-term experiments we studied showed one typical response over time to nutrient status and agricultural practices: less decrease in the nutrient concentration in the plots where soil disturbance is low, compared to the plots that had higher soil disturbance. In other words, reduced, minimum and no-tillage performed better than conventional tillage regarding nutrient concentrations in the long-term.

This positive effect of low soil disturbance is mainly due to the slow mineralization of soil organic matter and less loss of soil organic matter in these plots. Soil organic matter is the storehouse of essential plant nutrients that become available to plants upon mineralization. But rapid mineralization, which is enhanced by conventional tillage, increases nutrient loss over time.

Tillage practices, even the reduced or minimum tillage, were not enough to maintain the soil nutrients when compared to the nearly undisturbed grass pasture nearby. This indicates gradual but continuous nutrient loss even with these conservation tillage methods. On the other hand, nutrient concentrations in the upper 10-cm soil surface have started to increase in no-tilled plots compared to other treatments, which is a useful indicator of tillage-induced nutrient change in the soil. Since no-tillage treatment in WP-LTE is only 20 years old, its long-term effect is yet to be seen, but its impact so far shows a positive sign for nutrient restoration and soil resiliency.

The results from the crop residue long-term experiment (CR-LTE) supported current understanding of the positive effect of soil organic matter on soil nutrients, as most of the nutrients were maintained to the level of grass pasture by farmyard manure application only. The farmyard manure supplied extra soil nutrients and organic matter, which was not the case in the other CR-LTE treatments.

In a nutshell, the agricultural practices that include the balance of farmyard manure and inorganic N, significant surface plant residue cover after tillage, and less volume of soil structure disruption or inversion are the best agricultural practices that can sustain the dryland soils' nutrient-supplying capacity for the PNW and similar ecoregions.

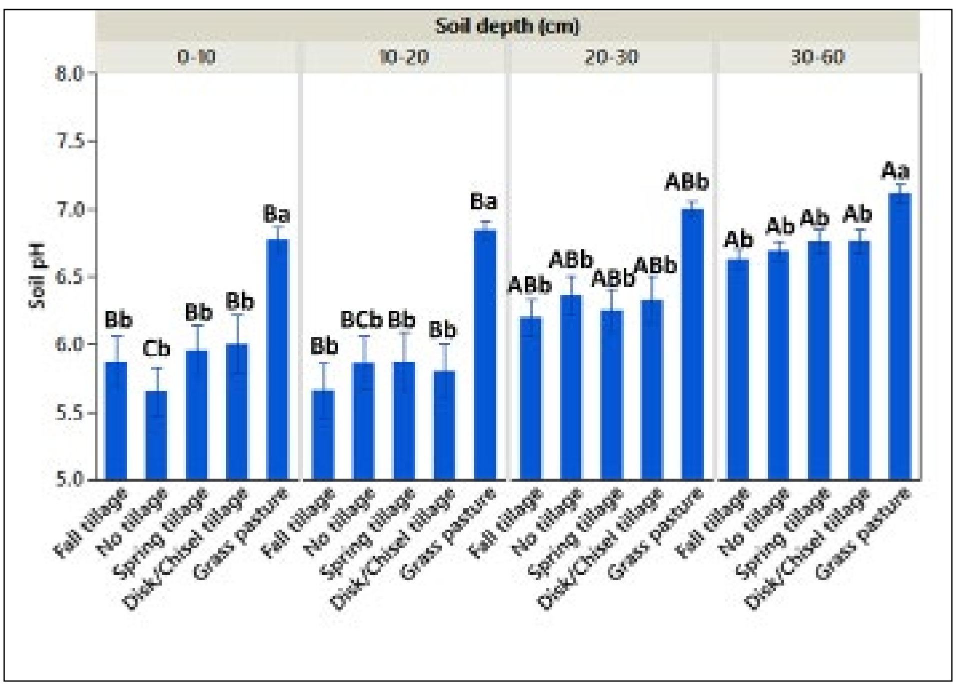

Figure 13. Soil pH in the WP-LTE and grass pasture plots in 2015 (Shiwakoti et al., 2018). Uppercase letters show a comparison of each treatment across four soil depths, and lower-case letters show a comparison of the treatments within each of the soil depths. Means sharing the same letter are not significantly different at 5% significance level.

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