AN ABSTRACT OF THE DISSERTATION OF

Santosh Shiwakoti for the degree of Doctor of Philosophy in Crop Science presented on August 30, 2018.

Title: Long-term Impacts of Nitrogen Fertilizer, Tillage and Crop Residue on Soil and Plant Nutrients in Winter Wheat Cropping Systems Under Dryland Conditions.

Abstract approved: ____

Valtcho D. Jeliazkov

Agricultural practices influence the nutrient dynamics of soil and plants, which may take more than a decade to be expressed in the drylands. The nutrient supplying capacity of soil is a crucial component of sustainable agriculture, and hence, this study can play an important role in policy making for the future of dryland agriculture. The objectives of this thesis were to evaluate the long-term impact of different methods of crop residue management, varying inorganic N application rates, different tillage systems, and tillage timing on soil pH and on plant essential macro and micronutrient in soil and tissue (wheat grain and straw) under winter wheat dryland cropping system of the inland Pacific Northwest (PNW). The studies were carried out on the three existing long-term experiments of Oregon State University, and were represented as (i) Crop residue study (CR), (ii) Tillage-Fertility study (TF), and (iii) Wheat-Pea study (WP). Responses included total N, C, S, and Mehlich III extractable P, K, Ca, Mg, Mn, Fe, Zn, Cu, and B in soil (four depths: 0-10, 10-20, 20-30, and 30-60 cm) and the total concentration of the same elements in plant tissue. The CR study examined the 84 years effect of residue burning, variable rates of inorganic N application, and organic amendments (farmyard manure and pea vines) on soil pH and the nutrient concentration in the wheat residue managed plots under winter wheat-fallow (WW-F) cropping system. No differences were observed between burned and unburned residue plots (excluding plots with the organic amendments) for nutrients in soil and wheat after 84 years of WW-F cropping. Residue incorporation with farmyard manure (FYM) reduced the rate of nutrient decline over time in soil, whereas inorganic N application decreased grain P, K, and Ca with the higher N rate application rates compared with the zero N application or FYM. In the TF study, the 75 years effect of moldboard plow (MP), sub-surface sweep (SP), and disk plow (DP) and variable rates of inorganic N on soil pH, and on soil and plant nutrients were investigated under WW-F. The soil under MP lost greater amount of total N, C, and extractable K, and Mg in the top 10 cm than the soil under SP and DP. The severity of C, N, Mehlich III extractable P, Ca, Mg, Cu, Mn, and Zn decline were lower in soil under DP than in soil under MP, and comparable with soil under SP for most nutrients. Long-term application of higher rates of N fertilizer improved soil C: N ratio and P accumulation in wheat grain. Decreased soil pH was also observed with higher N rates application in the TF study. The WP study consisted of 52 years effect of timing and tillage intensity on the same parameters as of CR and TF study under winter wheat- dry pea rotation. The treatments were spring tillage (ST), fall tillage (FT), disk/chisel tillage (DT/CT), and no tillage (NT). No differences were observed between ST and FT for nutrients in soil and wheat over time, however, NT had started to show its effect in 2015; greater soil total C, S, and extractable P, K, and Mn were evident under NT compared with FT, ST and DT/CT in the upper 10 cm soil depth. The NT plots were under minimum tillage until 1995, and under NT after that, so its long-term effect is yet to be seen. The results suggest that NT can be effective agricultural practice for improving resiliency of soil under dryland wheat production.

Long-term Impacts of Nitrogen Fertilizer, Tillage and Crop Residue on Soil and Plant Nutrients in Winter Wheat Cropping Systems Under Dryland Conditions

by
Santosh Shiwakoti

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented August 30, 2018
Commencement June 2019

Doctor of Philosophy dissertation of Santosh Shiwakoti presented on August 30, 2018

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Santosh Shiwakoti, Author

ACKNOWLEDGEMENTS

I would like to thank everyone who has been part of this wild ride and, especially my family, for patiently waiting me in the finish line of this long ride. A BIG thanks to my committee members, for serving and guiding me throughout my study!

I am very grateful to Columbia Basin Agricultural Research Center (CBARC), Adams, OR, for providing me the soil and wheat tissue samples. Special thanks to Paul Rasmussen (retired), Karl Rhinhart, and coworkers for collecting and archiving the soil and tissue samples of long-term experiments, and Chris Rogers (retired) and Joseph (Joe) St. Claire for the CNS analyses of the soil and tissue samples (USDA Agricultural Research Service, Columbia Plateau Conservation Research Center, Adams, OR).

Last but not the least, thank you Dr. Jay Noller and his wonderful office team (Kristin, Tracy (retired) and Emmalie).

CHEERS!

CONTRIBUTION OF AUTHORS

Dr. Valtcho Jeliazkov came up with the idea, conceptualization and the methodology, and provided all the financial support for this project. In addition, Dr. Jeliazkov was involved with editing and revision of all the chapters. Dr. Hero Gollany analyzed the carbon, nitrogen and sulfur of soil and wheat tissue for two of the studies (Chapters 2 and 6) and was involved in the review and edit of the manuscripts. Dr. Markus Kleber and Dr. Baoshan Xing reviewed and edited the manuscripts. Dr. Tesma Astatkie did statistical analysis of Chapter 2 and 3 and helped in the statistics of rest of the Chapters.

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Chapter 1

INTRODUCTION

Over the past century, a better supply of essential nutrients and a genetic potential of seeds have allowed farmers to increase crop yields per unit of land (Zhang et al., 2015). However, crop yields and production are no longer increasing at the rates observed a couple of decades ago, suggesting that there are various unknowns that must be revealed and resolved in order to improve yields and guarantee sustainable production (Bajzelj et al., 2014; Foyer et al., 2016; Rasmussen et al., 1998a; Reganold and Wachter, 2016; Wang et al., 2016; Yadav et al., 2008, 2000). According to a FAO report, global amount of productive land per person in 2050 will be only a quarter of the level in 1960, due to the growing populations and degradation of soil caused by its improper use (Arsenault, 2017).

Improper agricultural practices enhance soil degradation by depleting nutrients, degrading soil structure, acidifying soil, and adding sub-optimal rates of organic and inorganic fertilizers (Manna et al., 2007). Soil organic matter (SOM) loss and its associated nutrients losses, is one of the main reasons for soil degradation and eventually yield declines (Manna et al., 2007). Thus, crop production must be defined in terms of its effect on the rate and direction of changes in soil plant nutrients. This fact is corroborated by Masto et al. (2007) who stated that assessment of soil quality indicators like nutrient status and direction of change with time is a primary indicator of whether agriculture is sustainable. Previous researchers have already considered the concentration of nutrients in soil and soil-favorable physical, chemical, and biological properties as good indicators of sustainable crop production (Karami et al., 2012).

However, due to the slow soil response to management, evaluation of the long-term effects of agricultural practices on soil quality indicators requires long-term experiments (LTE) (Morari et al., 2008). Because year to year changes tend to be very small and methodological errors could be substantial, the LTE are needed to reveal patterns of change in the SOC and in nutrients availability (Wuest and Gollany, 2013). In addition, the LTE provide direct observation of soil changes across decades as well as an assessment of agricultural sustainability (Richter et al., 2007). The LTE become particularly more important in semi-arid climate since the effect of agricultural practices on soil nutrient dynamics takes more than a decade to get expressed in the semiarid environments (Ghimire et al., 2015; Rasmussen and Parton, 1994).

The Columbia Basin Agricultural Experiment Station (CBARC), near Pendleton, OR is part of the Oregon State University and has the oldest long-term experiments (LTEs) of western USA in semiarid environment. The LTEs at CBARC represent some of the dominant agricultural practices in the drylands of the inland Pacific Northwest (PNW). Maintenance of SOM and nutrient availability is a challenge in such environment due to less cropped year and less crop residues returned to the soil. Winter wheat- 14 months fallow (WW-F) rotation accompanied by the low precipitation limits the biomass production and annual return of the crop residue in some areas of the PNW. This type of conditions have negative impacts on the SOM and nutrient availability, and hence affect the sustainability of soil nutrients (Rasmussen et al., 1998a). This fact is supported by the earlier studies of 1990s (Rasmussen et al., 1998c; Rasmussen and Collins, 1991; Rasmussen and Parton, 1994) and a recent study (Ghimire et al., 2015) which found a significant decline in SOC and N in the cultivated plots since the establishment of the LTE in CBARC. The concentration of most of the plant essential nutrients in soil is modified by the mineralization of SOM, a process where N plays a pivotal role. Therefore, a marked decline in SOM and N is a serious concern for the sustainability of agriculture as this impact the availability of plant essential nutrients, and eventually the economics of farm.

There has been increasing interest in the impact of agricultural practices, such as crop residue management, tillage timing and intensities, inorganic N fertilizer application rates, and legumes in rotation with winter wheat, on SOM and nutrient cycling all over the world over the last few decades (Bhupinderpal-Singh et al., 2004; Dalal et al., 2011). The knowledge on the long- term impacts of such agricultural practices on plant essential nutrients status will provide insights on one of the important aspects of soil quality and hence, can play a vital role in maintaining sustainable agriculture systems. To this date, no studies have assessed the long-term impact of the above mentioned agricultural practices on soil pH and on wide range of plant essential macro and micro-nutrients in soil and tissue of the inland PNW, such as nitrogen (N), carbon (C), sulfur (S), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe), copper (Cu), zinc (Zn), and boron (B). This knowledge gap may result in reduced soil fertility management and inadequate cropping system strategies. Undoubtedly, crop yield is an important measure of best management practices, however, yield increments can be maintained over a brief period through improved seeds and fertilizer applications even though the natural nutrient supplying capacity of the soil is declining. By the time nutrient depletion in soil is detected, considerable amount of the physical, chemical and biological decline in soil quality has already occurred. Therefore, evaluation of the status and trends in essential nutrient concentrations in LTE is important. This presents the question for this study: Does evaluation of soil and plant samples from LTE help to decide on more sustainable farming system that enables maintaining soil nutrients over time in the PNW? This issue is important because of the vital role long-term soil nutrients dynamics play in policy making process of sustainable farming system. Year to year soil test is not capable to enlighten the prospective soil nutrient status because year to year changes tends to be very small and methodological errors are substantial, however, it helps with the decision for that year nutrient needs. Hence the evaluation of essential nutrients in soil and tissue from the long-term study will help to reveal long-term changes in soil and crops as a function of management, and to correct or develop current cropping management practices for sustainable agriculture in the PNW and in other regions with similar climate.

The objectives of this dissertation were to assess the long-term impacts of common agricultural practices of the drylands of the inland PNW on plant essential macro- and micronutrients in soil and in wheat grain and straw. The objectives were accomplished in six studies described in chapters 2, 3, 4, 5, 6, and 7. Beside assessment of the nutrient status, this study aimed to provide the best recommendation for maintaining, increasing, or reducing the nutrient mining from soil of winter wheat cropping system of PNW drylands.

Chapter 2 describes a study on the 84 years' effect of different methods of crop residue management on soil pH, soil C/N ratio, and plant essential macronutrients (N, C, S, P, K, Ca, and Mg) in soil and wheat grain and straw under winter wheat-14 months fallow cropping system.

Chapter 3 describes the same study as Chapter 2 but assess the plant essential micronutrients (Mn, Fe, Cu, Zn, and B) in soil and wheat (grain and straw).

Chapter 4 describes a study on the 75 years' impact of different tillage methods and N fertilization rates on soil pH, soil C/N ratio, and plant essential macronutrients (N, C, S, P, K, Ca, and Mg) in soil and wheat (grain and straw) under winter wheat- 14 months fallow cropping system.

Chapter 5 describes the same study as Chapter 4 but assess the plant essential micronutrients (Mn, Fe, Cu, Zn, and B) in soil and wheat (grain and straw).

Chapter 6 describes a study on the 52 years' impact of different tillage intensities and timing on soil pH, soil C/N ratio, and plant essential macronutrients (N, C, S, P, K, Ca, and Mg) in soil and wheat (grain and straw) under winter wheat- dry pea rotation system.

Chapter 7 describes the same study as Chapter 6 but assess the plant essential micronutrients (Mn, Fe, Cu, Zn, and B) in soil and wheat (grain and straw).

The soil and tissue samples from 1995, 2005, and 2015 were used for analysis. Soil samples from four depths (0-10, 10-20, 20-30, and 30-60 cm) were evaluated for the distribution profile of nutrients and soil pH. Nutrients in the soil were determined by inductively coupled plasma (ICP) spectroscopy following dry combustion method (Total N, SOC, and Total S), and Mehlich III extraction method (for plant available P, K, Ca, Mg, Mn, Cu, Fe, Zn, and B) while the total concentration of the same nutrients in tissue were determined following a dry ash method. Soil samples from a nearby undisturbed perennial grass pasture (GP, undisturbed since 1931) served as the reference to our studies. The soil pH and nutrients of GP and LTE were compared to interpret the changes brought by agricultural practices on the plant essential nutrients and pH in soil over time. Also, the effect on nutrient trends from each study were evaluated by comparing the treatments from the samples of 1995, 2005, and 2015.

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Chapter 2

MACRONUTRIENT STATUS OF SOILS AND WHEAT FROM LONG-TERM AGROEXPERIMENTS REFLECTS VARIATIONS IN RESIDUE AND FERTILIZER INPUTS

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Abstract

The effect of 84 years of residue and fertilizer management on macronutrient availability and uptake in a dryland winter wheat (*Triticum aestivum* L.)-fallow rotation (WW-F) was assessed in the long-term agroecosystem experiments maintained at the Columbia Basin Agricultural Research Center at Adams, OR. Previous research at these experiments was largely focused on organic matter cycling and soil acidification following nitrogen (N) fertilizer input, but the consequences of land management for nutrient status have received little attention so far. Soil and wheat (grain and straw) samples of 1995, 2005, and 2015 were analyzed to determine the macronutrient dynamics associated with different residue management methods. The treatments included: application of N fertilizer in three rates (0, 45, and 90 kg ha^{-1}) with no burn, fall and spring burn wheat residue incorporation, and no burn residue incorporation with farmyard manure (FYM) and pea vines. The soil results were compared among the treatments and with nearby undisturbed grass pasture (GP). The soil organic carbon (SOC), total N and S, and extractable Mg in the FYM plots declined in the top 10 cm soil depth by 43%, 46%, 73%, and 32%, respectively compared to the GP. The FYM had the closest values of these nutrients to the GP. In the upper 20 cm soil surface in FYM plots, extractable P and K increased by 63% and 32%, respectively, compared to the GP. High N fertilizer rates (90 kg ha^{-1}) acidified the soil and reduced the accumulation of P, K, and Ca in grain, but had higher grain N accumulation. The results indicate that (i) residue burn and no burn treatments have similar impact on macronutrient in soil and wheat, and (ii) FYM is vital to reduce soil macronutrient decline over time and can't be replaced by inorganic N application alone.

Keywords: Drylands, Farmyard manure, Nitrogen, Phosphorus, Soil Organic Carbon.

Abbreviations: WW-F, dryland winter wheat fallow rotation; FYM – farmyard manure; SOC – soil organic carbon; GP – grass pasture plot.

Introduction

Crop yields are no longer increasing at the rate of a couple of decades ago (Reganold and Wachter, 2016) and, simultaneously, the proportion of arable lands are also constantly shrinking (Foley et al., 2005)- a condition that demands the increased cultivation in drylands. Therefore, increasing amount of research of various soil management practices and its impact on soil quality parameters, such as macronutrient status, of such regions may contribute to the sustainable food production for the next 100 years. Despite the important roles of macronutrient in sustainable agriculture, limited studies have evaluated its dynamics under dryland cropping system over extended periods of time.

The drylands of the Pacific Northwest (PNW) receive an average annual precipitation of 150- 437 mm (Gollany 2016) while winter wheat (*Triticum aestivum* L.) requires 500-580 mm of water to complete its lifecycle (Al-Kaisi and Shanahan, 1999), and hence, annual wheat production may not be successful in this region. To overcome this water limitation, farmers in this production region of more than two million hectares have opted to winter wheat-14 months fallow (WW-F) rotation for over 100 years, and this system has been proven to be economical and stable so far (Williams et al., 2014). In this WW-F cropping system, wheat is grown for ten months and the land is fallow for 14 months to conserve winter precipitation for next year's wheat (Rasmussen and Parton, 1994; Schillinger and Papendick, 2008). However, during these 14 months of fallow, the surface is exposed to general degradation, wind erosion, accelerated C and N losses from soil etc. (Rasmussen and Parton, 1994). Nevertheless, WW-F cropping system has proven to be the best cropping system to sustain wheat production in these regions (Schillinger and Papendick, 2008), and hence, the management strategies that could maintain or enhance the soil productivity in a long-term under this cropping system is crucial for this region.

Wheat residue burning was a common soil management method during 1930's in WW-F cropping system (Rasmussen and Parton, 1994) and is still being practiced by some farmers in the PNW (Ghimire et al., 2015). The burning of crop residues is favored for better seedling growth, for suppression of plant disease and pest incidences, and to mitigate low soil temperature in the spring (Rasmussen and Parton, 1994). However, repeated burning may decrease SOC, reduce microbial activity, increase CO_2 emissions, and cause air pollution (Rasmussen et al., 1980). The burning of crop residue has decreased SOC by 20% to 60% within the last 40-50 years (Gollany et al., 2011; Peacock et al., 2001; Rasmussen and Parton, 1994). In contrast, incorporation of crop residues with N fertilizer and organic amendments have increased SOC storage, N, crop yield and biological activities in this region (Camara et al., 2003; Peacock et al., 2001; Rasmussen and Parton, 1994). However, excess N fertilization may be detrimental to soil pH, economically unjustified, and may result in net loss of SOC due to enhanced crop residue decomposition (Mulvaney et al., 2009). The preceding notion can be debated because studies have found N fertilization had slowed the SOC loss compared to no N fertilization (Ladha et al., 2011). This controversy highlights the uncertainty in the impacts of N fertilization on macronutrients whereas FYM is ubiquitously known for its positive impacts on macronutrient

(Mulvaney et al., 2009). Nevertheless, it is widely recognized that improved agricultural practices such as residue and manure incorporation and proper N application, minimize the risk of soil nutrient depletion over time (Lal, 2001). An understanding of how the above-mentioned crop residue management practices affect the soil macronutrient over time is critical to evaluate the potential success of these practices in the region.

Our study was conducted on one of the several long-term experiments (LTE) maintained by Columbia Basin Agricultural Research Center (CBARC), near Pendleton, OR. The LTE of our study, hereafter denoted by CR-LTE, was established in 1931 to evaluate the effect of different residue management practices (based on farmers practices in 1930's) on soil and crop productivity under the WW-F cropping system. Previous studies in CR-LTE demonstrated that N and SOC declined over time when compared with the nearby undisturbed grass pasture (GP) (Ghimire et al., 2015; Rasmussen and Parton, 1994). Besides N and SOC in the CR-LTE plots, the 84 years 'effect of different residue management methods on other plant essential macronutrients such as P, K, Ca, S, and Mg is unknown. The knowledge of such agricultural practices' effect on soil macronutrient over time will provide insights into the sustainability of these management practices. This knowledge can then be utilized to fine-tune the systems and make them more resilient and sustainable for crop production. However, the effect of agricultural practices on nutrient status takes decades to manifest (Rasmussen and Parton, 1994). Under such conditions, only the analysis of archived soil and crop samples from LTE can provide important resources to detect the subtle changes in soil and crop nutrients status over time caused by the different management practices.

We aimed to contribute to the limited knowledge of plant essential macronutrient dynamics in the soil and wheat of drylands of the inland PNW as affected by different residue management. To fulfil this aim, we took a conceptual approach that consisted of quantification of the long-term effect of different methods of crop residue management on the dynamics of N, C, S, P, K, Ca, S, Mg, and soil pH. For this approach, we analyzed soil from four depths (0-10, 10-20, 20-30, and 30-60 cm), and wheat (grain and straw) samples of 1995, 2005, and 2015 from CR-LTE plots and compared the concentration of macronutrients among the CR-LTE treatments. In addition, macronutrient status of soil samples from the CR-LTE was compared with that of the soil samples from nearby undisturbed grass pasture (GP) so that soil nutrient changes after 84 years of cultivation can be quantified. To our knowledge, this is the first study in this region to examine all of the plant essential macronutrients dynamics over time under different methods of crop residue management.

The objectives of this study were to answer the following questions:

i. Is inorganic N fertilizer application a better practice than the incorporation of organic amendments regarding soil and wheat macronutrients?
ii. Can inorganic N fertilizer application alleviate the detrimental effect of residue burning?
iii. Is there any nutrient stratification influenced by these agriculture practices over time?
iv. Does soil pH differ in different treatments over time?

The CR-LTE was initiated in 1931 with the hypothesis that application of inorganic N would alleviate detrimental effects caused by burning of crop residues and also replaces the use of pea vine and manure in dryland wheat production. This hypothesis assumed that inorganic N would increase the crop biomass production (above and below) and hence, will recharge the nutrient pool of the soil through the decomposition of increased amount of crop residue. To find out if this 84 years' old hypothesis is acceptable in 2015 or not, we tested the followings:

i. Inorganic N application (NB45, NB90, SB45 or SB90) increases or maintains the concentration of N, C, P, K, S, Ca, Mg and pH in soil over time compared to FYM and PV.
ii. The residues burned plots with inorganic N application (SB45 or SB90) have greater or similar concentrations of N, C, P, K, S, Ca, Mg, and pH in soil than no burn plots with inorganic N application (NB45 or NB90) over time.
iii. The concentration of macronutrient in SB45 or SB90 increases or maintains at any of the studied soil depths compared to NB45 or NB90 over time.
iv. The concentrations of N, C, P, K, S, Ca, and Mg in wheat grain and straw are greater or similar in NB45, NB90, SB45 or SB90 than FYM and PV application.
v. The concentrations of N, C, P, K, S, Ca, and Mg in wheat grain and straw are greater or similar in SB45 or SB90 than NB45 or NB90.

Materials and methods

Site description

The experiment site is at the Columbia Basin Agricultural Center (CBARC), 15 km northeast of Pendleton, OR (45°42' N, 118°36' W, 438 m asl). The CBARC is one of the 14 field experiment stations of Oregon State University. This experiment was initiated in 1931 and is one of the very few LTE that have survived in the Western US. The site has dry summer and wet winter with average annual precipitations of 437 mm (90% of precipitation occurs between November and June) (Gollany 2016), and the 81-yr (1932–2012) average annual maximum and minimum temperatures are 17.4°C and 3.06°C, respectively (CBARC, 2015). According to the Soil Survey Staff (2014), the soil at the experimental site is Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) derived from loess overlying basalt and is well drained. The main properties of the experimental site's soil are as follows: 18% clay, 70% silt (upper 20 cm), pH: 6.1- 7.0, and cation exchange capacity: 18 $cmol_c$ kg^{-1}.

Experimental design

The design of the experiment was an ordered block of two identical series (1400 and 1500) of nine treatments with two replications, each series representing wheat or fallow phase of the WW–F system. Although this experiment was established in 1931 without randomizing the treatments within each block, extensive investigation of plot by plot soil samples and yield data before the experiment started, and later on, revealed no biases (Rasmussen and Parton, 1994). The size of individual plots is 11.6 m by 40.2 m. The two series were offset by 1 year with the sole purpose of collecting wheat yield and biomass data each year. The wheat cultivars grown since 1992 were: Malcolm from 1992–1995, Stephens from 1996–2005, and ORCF102 from 2006–2015.

The undisturbed grassland pasture (GP) is 46 by 109 m that contains no experimental variables and serves as a baseline for evaluating changes in other experiments. Bluebunch wheatgrass (*Agropyron spicatum* var. 'Secar') and Idaho fescue (*Festuca idahoensis* var. 'Joseph') are the dominant grass species in the GP.

Treatments and field management

The CR-LTE treatments include: fall burning of wheat residue, no N addition (FB); spring burning of wheat residue with the addition of N at the rate of 0 kg ha^{-1} (SB), 45 kg ha^{-1} (SB45), and 90 kg ha^{-1} (SB90); no burning of wheat residue with the addition of N at the rate of 0 kg ha^{-1} (NB), 45 kg ha^{-1} (NB45) and 90 kg ha^{-1} (NB90); and no burning of wheat residue with farm yard manure (FYM); and pea vine (PV) incorporation.

The FYM at a rate of 11.2 Mg ha^{-1} yr^{-1} (Dry matter 47.5%, 0.85 Mg C ha^{-1}, and 70 kg N ha^{-1} yr^{-1}), and pea vine (PV), at a rate of 1.12 Mg ha^{-1} yr^{-1} (Dry matter 87.8%, 0.41 Mg C ha^{-1} yr^{-1}, and 18.5 kg N ha^{-1} yr^{-1}), were applied just prior to plowing in the spring of the fallow year. Nitrogen is supplied as urea- ammonium nitrate (UAN) one week before seeding wheat in SB and NB treatments, mostly in October. The N solution is applied by shank applicator and UAN 32% solution (Poole Chemical, Texline, Texas, US) as an N source. The undisturbed wheat stubble after harvests is burned in September for fall burn treatment (FB0) and in late March-early April for spring burn treatment (SB0, SB45, and SB90). The process of burning is rapid with temperatures reaching 300°C in the canopy for 3 minutes (Rasmussen and Parton, 1994). As soon as burning is complete, the soil is left undisturbed between burning and plowing for 195 days and 5 days for fall and spring burn, respectively (Rasmussen and Parton, 1994).

Late-winter or early-spring glyphosate is used to control vegetative growth in wheat stubble until plots are plowed. After burning and the organic amendments application, the entire experiment field is moldboard plowed 20 cm deep and smoothed with a field cultivator or a tine harrow. Before 2002, John Deere (JD 8300) drill was used to sow wheat at 90 kg ha^{-1}.

Thereafter, Case IH 5300 disc drill has been used to sow wheat at 92 kg ha^{-1} (Ghimire et al., 2015). Between April and October, the field is tilled three to four times with a rod weeder to control weeds and maintain seed-zone moisture. Huskie ® and glyphosate herbicides were used to control weeds during crop phase whereas tillage has been the method of choice to control weed infestation during fallow phase.

Soil sampling and laboratory analysis

The soil cores collected at the 0-10 cm, 10-20 cm, 20-30 cm, and 30- 60 cm depths from 1995, 2005, and 2015 were used in this study. We used the archived soil samples of 1995 and 2005 while soil samples of 2015 were collected in the summer of 2015. The soil cores (I.D. 3.6 cm) from two locations (north and south central) within each subplot were collected after wheat harvest using truck-mounted Giddings Hydraulic Probe (Giddings Machine Company, Inc., Windsor, CO). Soil samples from the two locations within a subplot were then composited. Soil pH (1:2 soil to 0.01M $CaCl_2$ solution) were measured after 30 min equilibrium time. The CR-LTE had slightly acidic soil to below 60 cm depth and thus, we assumed the total C determined in this study to be SOC. Earlier studies on this plot have confirmed total C in these plots are SOC (Ghimire et al., 2015, Rasmussen and Parton 1994).

The visible plant materials and debris were removed from the soil samples by sieving. The soil samples were oven dried at 60°C for 72 hours, and roller milled for 4 hours. The wheat grain and straw samples were collected from the center of each plot and were finely ground. A Vario Micro Cube combustion analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) was used to determine total C, N, and S in soil and plant tissue. Available concentrations of P, K, Ca, and Mg in soil and the total concentration of these nutrients in plants were determined following a Mehlich III extraction (Mehlich, 1984) of soil samples and dry ashing of plant samples (method) using an inductively coupled plasma-optical emissions spectroscopy (ICP-OES Model #2100 DV, Waltham, Massachusetts, US).

Statistical analysis

We included GP as one of the CR-LTE treatments for statistical comparisons. Repeated measures analysis (RMA) of a split-plot design with two blocks, year (1995, 2005, 2015) as the whole plot factor, and treatment (10 levels: GP, NB, SB45, SB90, NB45, NB90, FB, SB, FYM, and PV) as the subplot factor; and the response variables measured repeatedly in space at 4 soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm) was conducted to determine the effect of these factors (year, treatment and depth) on the concentrations of total N, S, and C and extractable P, K, Ca, and Mg. Tissue total concentration of P, K, Ca, and Mg in grain and straw was analyzed as a split-plot design with two blocks where year (1995, 2005, 2015) was a whole-plot factor and the 9 treatments were a sub-plot factor. For each response, the validity of model assumptions (normal distribution and constant variance of the error terms) were verified by examining the residuals as described in Montgomery (Montgomery, 2013). These assumptions were met either in the original data or after applying appropriate (square root or cubic root or natural log) transformation. For the responses that required transformation, the reported means were back-transformed to the original scale to facilitate easier reading of the results. However, in RMA, since independence assumption is likely to be violated, Akaike Information Criterion (Littell et al., 1998) was used to determine the most appropriate covariance structure and was incorporated in the model using the Mixed Procedure of SAS (SAS Institute Inc, 2014). For significant (p-value < 0.05) effects, multiple means comparisons were completed by comparing the least squares means of the corresponding treatment combinations. Letter groupings were generated using a 5% level of significance for the main effects and using a 1% level of significance for interaction effects to protect Type I experiment wise error rate from over inflation.

The minor differences in pH represent large differences since it is in a logarithmic scale. The pH data were converted to H^+ concentration (μmol L^{-1}) before analyses to unmask the differences of the treatments. The ANOVA table of pH is based on analysis of H^+ concentration. For multiple comparisons, original values of pH scale were used.

Results and discussion

The main and interaction effect for total N, S, and SOC, and extractable P, K, Ca, and Mg are presented in the ANOVA table (Table S2.1). The concentrations of studied macronutrients didn't show significant trends as a function of residue management methods of this study over 20 years period (1995-2005-2015), but the concentrations differed among the treatments, mostly in top 10 cm soil depth. Only the significant effects are described below.

Soil organic carbon (SOC) and total N

The SOC and N wer affected by the three-way interaction between treatments, depth and year (Table S2.1). In the 0-10 cm depth in 2015, the SOC was significantly higher in FYM (14.6 g kg^{-1}) than in the other treatments (Fig. 2.1A). However, SOC in FYM was lower than SOC in

GP (25.5 g kg^{-1}) in 2015 at the same soil depth (Fig. 2.1A). Similarly, the concentration of N in the top 0-10 cm was greater in GP than the rest of the CR-LTE plots in 2015, except in FYM plots (Fig. 2.1B). At 0-10 cm depth, N in the GP plot was 2.4 g kg^{-1}, whereas in FYM plot, it was 1.30 g kg^{-1} in 2015. After 84 years of WW-F rotation, the concentration of N in the 0-10 cm depth declined by 46, 59, 63, 63% in FYM, PV, SB90, and NB90 plots respectively compared with that in GP.

The decrease in SOC and N in these plots, in the upper 10 cm soil depths, were reported previously (Ghimire et al., 2015). Similarly, other researchers reported SOC and N decline over time during the 1990s in all the CR-LTE plots except in the FYM plots compared with GP (Rasmussen et al., 1998b; Rasmussen and Parton, 1994). The results from this and previous studies (Ghimire et al., 2015) suggest that even the application of FYM was not sufficient to maintain the SOC and soil total N compared with that in the GP plots, which indicated that long-term shifts in SOC have not reached steady state. However, long-term application of FYM and PV resulted in less SOC and soil N losses compared with the other treatments of CR-LTE. Thus, we refute our first hypothesis for N and C in soil that inorganic N application increases or maintains SOC and N in soil compared to FYM and PV application.

We did not observe significant differences in SOC and soil N as a function of inorganic N application, which contradicts earlier report by Rasmussen et al. (1998b). According to the latter study, SOC increased with the application of inorganic N because of its positive effect on the amount of crop residue produced. However, the results from this study agree with the results from other reports (Rasmussen and Parton, 1994; Ghimire et al., 2015). The plausible reason for unresponsive SOC and soil N to inorganic N application could be due to a rapid decomposition of crop residue in N applied plots compared with the one in the plots without N application. The high amount of N in the crop residue enhanced residue decomposition when incorporated into the soil (Rasmussen and Parton, 1994; Rasmussen et al., 1998a). As a result, crop residue contribution was insufficient to significantly impact SOC and soil N in the SB45, SB90, NB45, NB90, SB and NB plots (Rasmussen et al.,1998a). Even the SOC and N in FB plots (the most nutrient loss-prone plots of the CR-LTE) were comparable with SOC and N in the inorganic N applied plots in most of the studied year and depths (except in 1995 in 0-10 cm depth and in 10-20 cm depth in 2015). Hence, the results support our second hypothesis regarding SOC and soil N; that application of inorganic N in residues burned plots increases or maintains SOC and soil N compared to no burn plots with inorganic N application.

Mehlich III extractable phosphorus (P) and potassium (K) in soil

The concentration of K was significantly higher in the FYM plots than the rest of the CR-LTE plots (Table S2.4). In the 0-20 cm soil depth, the K increased in the FYM plots compared to the other CR-LTE plots and GP after 84 years of CR-LTE (Fig. 2.1C). The FYM and PV plots received more K with the addition of organic matter (OM) than the rest of the plots, but K concentrations were significantly higher only in FYM plots than other plots (Table S2.4). The results support our first hypothesis regarding extractable K and pea vines treatment because PV plots had comparable extractable K with that of inorganic N applied plots. The FYM plots had 33% more K in the top 20 cm soil than K in the same soil depth in GP. The increased concentration of K by the addition of FYM had been reported by earlier studies (Bhattacharyya et al., 2008; Singh et al., 2010). Since most nutrients come from the mineralization of OM, the addition of OM could have maintained or increased extractable K in FYM compared to CR-LTE plots.

The concentration of P in FYM plots was significantly higher at the 0-10 and 10-20 cm soil depths than in the rest of the CR-LTE plots in all the studied years (Table S2.5). In 2015, P was 62% higher in FYM in the top 20 cm soil depth than in GP (Fig. 2.1D). This refute our first hypothesis for extractable P that inorganic N application increases or maintains P in soil compared to FYM application. However, the hypothesis is supported when compared to PV plots because extractable P was comparable between PV and inorganic N applied plots. The most probable reason for greater extractable P in FYM plots than rest of the CR-LTE plots could be due to the addition of significant amount of P with the manure application in the FYM plots. Generally, when manure application is based on N requirement by crop, P and K would be over applied (Antoniadis et al., 2015). Another reason for increased P in FYM plots could be due to the decreased P adsorption to mineral surfaces and improved microbial population with manure addition, which enhances releasing of readily available P (Ohno and Erich, 1997). Overall, the concentration of soil extractable P at all the studied depths was in the following order: FYM > GP > PV> NB90, with the other treatments being between PV and NB90 (Table S2.5).

Soil total Sulfur (S) and Mehlich III extractable magnesium (Mg)

Among CR-LTE plots, FYM had higher S than the other plots in all studied depths except in the 30-60 cm depth in 2015 (Fig. 2.2A and B). The result supports our first hypothesis regarding S in soil, that inorganic N applied plots increase or maintain S compared to that of PV plots, because plots that received inorganic N maintained S with that of PV plots. Greater S under FYM treatment is plausible because S is an integral part of OM and apparently, FYM plots received more organic matter than the other plots. All CR-LTE treatments were comparable for S at 30-60 cm depth (Fig. 2.2A and B). However, GP had markedly greater S than FYM in all studied depths (Fig. 2.2A and B). The soil total S concentrations in GP were greater than these of FYM by 73%, 65%, 66%, and 73% in 0-10, 10-20, 20-30, and 30-60 cm depths respectively.

In the 0-10 cm soil depth, extractable Mg was greater in FYM and PV plots than in the SB45, SB90, NB45, and NB90 plots, which refute our first hypothesis regarding extractable Mg. The hypothesis assumed inorganic N application increases or maintains extractable Mg compared to FYM and PV. The higher amount of extractable Mg in FYM and PV plots could be attributed to the addition of OM through manure and pea vines that directly contributes to the soil Mg. However, the extractable Mg in FYM plot was markedly lower than that in the GP plot (Fig 2.2C). Higher K in FYM plots than in GP plots could be a factor for lower Mg in FYM plots than in GP plots. Magnesium concentration in soil decreases with higher soil K because of the competition between these ions for exchange sites, with K having the larger molecular size than Mg and can be easily displaced by K (Hovland and Caldwell, 1960). The displaced Mg move to the lower soil profile and so, this mechanism could be attributed to the higher concentration of Mg in 30-60 cm soil depth than in top soils (Fig. 2.2C and D).

Soil pH

After 84 years of WW-F rotation, FYM, FB, and SB plots maintained soil pH similar to that in GP in the top 10 cm soil depth (Fig. 2.3A and B). In fact, pH was slightly higher in the

FYM than in GP at all the studied depths except 30-60 cm depth (Fig. 2.3A and B). The addition of FYM replenishes the soil with basic cations and can maintain soil pH. The soil pH was significantly lower in the NB90 and SB90 than in the FYM, PV, FB, SB, NB45, and SB45 at top 20 cm soil depth. Greater acidity was observed in 10-20 cm soil depth in NB90 and SB90 plots than in other studied soil depths which could be attributed to the fertilizer placement (Fig. 2.3A and B).

The second hypothesis of this study was that SB45 or SB90 increases or maintains the concentration of macronutrients and pH in soil compared to NB45 or NB90. We did not observe differences in macronutrients and pH in soil between residue burn and no burn plots (excluding FYM and PV plots). Hence, we accept our second hypothesis. The benefits of residues burned and no burn over each other may have balanced their benefits and negated the differences between them. Perhaps the more favorable seedbed temperature and less insect/disease incident environment in burned plots during germination than in no burn plots may have offset the loss of nutrients to the atmosphere caused by burning and maintained the comparability in soil macronutrients and pH between spring residue burn plots and no burn plots. Another reason for similar impact of residue burning on soil nutrients could be due to no differences in C:N ratio between residue burn plots and no burn plots (Table S2.6). This is in line with an earlier study (Rasmussen and Parton, 1994). Carbon to N ratio is the prime factor which determines the fate of OM decomposition rate, nutrient immobilization, and nutrient release.

This study did not show significant differences in the concentration of SOC and N in the 30-60 cm soil depth among CR-LTE plots (Table S2.2 and S2.3). We found greater extractable P and K in the 30-60 cm soil depth under FYM treatment than under the rest of the CR-LTE treatments at the same depth (Table S2.4 and S2.5). However, no differences in extractable P and K were observed between SB45 or SB90 plots and NB45 or NB90 plots. The results support the third hypothesis of this study that residue burn plots with N application have similar soil N, SOC, extractable P, and extractable K compared to no burn plots with N application at all the studied soil depths.

Total concentration of nutrients in wheat grain and straw

There were main and interaction effects of year and treatments on the nutrient accumulation in wheat grain and straw (Table S2.7). In wheat grain, significant treatment effects were observed for tissue total concentrations of C, P, K, Ca, and Mg. Total concentration of C in wheat straw was affected by the treatment. Only the significant effects are discussed below.

Wheat tissue nitrogen (N) and sulfur (S): Nitrogen and sulfur are two most important nutrients for wheat grain and straw because the concentration of N and S determines grain and straw quality. Higher grain N was found in the plots under NB90 treatment compared with plots without inorganic N application (FB, SB, and NB), while N in grain in NB90 plots was comparable to that in FYM plots (Table S2.8). The NB90 plots had similar grain N under SB45 and SB90 treatment in 2015 (Table S2.8). Hence, we accept our fourth and fifth hypothesis with respect to grain N. The fourth hypothesis was that inorganic N application increases or maintains grain N compared with that of FYM and PV plots, while our fifth hypothesis was SB45 or SB90 increases or maintains N in grain compared to NB45 or NB90 over time. In this study, grain N linearly increased in 20 years (Fig. 2.4A), which could possibly be due to the lower amount of rainfall during the 2015 growing season compared with the rainfall in 2005, which was lower compared with the rainfall in 1995 (Fig. S2.1). According to Robinson et al. (1979), water stress increases nitrogen in grain.

The concentration of S in grain was noticeably higher in FYM plots in all the studied years than the one in the rest of the CR-LTE plots and increased linearly from 1995 to 2015 (Fig. 2.4B and Table S2.7). In fact, only FYM plots had S above the measurements threshold level and hence, rejects our fourth hypothesis for S in grain. Wheat grain has a higher pearling index and decreased dough elasticity when grain S is below the threshold level, which is not a desired trait for the marketable grain (Naeem, 2008). Grain S of 1.2 mg S g^{-1} is considered as the minimum threshold limits for S deficiency in wheat (Zhao et al., 1999). Furthermore, N:S ratio plays a key role in determining the threshold of grain S for acceptable wheat grain quality.

*Wheat tissue carbon (C) and phosphorus (P)***:** Carbon concentration in wheat grain was affected by treatments and was greater in the SB45, SB90, NB45, NB90 than in FB and SB (Table 2.1). The accumulation of N in grain has positive correlation with C in the grain (Barillot et al., 2016), and SB45, SB90, NB45, NB90 plots had greater N than in FB and SB plots. This could be the reason for greater concentrations of C in the N applied plots than the plots without N application. Regarding C in the straw, FYM plots had highest concentration of C among the CR-LTE plots (Table 2.1) suggesting the more pronounced effect of organic N (manure) on C in straw than inorganic N.

The P in grain under the FYM (3.21 g kg^{-1}) treatment was significantly higher than that under the rest of the treatments (Table 2.1). Nitrogen application decreased grain P in both the spring burn and in no burn plots (Table 2.1) which could be due to the low soil pH in the inorganic N applied plots. Wang et al. (2016) reported higher P in manure treated soil and subsequently higher P uptake by wheat in FYM treatment. The results from this study agree with the preceding report, as FYM had highest soil P and the highest grain P.

Wheat tissue total cations (K, Ca, and Mg): Organic and inorganic amendments affected the concentration of K, Ca, and Mg in grain (Table 2.1). The FYM plots had highest concentration of K, Ca, and Mg and decreased in inorganic N treatment plots (Table 2.1). The results indicate that inorganic N affected the absorption of cations, possibly, by the competition of NH_4^+ (URAN) with K, Ca, and Mg (cations) in the exchange sites and also due to the decreased soil pH. Consequently, low concentration of K, Ca, and Mg were observed under inorganic N applied plots. The decreased availability of cations in soil solution were reflected in the grain with low cations accumulation in inorganic N applied plots. There were no differences in K, Ca, and Mg in grain between residue burn plots and no burn plots (Table 2.1). Hence, we reject our fourth hypothesis and accept the fifth hypothesis for K, Ca, and M in wheat great.

The following inferences can be made from the results of this study:

a) Inorganic N application does not increase soil and tissue macronutrients compared to FYM over time and cannot replace FYM application. However, PV application can be replaced by inorganic N application and vice-versa.

b) Excluding FYM and PV plots, spring burning of plant residues and no burn treatments have similar impact on soil available and tissue total macronutrients over time under WW-F rotation in the drylands of the PNW.

c) Desirable lower protein content of soft white winter wheat can be obtained by spring burning of residues rather than no burning of residues. The NB90 plots had 12% (2.07% N*5.8) protein in grain whereas the SB45 and SB90 (9.4 % protein) plots maintained the optimum protein content for soft white winter wheat, which is 9-10%.

d) The soil acidification increases over time by the application of inorganic N whether the application was on residue burned or residue not burned plots.

e) The macronutrients do not stratify in the 0-30 cm soil depth under conventional tillage.

Conclusions

This study allowed to determine the long-term impacts of the inorganic N application, manure, and pea vines, in a residue incorporated (either burned or unburned) long-term plots. The results indicated that the application of pea vines can be replaced by the application of inorganic N, but manure application is irreplaceable by inorganic N application in the WW-F cropping system and is necessary to curb the macronutrient decline over time. In addition to the application of inorganic N, soil must be replenished periodically with the application of other macronutrients also to maintain healthy soil ecosystem so that FYM can be replaced. Despite having similar effects on soil macronutrient from both the residue burn and no burn treatments, avoiding residue burning may be preferable option based on the impact of residue burning on air quality. Nonetheless, residue burning can be a better management practice to manage residue, disease, weed, and to increase soil temperature in some field conditions compared with no burning. The fall burning of residue could be detrimental in the inland PNW; farming in most areas is performed on 8 to 30% slopes (some slopes as steep as 45%) and soils in such slopes can be vulnerable to erosion in the absence of cover for a prolonged period. Burning of residue could also result in erosion-induced nutrient loss over time. Future studies on physical properties and microbial activities in soils of CR-LTE plots may be needed to offer robust guidance in formulating farming strategies and to quantify other aspects of residue burning such as effects on overall soil health.

Acknowledgments

This research was supported by the Oregon State University startup funds awarded to Dr. Valtcho D. Jeliazkov (Zheljazkov). We thank Mr. Karl Rhinhart and his crews for their help with the field soil sampling. We also thank Dr. YanPing Qian and Ms. Shannon Andrews for their valuable help with the laboratory work. We gratefully acknowledge Paul Rasmussen (retired) and coworkers for collecting and archiving the soil and tissue samples of the long-term experiments, and Chris Rogers (retired) and Mr. Joseph St. Claire at USDA Agricultural Research Service (Columbia Plateau Conservation Research Center, Adams, OR) for the CNS analyses of the soil and tissue samples.

Appendix A. Supplementary data

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Table 2. 1 Mean concentration of significantly affected nutrients in the wheat grain after 84 years in the crop residue long-term experiment (CR-LTE), Pendleton, OR.

	<-----------------------------Grain (g kg^{-1}) --------------------------->					Straw (g kg^{-1})
Treatment	Carbon	Phosphorus	Potassium	Calcium`	Magnesium	Carbon
NB[1]	442 ab	2.78 b	3.84 ab	0.34 a	1.07 ab	425 ab
NB45	442 a	2.51 d	3.41 c	0.29 bc	1.03 bc	426 ab
NB90	442 a	2.54 d	3.25 c	0.29 bc	1.03 bc	424 b
FB	440 c	2.75 bc	3.85 ab	0.34 ab	1.08 ab	427 ab
SB	441 bc	2.74 bc	3.77 b	0.33 a	1.05 bc	424 b
SB45	443 a	2.42 d	3.33 c	0.28 c	1.00 c	424 b
SB90	442 a	2.59 cd	3.21 c	0.29 bc	1.05 bc	425 ab
PV	441 ab	2.73 bc	3.67 b	0.31 b	1.05 bc	426 ab
FYM	442 ab	3.21 a	4.00 a	0.35 a	1.12 a	431 a

Note: Means sharing the same letter within the columns are not significantly different at 0.05 probability level.

[1] NB= No burn, SB= spring burn, FB= fall burn, FYM= farmyard manure, and PV= pea vine. 0, 45, 90 accompanied by NB, SB, and FB represents rates of N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively.

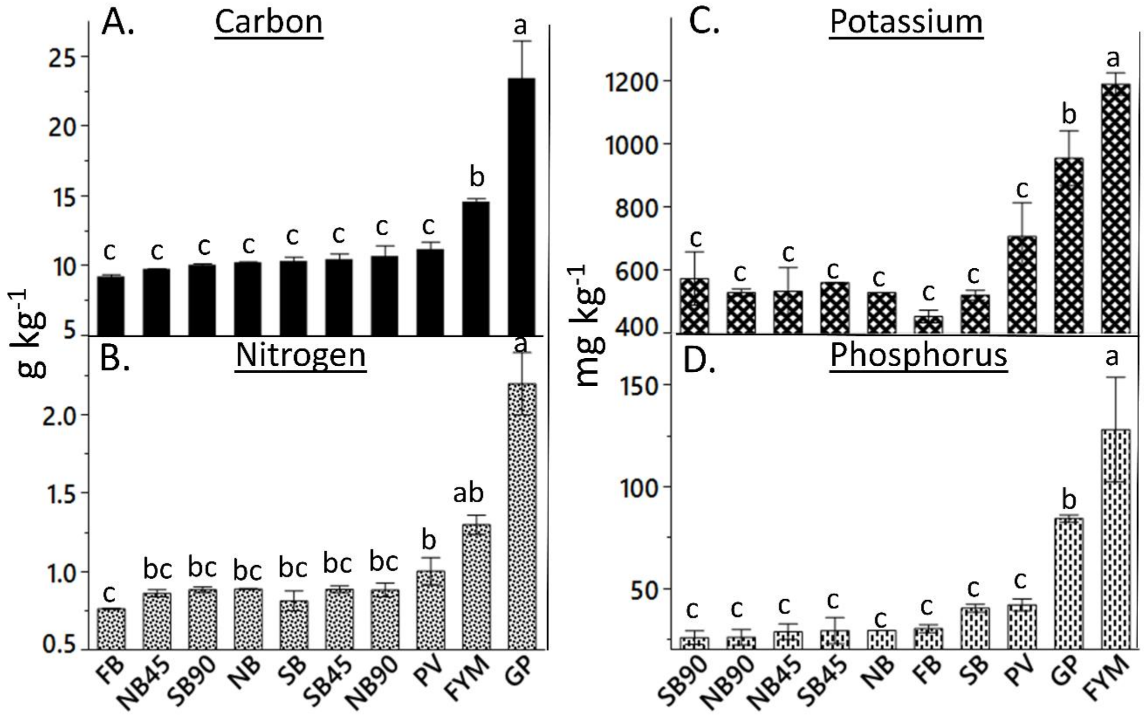

Fig. 2. 1 The effect of 84 years of residue management methods on soil nutrients in upper 10 cm soil surface. **A**. Concentration of carbon (Soil organic C), **B.** Concentration of nitrogen (Total N), **C.** Concentration of potassium (Mehlich III extractable K), and **D.** Concentration of phosphorus (Mehlich III extractable P).

FB = Fall burn; GP = Grass pasture; FYM =Farmyard manure; PV = Pea vine; NB= No burn; SB= Spring burn; and 45 and 90 after NB and SB represents the rates (kg ha^{-1}) of inorganic N applications in respective treatments.

Means sharing the same letter are not significantly different at the 0.05 probability level.

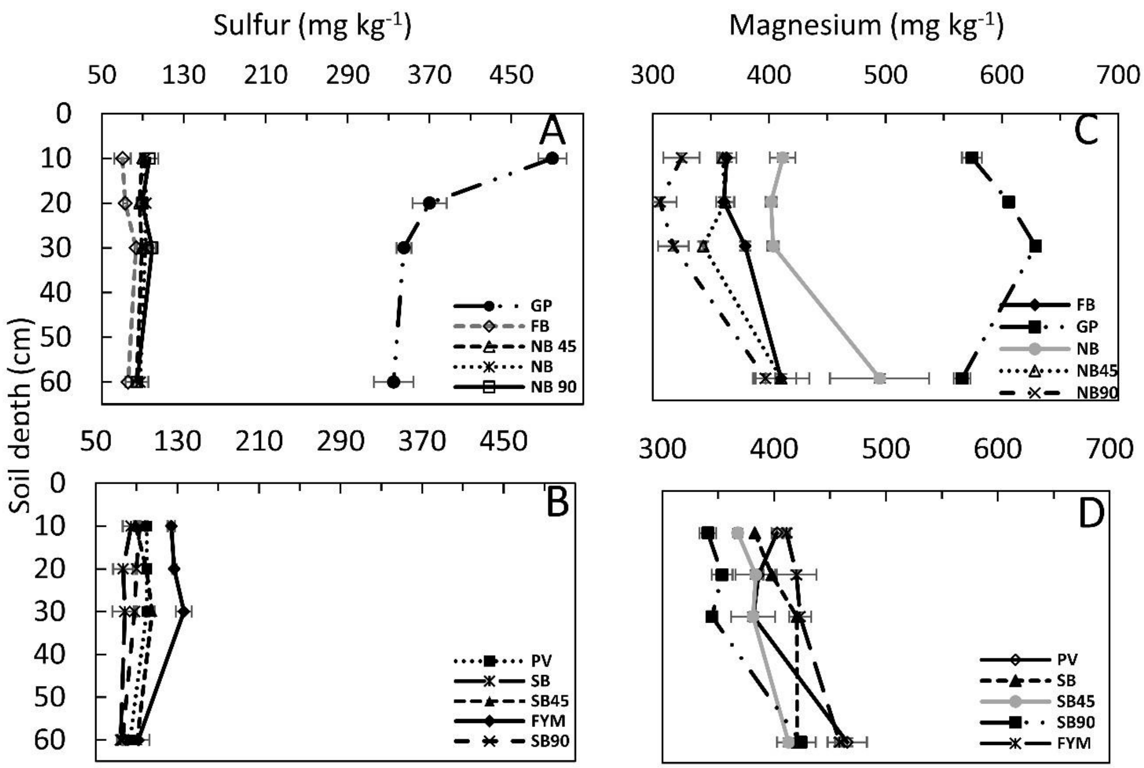

Fig. 2. 2 Soil depth function of total S in 2015 in (A) GP, FB, NB45, NB, and NB90 plots, (B) PV, FYM, SB, SB45, and SB90 plots. Soil depth function of Mehlich III extractable Mg in 2015 in (C) FB, GP, NB, NB45, and NB90 plots and (D) PV, SB, SB45, SB90, and FYM.

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.

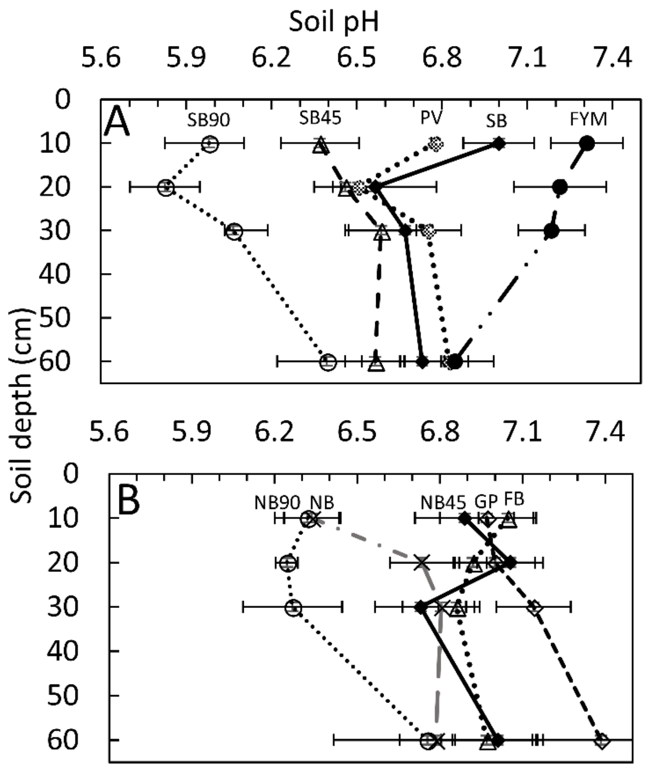

Fig. 2. 3 Soil pH depth function as affected by the different agricultural practices of CR-LTE and GP in 2015.FB = Fall burn; GP = Grass pasture; FYM =Farmyard manure; PV = Pea vine; NB= No burn; SB= Spring burn; and 45 and 90 after NB and SB represents the rates (kg ha^{-1}) of inorganic N applications in respective treatments.

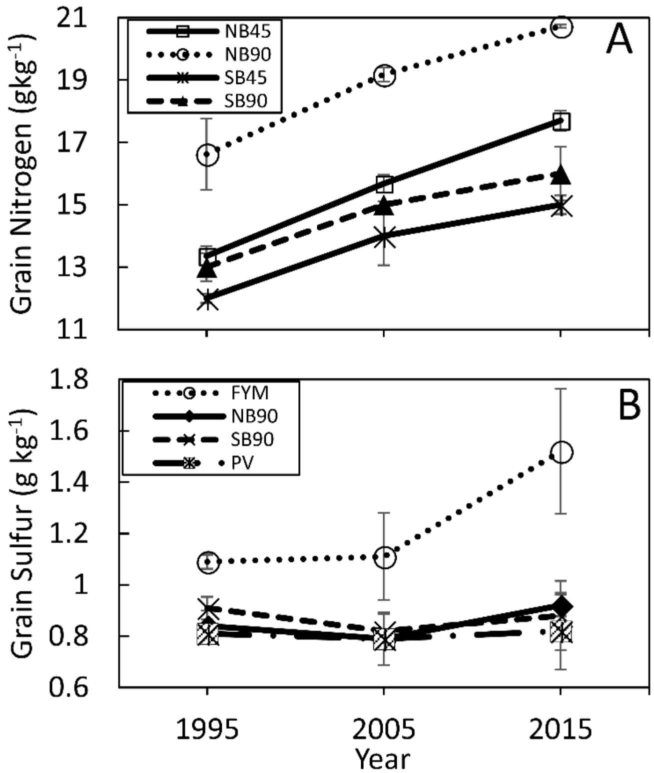

Fig. 2. 4 Effect of N rates on grain N over time (A) and effect of organic amendments and N on grain S over time (B).

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.

Table S2. 1 ANOVA table of the main and interaction effects of year, treatment (Trt) and depth on the concentration of soil total N, soil C, soil total S, extractable P, K, Ca, Mg, soil C:N ratio and pH in the crop residue long term experiment.

Source of variation	**N**	**C**	**S**	**P**	**K**	**Ca**	**Mg**	**C:N**	**pH**
Year	0.08	0.05	0.10	0.56	0.06	0.12	0.08	0.07	0.09
Trt	<0.01	<0.01	<0.01	<0.01	<0.01	0.14	<0.01	<0.01	<0.01
Year*Trt	<0.01	<0.01	0.42	<0.01	0.10	0.45	0.76	<0.01	0.93
Depth	<0.01	<0.01	<0.01	<0.01	<0.01	**<0.01**	<0.01	<0.01	<0.01
Year*Depth	<0.01	<0.01	0.15	0.16	<0.01	0.09	**<0.01**	<0.01	**<0.01**
Trt*Depth	<0.01	<0.01	**<0.01**	<0.01	<0.01	0.18	**<0.01**	<0.01	**<0.01**
Year*Trt*Depth	**<0.01**	**<0.01**	0.25	**<0.01**	**0.02**	0.84	0.99	**<0.01**	0.46

Note: Significant effects that require multiple means comparison are shown in bold.

Table S2. 2 Mean concentration of soil organic carbon (g C kg^{-1}) obtained from the 120 combinations of treatment, year and depth after 84 years in the crop residue long-term experiment (CR-LTE), Pendleton, OR.

Depth (cm)	Treatment FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
1995										
0-10	D[2] 10.15 a[3]	A 23.80 a	B 16.81 a	CD 11.23 a	CD 11.45 a	CD 12.09 a	C 13.09 a	CD 11.26 a	CD 12.31 a	CD 11.95 a
10-20	B 10.40 a	A 14.40 bc	A 15.42 ab	B 11.50 a	B 11.25 a	B 12.19 a	B 12.34 a	B 11.51 a	B 11.54 ab	B 11.59 a
20-30	A 8.99 ab	A 9.77 de	A 9.10 d	A 9.76 ab	A 8.71 abc	A 9.02 bc	A 9.45 bc	A 9.15 ab	A 9.46 bc	A 9.31 ab
30-60	AB 6.68 bc	A 8.47 e	AB 6.81 de	AB 6.44 c	AB 6.96 bcd	B 5.41 d	AB 6.71 d	AB 6.99 bc	AB 6.52d	AB 6.34 c
2005										
0-10	C 9.40 a	A 16.50 b	AB 14.18 abc	C 11.08 a	C 10.87 a	C 11.27 ab	BC 11.95 ab	C 10.80 a	C 10.93 ab	C 11.33 a
10-20	B 8.92 ab	AB 9.95de	A 12.11 c	B 9.36 ab	AB 9.67 ab	AB 10.06 ab	AB 10.83 ab	AB 9.55 ab	AB 9.86 ab	AB 9.45 ab
20-30	AB 7.79 abc	AB 8.42 e	AB 7.79de	AB 7.47 bc	B 6.69 cd	A 9.77 abc	AB 8.21 cd	AB 7.27 bc	B 6.92 cd	AB 7.28 bc
30-60	A 5.99 c	NA[4]	A 6.27e	A 6.01 c	A 5.87 d	A 7.82 cd	A 6.79 cd	A 6.06 c	A 5.87d	A 5.96 c
2015										
0-10	C 9.19 ab	A 25.45 a	B 14.56 abc	C 10.22 a	C 9.72 ab	C 10.67 ab	C 11.15 ab	C 10.29 a	C 10.43 ab	C 10.04 a
10-20	C 9.52 a	A 16.47 b	B 13.16 bc	C 10.01 ab	BC 10.60 a	C 10.43 ab	BC 11.64 ab	C 10.44 a	C 10.26 ab	C 9.75 ab
20-30	C 8.71 abc	AB 12.40 cd	A 13.98 bc	C 9.04 ab	BC 10.53 a	BC 10.73ab	AB 11.83 ab	BC 10.33 a	BC 10.35 ab	BC 9.87 ab
30-60	B 6.14 c	A 12.35 cd	B 6.96 de	B 6.43 c	B 7.28 bcd	B 7.50 cd	B 5.46 d	B 6.18 c	B 6.64 d	B 5.92 c

[1] 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] Upper case letters show comparison of the 10 treatments within each year and depth, and [3] lower-case letters show comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

[4] NA = not available.

Table S2. 3 Mean concentration of soil total nitrogen (g N kg^{-1}) obtained from the 120 combinations of treatment, year and depth after 84 years in the crop residue long-term experiment (CR-LTE), Pendleton, OR.

Depth					Treatment					
(cm)	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
1995										
0-10	D[2] 0.72 a[3]	A 2.30 a	B 1.37 a	CD 0.88 ab	C 0.92 ab	C 0.95 a	C 1.01 a	CD 0.86 ab	C 0.93 a	C 0.95 a
10-20	C 0.76 a	A 1.45 c	A 1.31 a	BC 0.92 a	B 0.95 a	B 0.97 a	B 1.03 a	BC 0.89 a	BC 0.95 a	B 0.98 a
20-30	B 0.85 a	A 1.07 ef	AB 0.91 cd	AB 0.92 a	AB 0.92 ab	AB 0.89 ab	AB 0.93 abc	AB 0.88 a	AB 0.89 ab	AB 0.88 ab
30-60	B 0.69 a	A 0.95 f	B 0.73 d	B 0.71 bc	B 0.73 bc	AB 0.76 abc	AB 0.77 cd	AB 0.76 ab	B 0.72 b	B 0.74 bc
2005										
0-10	D 0.75 a	A 1.65 b	B 1.18 ab	CD 0.92 a	CD 0.92 ab	CD 0.92 a	C 0.97 abc	CD 0.83 ab	CD 0.85 ab	CD 0.92 ab
10-20	C 0.77 a	A 1.22 de	AB 1.09 bc	C 0.85 abc	C 0.87 abc	BC 0.88 ab	BC 0.94 abc	C 0.87 a	C 0.88 ab	C 0.84 abc
20-30	B 0.75 a	A 1.05 ef	AB 0.85 d	B 0.78 abc	B 0.74 bc	B 0.83 abc	B 0.82 bcd	B 0.80 ab	B 0.77 ab	B 0.79 abc
30-60	A 0.70 a	NA[4]	A 0.72 d	A 0.66 c	A 0.68 c	A 0.67 c	A 0.73 d	A 0.67 b	A 0.68 b	A 0.68 c
2015										
0-10	C 0.76 a	A 2.41 a	A 1.30 a	BC 0.89 ab	BC 0.86 abc	BC 0.88 ab	AB 1.00 ab	BC 0.81 ab	BC 0.89 ab	BC 0.88 ab
10-20	D 0.69 a	A 1.67 b	B 1.20 ab	CD 0.85 abc	C 0.92 ab	C 0.91 a	C 0.97 abc	CD 0.78 ab	C 0.88 ab	CD 0.86 abc
20-30	C 0.74 a	A 1.30 cd	A 1.25 ab	BC 0.83 abc	BC 0.91 ab	BC 0.94 a	B 1.04 a	C 0.79 ab	BC 0.88 ab	BC 0.85 abc
30-60	B 0.67 a	A 1.35 cd	B 0.76 d	B 0.68 bc	B 0.71 c	B 0.71 bc	B 0.68 d	B 0.70 ab	B 0.73 b	B 0.71 bc

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.
[4] NA = not available.

Table S2. 4 Mean concentration of extractable potassium (mg K kg^{-1}) obtained from the 120 combinations of treatment, year and depth after 84 years in the crop residue long-term experiment (CR-LTE), Pendleton, OR.

Depth (cm)	FB[1]	GP	FYM	NB	NB45	Treatment NB90	PV	SB	SB45	SB90
1995										
0-10	C[2] 533 a[3]	B 760 abc	A 1237 ab	BC 589 a	BC 632 a	BC 568 ab	B 791 a	BC 651 a	C 532 a	BC 652 a
10-20	B 566 a	B 626 c	A 1341 a	B 569 a	B 594 a	B 633 a	B 741 a	B 668 a	B 575 a	B 635 a
20-30	B 525 a	B 552 c	A 1072 bc	B 559 a	B 564 ab	B 595 a	B 757 a	B 598 ab	B 550 a	B 594 ab
30-60	B 442 a	AB 535 c	A 735 de	B 407 a	B 463 ab	B 456 ab	AB 629 abc	B 478 ab	B 424 a	B 407 b
2005										
0-10	C 431 a	AB 713 bc	A 862 cd	BC 518 a	BC 486 ab	BC 530 ab	BC 566 abc	C 478 ab	BC 578 a	BC 531 ab
10-20	B 455 a	B 553 c	A 793 d	B 510 a	B 489 ab	B 514 ab	B 549 abc	B 485 ab	B 516 a	B 530 ab
20-30	B 438 a	AB 549 c	A 697 de	B 403 a	B 429 ab	AB 470 ab	AB 476 bc	B 432 ab	AB 486 a	AB 468 ab
30-60	B 349 a	A 671 bc	A 520 e	B 396 a	B 353 b	B 354 b	A 435 c	B 386 b	B 366 a	B 375 b
2015										
0-10	C 452 a	B 957 a	A 1190 ab	C 528 a	C 533 ab	C 528 ab	C 707 a	C 520 ab	C 560 a	C 573 ab
10-20	C 480 a	B 871 ab	A 1253 ab	C 479 a	C 554 ab	C 523 ab	BC 687 ab	C 539 ab	C 590 a	C 607 a
20-30	C 476 a	BC 695 bc	A 1240 ab	BC 542 a	BC 539 ab	BC 565 ab	B 744 a	BC 569 ab	BC 545 a	BC 597 ab
30-60	C 436 a	AB 682 bc	A 843 cd	BC 525 a	C 417 ab	C 424 ab	BC 566 abc	C 434 ab	BC 491 a	C 442 ab

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

Table S2. 5 Mean concentration of soil extractable phosphorous (mg P kg^{-1}) obtained from the 120 combinations of treatment, year and depth after 84 years in the crop residue long-term experiment (CR-LTE), Pendleton, OR.

Depth					Treatment					
(cm)	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
1995										
0-10	B[2] 35.7 a[3]	A 97.6 a	A 83.6 b	B 28.4 a	B 29.4 a	B 28.1 a	B 41.4 abc	B 43.9 ab	B 24.3 b	B 29.1 a
10-20	C 38.4 a	B 71.6 bc	A 94.4 b	C 30.9 a	C 29.2 a	C 28.6 a	C 44.0 abc	C 46.8 ab	C 26.9 ab	C 29.2 a
20-30	C 35.6 a	AB 58.8 bcd	A 79.1 bc	BC 42.9 a	C 33.4 a	C 34.9 a	AB 57.8 a	BC 54.5 a	C 34.3 ab	C 34.6 a
30-60	AB 35.2 a	A 52.5 cde	A 54.1 d	AB 39.6 a	AB 38.3 a	B 24.3 a	A 54.9 ab	AB 37.7 ab	B 22.3 b	B 31.0 a
2005										
0-10	B 38.4 a	A 80.2 ab	A 72.5 bc	B 38.3 a	B 33.3 a	B 31.3 a	B 34.5 bc	B 36.8 ab	B 35.5 ab	B 35.6 a
10-20	B 38.3 a	B 39.3 de	A 75.6 bc	B 41.0 a	B 35.2 a	B 34.3 a	B 36.0 bc	B 37.3 ab	B 38.3 ab	B 36.2 a
20-30	B 36.0 a	AB 46.5 de	A 60.3 cd	B 32.5 a	B 34.9 a	B 26.9 a	B 34.8 bc	B 32.6 b	AB 48.2 a	AB 40.9 a
30-60	AB 29.7 a	AB 34.5 e	A 51.0 d	AB 31.3 a	AB 33.4 a	B 23.8 a	AB 30.6 c	AB 33.0 b	AB 40.3 ab	AB 39.4 a
2015										
0-10	C 30.3 a	B 93.6 a	A 128.2 a	C 29.4 a	C 28.8 a	C 26.0 a	C 41.9 abc	C 40.3 ab	C 29.3 ab	C 25.8 a
10-20	C 30.6 a	B 76.7 ab	A 147.1 a	C 30.4 a	C 28.4 a	C 24.0 a	C 34.9 bc	C 36.5 ab	C 23.0 b	C 22.0 a
20-30	BC 30.7 a	B 48.0 de	A 141.8 a	BC 31.5 a	C 24.5 a	C 25.6 a	BC 35.3 bc	BC 39.7 ab	C 23.1 b	BC 26.8 a
30-60	CD 25.7 a	AB 50.6 cde	A 61.9 cd	BCD 35.7 a	CD 27.6 a	D 17.0 a	BC 39.9 abc	BCD 36.5 ab	CD 25.0 b	CD 25.2 a

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

Table S2. 6 Mean soil C:N ratio obtained from the 120 combinations of Treatment, Year and Depth after 84 years in the crop residue long-term experiment (CR-LTE).

Depth					Treatment					
(cm)	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
1995										
0-10	A[2] 14.18 a[3]	C 10.34 ab	B 12.22 a	AB 12.73 a	B 12.40 a	AB 12.73 ab	AB 12.88 a	AB 13.06 a	AB 13.30 a	B 12.58 a
10-20	A 13.71 ab	C 9.93 ab	B 11.78 a	AB 12.48 a	B 11.81 a	AB 12.55 ab	B 11.90 ab	AB 12.89 a	AB 12.19 abc	B 11.87 ab
20-30	A 10.64 def	B 9.09 bc	AB 10.07 bc	A 10.66 bcd	AB 9.52 c	AB 10.04 c	AB 10.21 cd	AB 10.33 bc	A 10.57 cd	AB 10.54 bc
30-60	A 9.71 fg	A 8.79 bc	A 9.27 c	A 9.06 e	A 9.54 c	B 7.16 d	AB 8.60 e	A 8.98 c	A 9.05 de	AB 8.56 d
2005										
0-10	A 12.51 bc	B 10.00 ab	A 11.96 a	A 12.05 ab	A 11.81 a	A 12.27 ab	A 12.34 ab	A 12.94 a	A 12.91 ab	A 12.37 a
10-20	A 11.58 cde	B 8.11 c	A 11.01 ab	A 11.03 bc	A 11.12 ab	A 11.35 bc	A 11.54 abc	A 10.95 b	A 11.22 c	A 11.32 ab
20-30	B 10.34 ef	C 8.01 c	BC 9.13 c	B 9.61 cde	BC 9.06 c	A 13.69 a	B 10.01 cd	BC 9.07 c	BC 8.94 e	BC 9.26 cd
30-60	A 8.62 g	A 7.67 c	A 8.65 c	A 9.07 e	A 8.60 c	NA[4]	A 9.26 de	A 9.02 c	A 8.64 e	A 8.78 d
2015										
0-10	AB 12.06 cd	B 10.70 a	AB 11.22 ab	AB 11.50 ab	AB 11.30 ab	AB 12.08 b	B 11.16 bc	A 12.72 a	AB 11.75 bc	AB 11.35 ab
10-20	A 13.91 ab	D 9.83 ab	CD 11.05 ab	BC 11.81 ab	C 11.53 ab	C 11.46 bc	BC 11.98 ab	AB 13.37 a	C 11.59 bc	C 11.31 ab
20-30	AB 11.75 cd	C 9.51 ab	B 11.13 ab	BC 10.84 bc	B 11.57 ab	B 11.44 bc	B 11.50 abc	A 13.16 a	AB 11.73 bc	AB 11.64 ab
30-60	AB 9.16 fg	AB 9.14 bc	AB 9.08 c	AB 9.35 de	A 10.22 bc	A 10.40 c	B 8.08 e	B 8.61 c	AB 9.13 de	B 8.33 d

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

[4] NA = not available.

Table S2. 7 ANOVA table of the main and interaction effects of year and treatment on the accumulation of N, C, S, P, K, Ca, and Mg in the grain and straw of wheat in the crop residue long term experiment. Significant effects that require multiple means comparison are shown in bold.

Source of variation	Nitrogen	Carbon	Sulfur	Phosphorous	Potassium	Calcium	Magnesium
				Wheat Grain			
Year	0.01	0.61	0.04	0.14	0.97	0.11	0.15
Treatment	<0.01	**<0.01**	<0.01	**<0.01**	**<0.01**	**<0.01**	**0.02**
Year*Treatment	**<0.01**	0.27	**0.02**	0.27	0.52	0.52	0.48
				Wheat Straw			
Year	0.05	0.10	0.02	0.90	0.18	0.39	0.02
Treatment	<0.01	**0.01**	<0.01	0.36	<0.01	0.02	<0.01
Year*Treatment	**<0.01**	0.18	**<0.01**	**0.02**	**<0.01**	**<0.01**	**<0.01**

Table S2. 8 Multiple comparisons of the concentration of N and S accumulation in the wheat grain as affected by the interaction of treatment and year.

Year	NB[1]	NB45	NB90	FB	SB	SB45	SB90	PV	FYM
					N (g kg^{-1})				
1995	B[2] 12.26 d[2]	C 13.35 bcd	B 16.62 a	B 11.46 d	B 12.01 d	A 13.36 bcd	A 13.36 bcd	B 15.06 abc	A 15.34 ab
2005	B 12.38 de	B 15.67 b	AB 19.17 a	B 11.87 e	B 11.92 e	A 15.01 bc	A 15.01 bc	A 18.81 a	A 14.15 bcd
2015	A 13.32 c	A 17.70 abc	A 20.72 ab	A 13.40 c	A 13.49 c	A 16.19 bc	A 16.19 bc	A 18.50 abc	A 21.75 a
					S (g kg^{-1})				
1995	A 0.64 ab	A 0.92 ab	A 0.84 ab	A 0.95 ab	B 0.91 ab	A 0.91 ab	A 0.91 ab	A 0.81 b	B 1.09 a
2005	A 0.95 abc	A 0.81 bc	A 0.79 bc	A 0.93 abc	B 0.74 c	A 0.82 bc	A 0.82 bc	A 0.79 bc	B 1.11 a
2015	A 1.01 bc	A 1.01 bc	A 0.92 bc	A 1.04 bc	A 1.06 bc	A 0.88 c	A 0.88 c	A 0.82 c	A 1.52 a

[1] NB= No burn, SB= spring burn, FB= fall burn, FYM= farmyard manure, and PV= pea vine. 0, 45, 90 accompanied by NB, SB, and FB represents rates of N applied at 0 kg ha-1, 45 kg ha-1, and 90 kg ha-1, respectively.

Means sharing the same letter are not significantly different at the 0.05 probability level.

[2] Upper case letters are comparison of the 3 years within each of the 9 treatments (for year*treatment interaction) and lower-case letters are comparison of the 9 treatments within each of the 3 years (for year*treatment interaction).

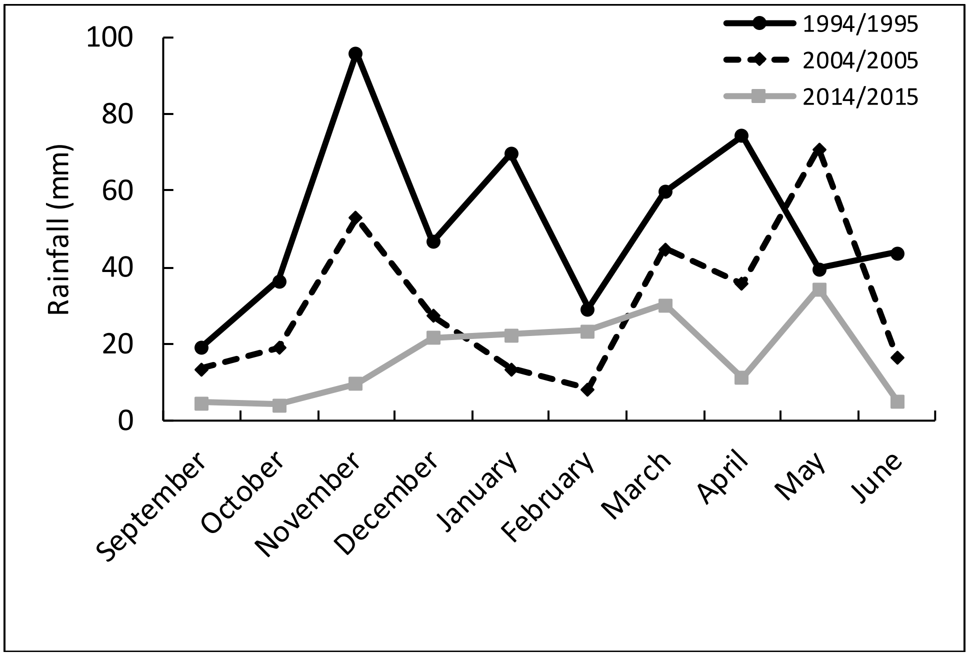

Fig. S2. 1 Rainfall in winter wheat growing season in Pendleton, Oregon.

Chapter 3

MICRONUTRIENTS IN THE SOIL AND WHEAT GRAIN AND STRAW: IMPACT OF 84 YEARS OF ORGANIC OR SYNTHETIC FERTILIZATION AND CROP RESIDUE MANAGEMENT

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Abstract

Crop residues are an important source of plant essential nutrients. However, the information on the effect of crop residue on micronutrients in soil and wheat over time is limited. A long-term agroecosystem experiment (84 years old) was assessed to determine the impact of different methods of crop residue management on plant essential micronutrients over time in the dryland winter wheat (*Triticum aestivum* L.) -fallow rotation (WW-F) under conventional tillage. The treatments were: no N application with residue burning in fall (FB), spring burn (SB) and no residue burn (NB), 45kg N ha^{-1} with SB (SB45) and NB (NB45), 90 kg N ha^{-1} with SB (SB90) and NB (NB90), pea vines (PV), farmyard manure (FYM), and a nearby undisturbed grass pasture (GP). This study used wheat grain, straw, and soil samples from 1995, 2005, and 2015, to determine tissue total and soil Mehlich III extractable Mn, Cu, B, Fe, and Zn, and soil pH. After 84 years of the experiment, extractable Mn and B in the top 10 cm soil decreased in all plots, except in FYM and SB for B. The FYM plots had the highest extractable Mn (114 mg kg^{-1}) in the top 10 cm soil; however, it declined by 33% compared with Mn in the GP (171 mg kg^{-1}). Similarly, extractable Zn increased with FYM application and decreased with inorganic N in 2015 in the top10 cm soil, however, total Zn in grain increased with N application. The results suggest that (i) residue burn and no burn plots had similar impact on micronutrients in soil and (ii) application of inorganic N and FYM can be integrated to reduce the micronutrient loss from cultivation.

Keywords: Boron, Burning, Copper, Iron, Manganese, Residue, Zinc

Abbreviations: WW-F, dryland winter wheat fallow rotation; FYM – farmyard manure; SOC – soil organic carbon; GP – grass pasture plot; PV – pea vines.

Introduction

Sustainable food production system largely depends on the maintenance and management of soil fertility and thereby increasing the efficiency of output per unit of resource input (Saïdou, et al., 2004). Soil fertility is primarily related to the management of essential plant macronutrients and micronutrients. Micronutrients play important roles in plant development and growth; Zn is involved in the formation of auxins and chloroplasts, Mn has a role in photosynthesis and oxidation-reduction process, Fe is a structural component of cytochromes, perichrome, and leghemoglobin, Cu is a constituent of chlorophyll and protein metabolism and B plays a role in seed germination, and N metabolism (Prasad and Power, 1997).

Micronutrient deficiencies are a serious problem threatening food production worldwide (Jones et al., 2013). With the advent of high yielding and with high grain/straw ratio wheat varieties, micronutrients deficiency is not uncommon in wheat. Since the micronutrients concentrations in soil are relatively low, they need mobilization by roots and hence, high-yielding varieties may have lower micronutrients tissue accumulation than the low-yielding ones as the root biomass may not increase at the same rate as the aboveground biomass (Kirchmann et al., 2009). Micronutrients are important not only for improving crop yields and the sustainability of crop production, they are also important for human health and play significant role in controlling micronutrient induced malnutrition in humans (Li et al., 2010). For example, Zn deficiency affects over two billion people worldwide, and Fe deficiency contributes to about 800,000 deaths annually (Mayer et al., 2008). Although the micronutrients play important roles in agriculture and human nutrition, the knowledge on the effect of agricultural practices on micronutrient dynamics is limited. Thus, it is important to explore the long-term impacts of agricultural practices on micronutrients availability and their accumulation in widely consumed food crops.

Micronutrients in soil and crop are influenced by the cropping practices and fertilization (Wei et al., 2006). Cropping practices such as crop residue incorporation in soil result in an accumulation of micronutrients along with macronutrients (Prasad and Power, 1997). On the other hand, nutrients loss via volatilization occurs to some extent when crop residues are burned (Biederbeck et al.,1980; Daubenmire, 1968). Micronutrients are mostly added to the arable land through organic amendments such as manure and green manures, whereas micronutrients addition through commercial fertilizers is not well documented and in many instances is neglected (Li et al., 2010). Many studies have reported that farmyard manure (FYM) increase soil macronutrients availability (Li et al., 2007). However, excess FYM application can lead to Zn precipitation with PO_4^{2-}, $H_2PO_4^-$, or HPO_4^{2-} anions and thereby can decrease Zn mobility in soil (Li et al., 2007). The dynamics of micronutrient availability to crops shift with changes in pH, SOM, nutrient interactions, and nutrient response to long-term fertilization (Li et al., 2007). For example, high soil pH decreases Cu, Zn, and Fe availability due to precipitation (Li et al., 2010). In a long-term, SOM (Zhang et al., 2001) and different fertilization treatments (Li et al.,

2007) exert a significant impact on available micronutrients. For example, continuous application of ammonium fertilizers will decrease the soil pH, which in turn, will increase the availability of micronutrients, except molybdenum (Mo). Similarly, the organic materials added to the soil produce chelating agents such as phenols, phenolic acids etc., which can increase Fe and Mn availability. In contrast, SOM has little to no effect on Cu availability (Rui et al., 2004). Micronutrient availability is affected by the macronutrient application rates also (Rui et al., 2004). High N rate increased the concentration of available Cu, Zn, Fe, and Mn, while a shortage of potassium (K) increased the availability of the same nutrients (E et al., 2005). Morgounov et al. (2007) suggested that management of N fertilizer could affect grain micronutrient status as he found a strong positive relationship between Fe, Zn, and protein content in spring wheat. Xue et al. (2014) found increased micronutrients in grain and straw of maize by optimized N fertilizer application when compared to zero or lower N supply. In contrast, several researchers found that increasing N fertilization had little to no effect on grain micronutrients (Feil et al., 2005; Losak et al., 2011; Yu et al., 2011). These contrasting reports of N fertilization effects and FYM dual role in micronutrients availability make the role of inorganic N and FYM on micronutrient dynamics debatable. A long-term field study can provide helpful insights to micronutrients dynamics as a function of crop residue incorporation (burned vs unburned) with inorganic N or organic amendments (FYM and pea vine).

The Columbia Basin Agricultural Research Center (CBARC), situated in Adams, OR, has several long-term ongoing experiments under dryland environment. The Crop Residue experiment (CR-LTE) is one of the long-term agricultural experiment of CBARC, and can provide useful data on the effect of diverse types of wheat residue management on the micronutrients availability in soil and micronutrient accumulation in wheat grain and straw over time. The conceptual approach of our study consists of comparing the micronutrients of soil (in four depths: 0-10, 10-20, 20-30, and 30-60 cm) and wheat grain and straw samples from 1995, 2005, and 2015 among the CR-LTE plots, and to find a trend. In addition to the comparison between CR-LTE plots, micronutrient status of soil samples was compared with that of the soil samples from nearby undisturbed grass pasture (GP). This comparison may demonstrate nutrient changes in the soil after 84 years of cultivation. The objective of this study was to quantify the effect of different crop residue management methods on soil micronutrients availability and micronutrients accumulation in wheat grain and straw over time, and subsequently suggest a solution that can maintain and improve efficient nutrient cycling and resource base in dryland of Pacific Northwest (PNW) and possibly in other regions with similar environmental conditions.

The CR-LTE was established in 1931 with the hypothesis that the application of inorganic N could replace the use of FYM and PV and could also alleviate the detrimental effect of residue burning. It was assumed that the application of inorganic N will increase wheat biomass and when this biomass is returned to the soil, more nutrients would be released through the mineralization of increasing amount of organic matter. We tested the following to find whether the hypothesis assumed 84 years ago can still be accepted or not.

i. Inorganic N application (NB45, NB90, SB45 or SB90) increases or maintains the concentration of Mn, Zn, Cu, Fe, and B in soil over time compared with the application of FYM or PV.

ii. The spring residues burned plots with inorganic N application (SB45 or SB90) have greater or similar concentrations of Mn, Zn, Cu, Fe, and B in soil than no burn plots with inorganic N application (NB45 or NB90) over time.

iii. The concentrations of Mn, Zn, Cu, Fe, and B in wheat grain and straw are greater or similar in NB45, NB90, SB45 or SB90 plots to these in FYM and PV application plots.

iv. The concentrations of Mn, Zn, Cu, Fe, and B in wheat grain and straw are greater or similar in the SB45 or SB90 than these in the NB45 or NB90.

Materials and methods

Site descriptions and treatments

The CR-LTE was established at the Columbia Basin Agriculture Center (CBARC), 15 km northeast of Pendleton, OR (45°42' N, 118°36' W, elev. 438 m asl) on a well-drained Walla Walla silt loam soil. Annual precipitation averages 437 mm, with 90% of precipitation between November and June (Gollany 2016). The 81-year (1932-2012) maximum and minimum average annual temperatures were 17.4°C and 3.06°C respectively (CBARC, 2015). The soil contains 18% clay, 70% silt with pH 6.1- 7.0, and has a cation exchange capacity of 18 $cmol_c$ kg^{-1} in the upper 20 cm depth.

The study has an ordered block of two identical series (1400 and 1500) of nine treatments with two replications. Each series represents a wheat or a fallow phase of the WW-SF cropping system. This experiment does not have randomized treatments; however, extensive investigation of these soil samples and yield data has revealed no biases (Rasmussen and Parton, 1994). The individual plots are 11.6 m by 40.2 m and are offset by 1 year to collect wheat yield and biomass data annually. Since the establishment of these experiments, various wheat varieties have been grown. The wheat cultivars grown since 1992 were: Malcolm from 1992 to1995, Stephens from 1996 to 2005, and ORCF102 from 2006 to 2015.

The nine treatments of this experiment (CR-LTE) are: fall burning of wheat residue without inorganic N (FB); spring burning of wheat residue without inorganic N (SB), 45 kg ha^{-1} (SB45), and 90 kg ha^{-1} (SB90); no burning of wheat residue without inorganic N (NB0), 45 kg ha^{-1} (NB45) and 90 kg ha^{-1} (NB90); and no burning of wheat residue with manure (FYM); and pea vine (PV) incorporation. The results from these nine treatments of CR-LTE were compared with the near long-term (undisturbed since 1931) grassland pasture (GP) to determine the changes influenced by the management practices.

The organic amendments were applied just prior to plowing in the spring of the fallow year; manure (FYM), at a rate of 11.2 Mg ha^{-1} yr^{-1} (47.5% DM, 0.85 Mg C ha^{-1}, and 70 kg N ha^{-1} yr^{-1}), and pea vine (PV), at a rate of 1.12 Mg ha^{-1} yr^{-1} (87.8% DM, 0.41 Mg C ha^{-1} yr^{-1}, and 18.5 kg N ha^{-1} yr^{-1}). Urea-ammonium nitrate (UAN) was applied one week before seeding wheat in SB and NB treatments in October. The wheat stubbles after harvest were left undisturbed and burned in September for FB and in late March-early April for SB, SB45, and SB90. After the burning was complete, the soil in the FB was left undisturbed between burning and plowing for 195 days, while the soil in the SB was left undisturbed for 5 days (Rasmussen and Parton, 1994). Glyphosate is used to control growth in wheat stubble. After the residue burning and the addition of organic amendments, the field was moldboard-plowed 20 cm deep. Plots were seeded with wheat using a John Deere (JD 8300) drill at 90 kg ha^{-1} before 2002, while a Case IH 5300 disc drill has been used to plant wheat at 92 kg ha^{-1} thereafter (Ghimire et al., 2015).

Soil sampling and laboratory analysis

The soil cores from 1995, 2005, and 2015 were used in this study. We used archived soil from 0-10 cm, 10-20 cm, 20-30 cm, and 30- 60 cm soil depths and plant samples (wheat straw and grain) from 1995 and 2005. The soil and tissue samples from 2015 were collected in the summer of 2015. Truck-mounted Giddings Hydraulic Probe (Giddings Machine Company, Inc., Windsor, CO) and a steel sampling tube (internal diameter 3.6 cm) were used to sample the soil after the wheat harvest. The soil samples collected from north-central and south-central part of the plots were composited and used in our study. The soil cores were placed inside an oven at 105˚C for 24 hours. The oven-dried soils were pulverized using a vial rotator for four hours. The wheat grain and straw samples were collected from the center of the plot and were ground. The pulverized soils and ground grain and straw samples were then chemically analyzed for the available micronutrients. Mehlich III extraction method (Mehlich, 1984) was used in the Central Analytical Lab (CAL, Oregon State University) to determine the soil extractable micronutrients whereas the ground tissue samples were extracted by dry ash method (Isaac and Johnson, 1975). The extracts were run in an inductively coupled plasma-optical emissions spectroscopy (ICP-OES, Model #2100 DV, Waltham, Massachusetts, USA).

The CBARC station provided the soil pH data, which were measured in a 1:2 soil to 0.01M $CaCl_2$ solution using pH electrodes after 30 min equilibrium time.

Statistical analysis

The data from the grass pasture (GP) was included as one of the CR-LTE for statistical comparison in this study. Repeated measures analyses (RMA) of a split-plot design with two-blocks were conducted to determine the effect of the factors (Year, Treatment and Depth) on Mehlich III extractable Mn, Cu, Zn, B, and Fe in soil. Year (1995, 2005, 2015) was used as the whole plot factor, treatment (10 levels: GP, NB, SB45, SB90, NB45, NB90, FB0, SB0, FYM, and PV) as the subplot factor and responses were measured repeatedly in space at 4 soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm). For the total concentrations of Mn, Cu, Zn, B, and Fe in grain and straw, a split-plot design with two blocks was used; year (1995, 2005, 2015) was the whole-plot factor and treatment was the subplot factor. Residuals, as described in Montgomery (Montgomery, 2013), were used to verify the model assumptions (normal distribution and constant variance of the error terms) of each response. Multiple means comparisons were carried out for the significant effects (p-value < 0.05) by comparing the least squares means of the corresponding treatment combinations. Letter groupings were generated using a 5% level of significance.

Results and discussion

Over the 84 years of cultivation, Mehlich III extractable Mn, Cu, B, Zn, and pH in soil were influenced by residue management methods in CR-LTE. An ANOVA Table is presented in a supplementary file (Table S3.1). Due to a technical problem, we were not able to analyze Fe in the GP soil samples, however, Fe for CR-LTE samples was analyzed. Table S3.2, S3.3, and S3.4

had detailed depth, year, and treatment wise analysis (three- way interaction) report of Mehlich III Mn, B, and Zn in soil. Only significant results were discussed here.

The availability and uptake of micronutrients were largely determined by soil pH. Soil pH was significantly influenced by the treatments over the time frame chosen in this study in the 0-10 cm and 10-20 cm soil depths (Fig. S3.1). Plots with higher N rates application of inorganic fertilizer had lower soil pH than the rest of the CR-LTE plots, whereas FYM maintained soil pH over time compared with the soil pH of GP plots. In fact, after 84 years of cultivation, FYM plots had modestly higher soil pH than that in GP plots (Fig. S3.1).

Mehlich III extractable manganese (Mn) in soil

The concentration of Mn in top 10 cm soil decreased over time in all the CR-LTE plots (Fig. 3.1A-D). Among the CR-LTE plots, the concentration of Mn in the top10 cm soil depth was significantly higher in the FYM and PV plots in 2015 than in the same depth in the rest of the plots (Fig. 3.1A-D). Thus, we refute our first hypothesis for Mn that inorganic N application (NB45, NB90, SB45 or SB90) increases or maintains the concentration of Mn in soil over time compared to FYM and PV.

Despite greater Mn in the FYM plots than that in the rest of the CR-LTE plots, FYM (114 mg kg^{-1}) plots lost the available Mn (33%) in upper 10 cm soil compared to that of GP (171 mg kg^{-1}) after 84 years of CR-LTE (Fig. 3.1C). Undoubtedly, undisturbed GP has higher SOM and SOM supplies and promote the availability of most of the micronutrients (Gao et al., 2000; Wei et al., 2006). Significant positive correlation between SOM and micronutrients cation availability is well documented (Heredia et al., 2002; Panwar et al., 2010). The result from this study was somewhat similar to the 8-years study results obtained by Sanchez et al. (1983) who found decline in extractable Mn after clearing of the forest for cultivation. In 2015, FYM plots had markedly higher Mn in the top 10 cm soil depth than in the treatments that received inorganic N fertilizers (Fig. 3.1A-C). The higher amount of available Mn in FYM plots can be attributed to OM addition through FYM. Soil OM complexes Mn in soil and increases the mobility and availability of Mn (Srivastava and Gupta, 1996). Inorganic N fertilizer application may also increase the Mn availability, which may be due to the low pH resulting from the continuous use of inorganic N fertilizer; the solubility of Mn increases with the decrease in pH (Cheng and Ouellette, 1970). In contrast to this report, the results from this study showed lower Mn in the N fertilizer application plots. The plausible reason for low Mn in inorganic N applied plots in this study may be associated with the greater wheat yield and greater Mn removal in these plots compared with that in the other CR-LTE plots. There were no differences in Mn in soil between SB and NB plots. Hence, we accept our second hypothesis for Mn in soil that SB45 or SB90 have greater or similar concentrations of Mn in soil than NB45 or NB90 over time.

Mehlich III extractable boron (B) in soil

The extractable B in upper 10 cm soil consistently decreased over the 20 years' time in CR-LTE plots, except in the FYM and SB (Fig. 3.2A-D). After 84 years of CR-LTE, no differences between treatments were observed for B in the top 10 cm soil (Fig. 3.2A-D), however, the inorganic N applied plots had greater B in 1995 than B in the rest of the treatments (Table S3.3). Hence, we accept our first hypothesis for B in soil that that inorganic N application

(NB45, NB90, SB45 or SB90) increases or maintains the concentration of B in soil over time compared to FYM and PV. In 1995, B in the 0-10 and 10-20 cm soil depths was higher in the plots that received inorganic N fertilizer than B in the plots that received no inorganic N (Table S3.3). This can be attributed to the low pH in inorganic N applied plots, since B is more available in the acidic soil. However, apparently soil pH was not the only factor responsible for greater B in those plots; B should still have been greater in inorganic N applied plots than in other plots because soil pH was still lower in inorganic N applied plots compared to the rest of the CR-LTE plots (Fig. S3.1). Therefore, the results suggest that there were other factors that controled the B availability in soils. The observed results on B could be due to the depletion of B in soil because of the continuous removal of B with wheat harvest without replenishment. There were no differences in extractable B between SB and NB plots and hence, we accept second hypothesis that inorganic N application (SB45 or SB90) have greater or similar concentrations of B in soil than in NB plots with inorganic N application (NB45 or NB90) over time.

The role of SOM in B availability is not well understood. Several reports showed a positive relation of SOM to B availability, whereas others found negative relation between B availability and OM accumulation (Mahler et al., 1985). Despite having greater OM in GP plots (Rasmussen et al., 1998), in 1995, B in the top 10 cm soil was markedly lower in GP (0.17 mg kg^{-1}) than in the CR-LTE treatments (Table S3.3). In addition, B was below detection limits in the GP in all the studied soil depths, except for the 0-10 cm in 1995, 2005 and 2015 (Table S3.3). According to Srivastava and Gupta (1996), SOM tightly retains B, which is only released by microbial activities and that can be accounted for lower B found in GP and in organic amendments treatments of this study.

Mehlich III extractable zinc (Zn) in soil

The extractable Zn in the 0-10 cm soil depth was similar between the CR-LTE treatments in 1995 and 2005 (Table S3.4). However, in 2015, Zn was greater in the FYM than that in the other CR-LTE treatments at all the studied depths except for the 30-60 cm depth (Table S3.4). This suggest the effect of residue management has started to manifest. The observed change in extractable soil Zn refutes the first hypothesis for Zn in soil. The first hypothesis was that inorganic N application (NB45, NB90, SB45 or SB90) increases or maintains the concentration of Zn in soil over time compared to FYM and PV. In 2015 in the top 10 cm soil, the concentration of Zn declined with inorganic N application (Fig. 3.3A), possibly due to Zn precipitation by high concentration of soil phosphorus (P) in these plots (Robson and Pitman, 1983). Zinc availability did not decrease significantly in the CR-LTE plots after cultivation for 84 years (Table S3.4). These results agree with those by Sanchez et al. (1983) who reported relatively constant Zn in 8 years after cultivation in the rainforest of Peru. The extractable Zn was markedly higher in the GP plots than that under CR-LTE treatments in the 0-10 cm soil depth in 1995 and 2005 (Table S3.4), and was comparable to Zn in the FYM plots in 2015 (Fig. 3.3A). The formation of soluble complexes and poor retentions on the surface of SOM may be attributed to the greater extractable Zn in the GP plots (Randhawa and Broadbent, 1965).

Mehlich III extractable copper (Cu) in soil

Extractable Cu was significantly affected by the interaction of year and treatment (Table S3.5). In 1995, Cu was lower in the GP (2.68 mg kg^{-1}) than in the NB90 plots (4.02 mg kg^{-1}), in 2005 Cu was comparable among all CR-LTE treatments, and in 2015, Cu was lower in GP than the one in all CR-LTE plots when averaged over the soil depths (Table S3.5). This result corresponds to that of Fan et al. (2008) who reported increased Cu following a 160 years of cultivation. Copper strongly binds to both soluble and insoluble soil OM, however low molecular weight (<1000 MW) fractions of soluble organocomplexes of Cu like those in FYM and sewage sludges improve the availability of Cu in soils and plant uptake (Srivastava and Gupta, 1996). This could be the reason for low available Cu in the GP plots (average: 2.71 mg kg^{-1}) in this study and relatively higher Cu in the FYM plots (average: 3.21 mg kg^{-1}). In 2015 at 0-10 cm soil depth, except GP and NB, all plots had similar Cu (Fig. 3.3B) and hence accept our first and second hypothesis for Cu in soil. The hypotheses were: (i) inorganic N application (NB45, NB90, SB45 or SB90) increases or maintains the concentration of Cu in soil over time compared to FYM and PV, and (ii) the residues burned plots with inorganic N application (SB45 or SB90) have greater or similar concentrations of Cu in soil than no burn plots with inorganic N application (NB45 or NB90) over time.

Total micronutrient accumulation in wheat grain and straw

Over the 84 years, grain total Zn and Mn were affected by the treatments whereas no main effects of treatments were observed for total Zn and Mn in straw (Table S3.6).

The concentrations of Zn in grain were comparable among the FYM (15 mg kg^{-1}), SB90 (16 mg kg^{-1}), and NB90 (16 mg kg^{-1}) plots and were significantly higher than in the FB (12 mg kg^{-1}), SB (13 mg kg^{-1}), SB45 (12 mg kg^{-1}), NB (13 mg $kg^{-1)}$ (Fig. 3.4A). Hence, we accept our third hypothesis for Zn in grain that the concentration of Zn is similar or greater in inorganic N applied plots than in FYM or PV. This result suggests that higher N rates have a positive effect on Zn accumulation in wheat grain, which can be explained by the fact that low N availability in soil negatively affect the chelate levels and reduced chelates lead to the reduction of translocation of Zn to grain (Shi et al., 2010). According to Srivastava and Gupta (1996), Cu is mutually antagonistic with Zn and compete for the common career sites, and hence inhibits the uptake of Zn. The results from this study do not agree with the latter statement as higher availability of Cu in soil did not affect Zn accumulation in the grain. The possibility of this disagreement could be attributed to the increased OM production in higher rates of N fertilizer application and FYM plots compared to no N or lower N rates plots because OM can form simple complexes with Zn to increase its availability (Srivastava and Gupta, 1996).

The accumulation of Mn in wheat grain was influenced by the residue management methods in this study (Fig. 3.4B). The NB45 and NB90 plots had greater Mn in grain than FYM and PV plots and, hence, we accept our third hypothesis regarding Mn in grain that the concentration of Mn in grain is similar or greater in inorganic N applied plots than in FYM or PV plots. Svecnjak et al. (2013) reported greater Mn in wheat grain with increased N rates which is in line with our result. However, the mechanism involved in Mn uptake by N application are still not known. Also, the Mn in grain was significantly greater in NB plots with inorganic N compared to SB plots with inorganic N application (Fig. 3.4B). Grain total Mn was evidently greater in the NB45 (31 mg kg^{-1}) and NB90 (34 mg kg^{-1}) plots than in the SB45 (28 mg kg^{-1}) and SB90 (32 mg kg^{-1}) plots, respectively (Fig. 3.4B). Hence, we refute our fourth hypothesis for Mn in grain that concentration of Mn in grain is greater or similar in SB45 or SB90 than NB45 or NB90 plots.

Conclusions

This paper reports micronutrient dynamics for different treatments in four soil depths and in the wheat straw and grain over 20 years (1995, 2005, and 2015) for the CR-LTE plots and the changes after the cultivation since 1931. Overall, the results of this long-term study demonstrated that Mehlich III extractable Mn and B declined considerably whereas Mehlich III extractables Cu increased after the cultivation in 84 years compared to the GP. This study revealed that none of the CR-LTE treatments curbed the micronutrient (except Cu) decline over time. However, some micronutrients declined at lower rate with FYM and some with inorganic N application, suggesting that the combination of inorganic N with FYM could reduce the micronutrient decline over time. The low pH and increased OM could play important role in increasing micronutrients in soil and wheat in dryland WW-F cropping system.

Acknowledgments

This research was supported by the Oregon State University startup funds awarded to Dr. Valtcho D. Jeliazkov (Zheljazkov). We thank Mr. Karl Rhinhart and his crews for their help with the field soil sampling. Special thanks to Paul Rasmussen (retired) and coworkers for collecting and archiving long-term grass soil and plant samples.

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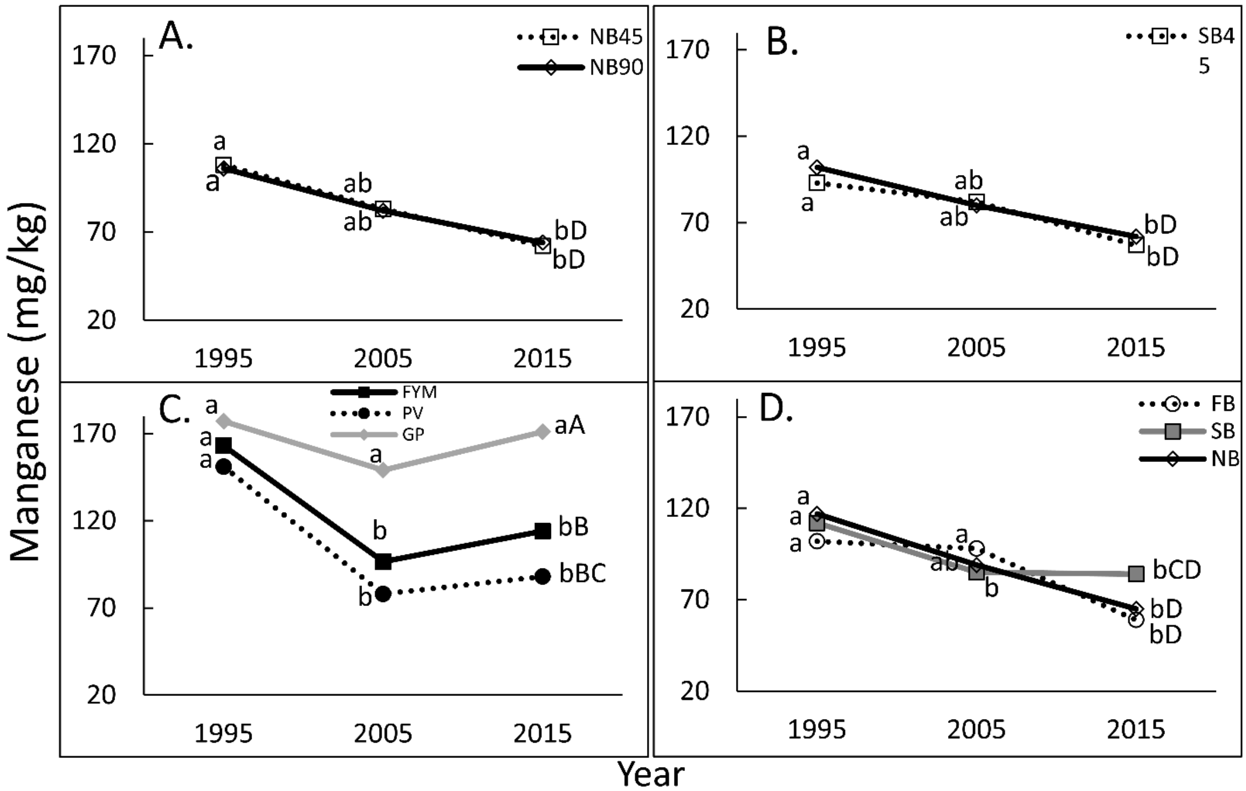

Fig. 3. 1 Mehlich III extractable manganese dynamics in upper 10 cm soil surface over 20 years in Crop Residue Long-term Experiment (CR-LTE), Adams, OR. **A.** No burn (NB) plots with 45 and 90 kg N ha^{-1} (NB45 and NB90); **B.** Spring burn (SB) plots with 45 and 90 kg N ha^{-1} (SB45 and SB90); **C.** Farm year manure (FYM), Pea vine (PV), and grass pasture (GP); and **D.** Fall burn (FB), SB and NB.

Lower-case letters compare three years for each treatment and upper-case letters compare among treatments (Fig. A-D) in 2015. Means sharing the same letter are not significantly different ($P \leq 0.05$).

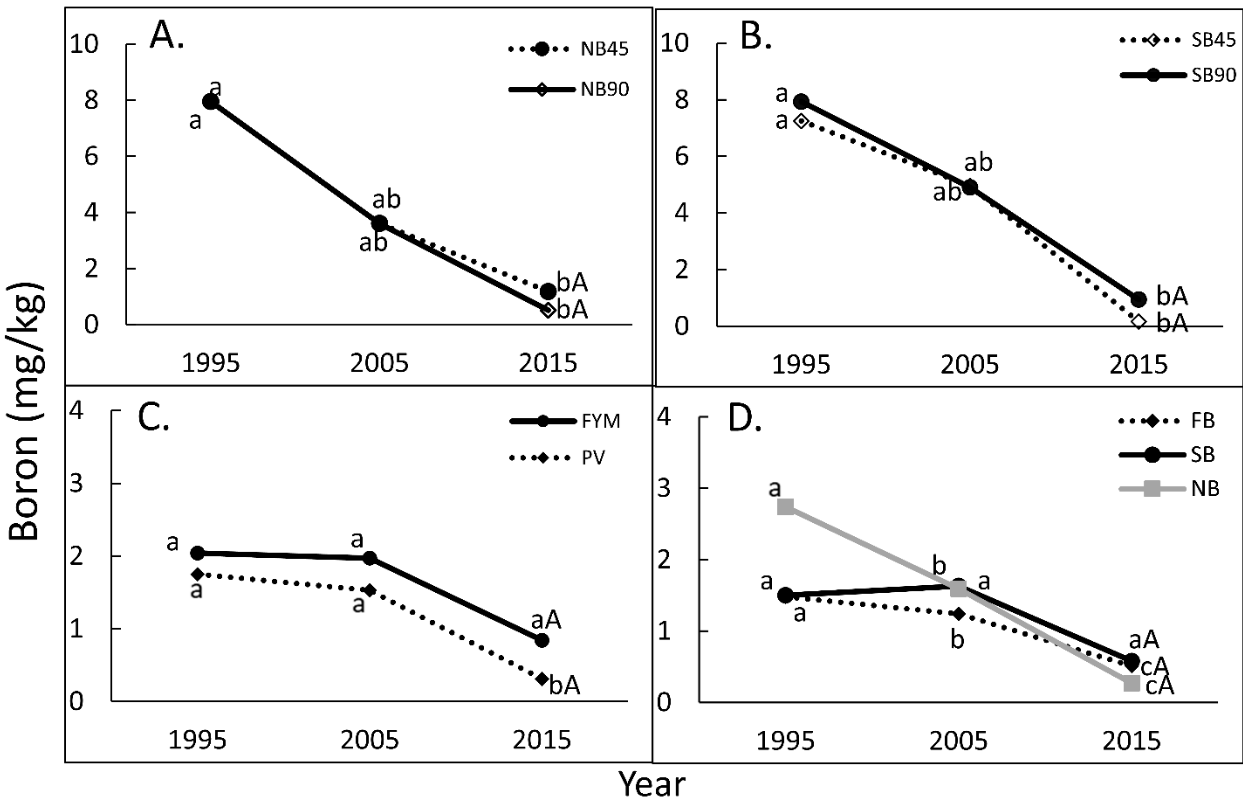

Fig. 3. 2 Mehlich III extractable boron dynamics in upper 10 cm soil surface over 20 years in Crop Residue Long-term Experiment (CR-LTE), Adams, OR. **A.** No burn (NB) plots with 45 and 90 kg N ha^{-1} (NB45 and NB90); **B.** Spring burn (SB) plots with 45 and 90 kg N ha^{-1} (SB45 and SB90); **C.** Farm year manure (FYM), Pea vine (PV), and grass pasture (GP); and **D.** Fall burn (FB), SB and NB.

Lower-case letters compare three years for each treatment and upper-case letters compare all treatments of CR-LTE in 2015. Means sharing the same letter are not significantly different ($P \leq 0.05$).

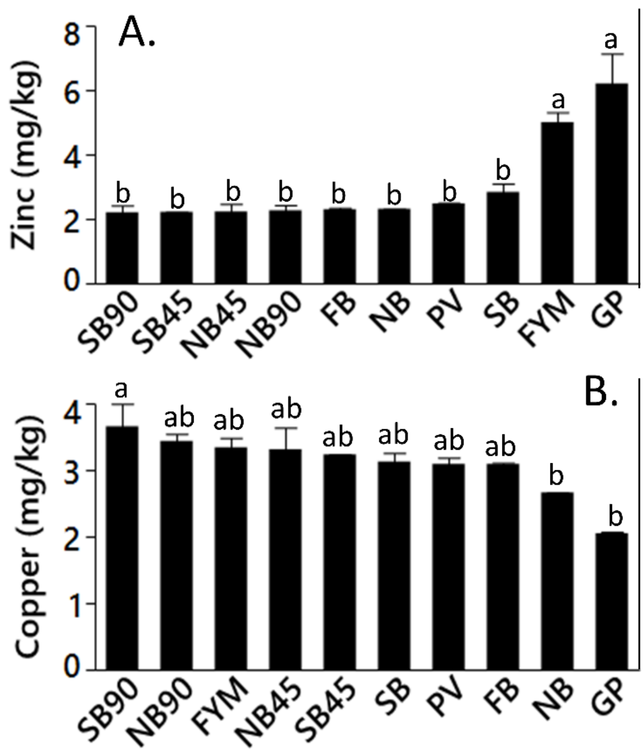

Fig. 3. 3 Mehlich III extractable zinc (**A.**) and copper (**B.**) dynamics in upper 10 cm soil surface after 84 years of Crop Residue Long-term Experiment (CR-LTE) in Adams, OR.

NB= No burn, SB= spring burn, FB= fall burn, GP= grass pasture, FYM= farmyard manure, and PV= pea vine. 0, 45, 90 accompanied by NB, SB, and FB represents rates of N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively.

Means sharing the same letter are not significantly different ($P \leq 0.05$).

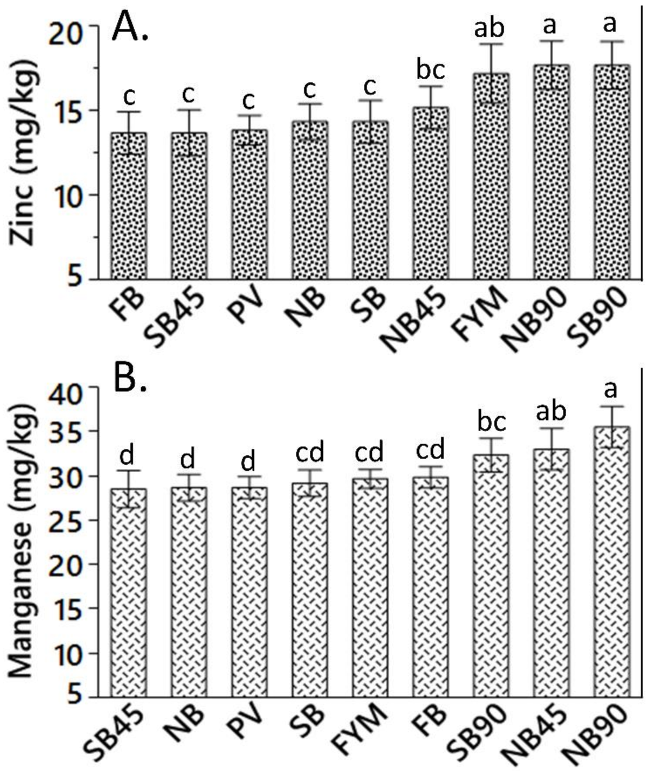

Fig. 3. 4 Total zinc (**A.**) and manganese (**B.**) dynamics in wheat grain after 84 years of Crop Residue Long-term Experiment (CR-LTE) in Adams, OR.

NB= No burn, SB= spring burn, FB= fall burn, FYM= farmyard manure, and PV= pea vine. 0, 45, 90 accompanied by NB, SB, and FB represents rates of N applied at 0 kg ha^{-1}, 45 kg ha^{-1}, and 90 kg ha^{-1}, respectively.

Means sharing the same letter are not significantly different ($P \leq 0.05$)

Table S3. 1 ANOVA table of the main and interaction effects of year, treatment (Trt) and depth on the concentration of Mehlich III extractable Manganese, Copper, Boron, Zinc, Iron, and pH in the crop residue long term experiment. Significant effects that require multiple means comparison are shown in bold.

Source of variation	**Manganese**	**Copper**	**Boron**	**Zinc**	**Iron**	**pH**
Year	0.07	0.53	0.02	0.07	<0.01	0.09
Trt	<0.01	<0.01	<0.01	<0.01	0.32	<0.01
Year*Trt	<0.01	**0.04**	0.02	<0.01	0.32	0.93
Depth	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Year*Depth	<0.01	**<0.01**	<0.01	<0.01	**<0.01**	**<0.01**
Trt*Depth	<0.01	0.80	<0.01	<0.01	0.51	**<0.01**
Year*Trt*Depth	**0.03**	0.72	**<0.01**	**<0.01**	0.10	0.46

Table S3. 2 Mean concentration of Mehlich III extractable manganese (mg Mn kg^{-1}) obtained from the 120 combinations of Treatment, Year and Depth (cm) after 84 years of the crop residue long-term experiment (CR-LTE).

Depth	Treatment									
(cm)	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
	mg Mn kg^{-1} soil									
1995										
0-10	B[2] 102 ab[3]	A 177 a	A 163 a	B 117 a	B 108 a	B 106 ab	A 151 a	B 112 a	B 93 a	B 102 a
10-20	CD 108 a	A 149 a	AB 144 a	CD 112 a	D 103 a	CD 109 a	ABC 133 a	BCD 115 a	D 96 a	D 98 a
20-30	ABC 78 bc	AB 90 bcd	ABC 80 cd	ABC 78 b	BC 75 bc	BC 71 cd	A 101 b	AB 85 b	C 64 bcd	BC 66 bc
30-60	ABC 67 cd	A 90 bcd	AB 77 cd	C 56 cd	BC 64 bcd	BC 61 cde	AB 83 bc	BC 62 cde	C 48 de	C 49 cd
2005										
0-10	B 98 ab	A 149 a	B 97 bc	B 89 ab	B 83 ab	B 82 bc	B 79 bc	B 85 b	B 82 ab	B 80 ab
10-20	A 61 cde	A 80 cd	A 80 cd	A 72 bc	A 69 bc	A 72 cd	A 72 cd	A 74 bcd	A 71 abc	A 69 bc
20-30	AB 54 de	A 68 d	AB 54 e	B 45 d	AB 48 de	B 38 f	AB 55 de	AB 48 e	B 45 de	AB 48 cd
30-60	B 46 e	A 84 cd	B 56 e	B 53 cd	B 59 cde	B 45 ef	B 47 e	B 56 de	B 55 cd	B 49 cd
2015										
0-10	E 59 cde	A 171 a	B 114 b	DE 65 bc	DE 62 bcd	DE 64 cde	BC 88 bc	CD 84 bc	E 57 cd	DE 61 bc
10-20	CD 69 cd	A 162 a	B 99 bc	CD 71 bc	D 56 cde	D 57 def	B 95 b	BC 84 b	D 55 cde	D 53 cd
20-30	D 57 cde	A 115 b	AB 106 b	CD 69 bc	CD 64 bcd	D 60 cde	AB 93 bc	BC 87 b	D 50 cde	D 53 cd
30-60	CD 42 e	A 106 bc	B 70 de	CD 41 d	CD 42 e	CD 42 f	BC 56 de	BCD 52 e	D 37 e	D 37 d

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

Table S3. 3 Mean concentration of Mehlich III extractable boron (mg B kg^{-1}) in soil obtained from the 120 combinations of Treatment, Year and Depth (cm) after 84 years of the crop residue long-term experiment (CR-LTE).

Depth	Treatment									
(cm)	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
	------ mg B kg^{-1} of soil ------									
1995										
0-10	C[2] 1.5 a[3]	D 0.2 a	BC 2.1 a	BC 2.7 a	A 8.0 a	A 7.9 a	C 1.8 ab	C 1.5 a	A 7.3 a	A 7.9 a
10-20	B 1.5 a	C 0.00 a	B 2.2 a	AB 3.7 a	A 8.0 a	A 8.0 a	B 1.7 ab	B 1.6 a	A 6.9 a	A 8.0 a
20-30	BC 1.5 a	D 0.00 a	BC 2.0 a	AB 3.8 a	A 8.1 a	BC 2.0 bc	BC 1.9 a	BC 1.8 a	A 7.1 a	A 8.1 a
30-60	BC 1.8 a	D 0.00 a	BC 2.0 a	AB 3.9 a	A 8.4 a	BC 2.0 bc	B 2.1 a	BC 1.8 a	A 7.9 a	A 8.3 a
2005										
0-10	B 1.2 a	C 0.00 a	AB 2.0 a	AB 1.6 a	AB 3.6 ab	AB 3.6 ab	B 1.5 ab	B 1.6 a	A 5.0 a	A 4.9 ab
10-20	B 1.4 a	B 0.00 a	B 2.0 a	A 2.5 a	A 3.5 ab	A 3.2 ab	B 1.5 ab	B 1.6 a	A 4.6 a	A 4.7 ab
20-30	B 1.4 a	B 0.00 a	AB 1.6 a	AB 2.5 a	AB 3.6 ab	AB 3.3 ab	AB 1.5 ab	AB 1.6 a	A 5.0 a	A 4.7 ab
30-60	AB 1.3 a	B 0.00 a	AB 1.7 a	AB 2.6 a	AB 3.4 ab	AB 3.3 ab	AB 1.4 ab	AB 1.6 a	A 4.7 a	AB 2.4 bc
2015										
0-10	B 0.5 a	C 0.00 a	B 0.8 a	B 0.3 b	B 1.2 b	B 0.5 c	B 0.3 b	B 0.6 a	B 0.2 b	B 0.9 c
10-20	B 0.5 a	C 0.00 a	B 0.9 a	B 0.2 b	B 1.2 b	B 0.5 c	B 0.4 ab	B 0.5 a	B 0.2 b	B 0.8 c
20-30	A 0.5 a	B 0.00 a	A 0.6 a	A 0.2 b	A 1.1 b	A 0.6 c	A 0.4 ab	A 0.7 a	A 0.2 b	A 1.5 bc
30-60	A 0.6 a	B 0.00 a	A 0.5 a	A 0.3 b	A 1.4 b	A 0.6 c	A 0.3 b	A 0.8 a	A 0.9 b	A 1.2 c

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

Table S3. 4 Mean concentration of Mehlich III extractable zinc (mg Zn kg^{-1}) in soil obtained from the 120 combinations of Treatment, Year and Depth (cm) after 84 years of the crop residue long-term experiment (CR-LTE).

Depth (cm)	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
	--- mg Zn kg^{-1} soil ---									
1995										
0-10	B[2] 1.5 bc[3]	A 6.1 a	B 2.3 b	B 2.5 ab	B 1.2 bcd	B 1.2 cd	B 1.7 abcd	AB2.6 abc	B 1.3 abc	B 1.3 abcd
10-20	B 1.7 bc	AB 3.0 ab	A 2.8 b	B 1.5 bc	B 1.1 bcd	B 1.2 bcd	B 1.6 bcde	AB 2.1 abcd	B 1.4 ab	B 1.4 abc
20-30	AB 0.7 cd	C 0.7 cd	AB 0.9 c	A 1.5 bc	AB 0.6 cd	AB 0.7 d	AB 0.7 ef	AB 0.9 efg	AB 0.7 bc	AB 0.6 cd
30-60	A 0.3 d	C 0.4 d	A 0.5 c	A 0.8 c	A 0.3 d	A 0.6 d	A 0.3 f	A 0.3 g	A 0.4 c	A 0.3 d
2005										
0-10	B 1.3 bc	A 6.2 a	B 2.6 b	B 1.6 abc	B 1.4 abc	B 1.4 abcd	B 1.7 abcd	B 1.9 bcde	B 1.5 ab	B 1.4 abc
10-20	A 1.3 cd	B 0.4 d	A 1.9 b	A 1.3 c	A 1.2 bcd	A 1.2 bcd	A 1.5 cde	A 1.5 def	A 1.2 abc	A 1.2 bcd
20-30	A 1.0 cd	A 0.9 cd	A 0.8 c	A 0.7 c	A 0.8 cd	A 0.7 d	A 0.7 def	A 0.7 fg	A 0.7 bc	A 0.9 cd
30-60	AB 0.7 cd	AB 1.1 cd	AB 0.9 c	AB 0.8 c	A 1.4 abc	AB 0.8 d	AB 0.8 def	AB 0.9 efg	AB 0.8 bc	AB 0.8 cd
2015										
0-10	B 2.3 ab	A 6.4 a	A 5.0 a	B 2.3 ab	B 2.2 a	B 2.3 a	B 2.5 abc	B 2.8 ab	B 2.2 a	B 2.2 a
10-20	B 2.8 a	A 5.0 ab	A 4.6 a	B 2.6 a	B 2.3 a	B 2.0 ab	B 2.7 a	B 3.0 a	B 2.2 a	B 2.1 ab
20-30	B 2.2 ab	B 1.5 cd	A 5.1 a	B 2.4 ab	B 2.1 ab	B 2.2 ab	B 2.6 ab	B 2.9 a	B 2.1 a	B 2.2 a
30-60	A 1.7 bc	A 1.4 cd	A 2.0 b	A 1.6 bc	A 1.8 ab	A 1.9 abc	A 1.7 bcd	A 1.6 cdef	A 1.9 a	A 2.1 ab

[1] 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] Upper case letters are comparison of the 10 treatments within each year and depth, and [3] lower-case letters are comparison of the 12 combinations of year and depth within each of the 10 treatments. Means sharing the same letter are not significantly different.

Table S3. 5 Mean concentration of Mehlich III extractable copper (mg Cu kg^{-1}) obtained from the 30 combinations of Treatment and Year after 84 years of the crop residue long-term experiment (CR-LTE).

	Treatment									
	FB[1]	GP	FYM	NB	NB45	NB90	PV	SB	SB45	SB90
	---------- mg Cu kg^{-1} ----------									
Year										
1995	AB[2] 3.5 a[3]	BC 2.7 a	BC 3.0 a	BC 3.0 a	AB 3.4 a	A 4.0 a	AB 3.3 a	AB 3.4 a	C 2.5 b	BC 2.9 a
2005	A 3.3 a	A 2.9 a	A 3.3 a	A 3.5 a	A 3.8 a	A 3.3 a	A 3.3 a	A 3.5 a	A 3.6 a	A 3.5 a
2015	AB 3.3 a	B 2.6 a	A 3.5 a	AB 3.1 a	AB 2.9 a	AB 3.3 a	AB 3.2 a	A 3.6 a	AB 3.1 a	AB 3.4 a

[1] 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] For each variable, upper case letters are comparison of the 10 treatments within each year for copper, and [3] lower-case letters are comparison of the 3 years for copper within each of the 10 treatments. Means sharing the same letter are not significantly different.

Table S3. 6 ANOVA table of the main and interaction effects of year and treatment on the accumulation of Mn, Cu, B, Fe, and Zn in the grain and straw of wheat in the crop residue long-term experiment. Significant effects that require multiple means comparison are shown in bold.

Source of variation	Manganese	Copper	Boron	Zinc	Iron
			Wheat Grain		
Treatment	**<0.01**	0.12	ND[1]	**<0.01**	<0.01
Year	**0.05**	**0.02**	ND	**0.03**	0.13
Treatment*Year	0.76	0.08	ND	0.99	**0.01**
			Wheat straw		
Treatment	<0.01	0.07	0.06	0.71	0.01
Year	0.02	**0.02**	0.16	**0.04**	**<0.01**
Treatment*Year	**<0.01**	0.26	0.19	0.71	0.11

[1]ND: Not detected

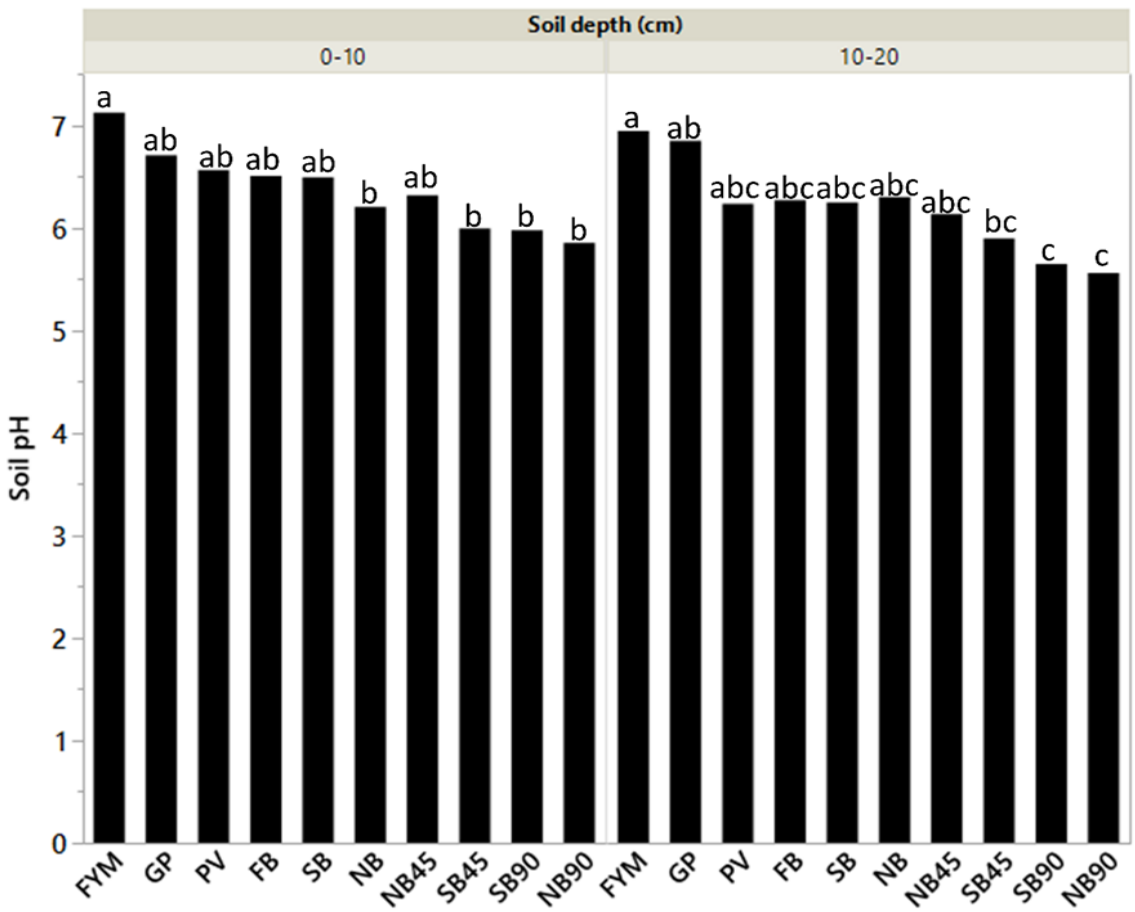

Fig. S3. 1 Effect of residue management on soil pH over time in 0-10 cm and 10-20 cm soil depths.

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. Means sharing the same letter are not significantly different within each soil depth.

Chapter 4

LONG-TERM IMPACTS OF TILLAGE AND NITROGEN FERTILIZATION ON SOIL AND WHEAT MACRONUTRIENTS OF DRYLAND WINTER WHEAT- FALLOW ROTATION

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Abstract

The insights gained on the effects of long-term soil management practices, such as tillage and nitrogen (N) fertilization on soil fertility are crucial for the fine-tuning of existing and the development of future sustainable cropping systems. The objectives of this study were to quantify the long-term effects of tillage systems and N fertilization rates on macronutrients in soil and tissue (wheat grain and straw) under 75 years of winter wheat (*Triticum aestivum* L.)-fallow (WW-F) cropping system. The experiment had three tillage systems (disk plow, DP; sweep, SW; and moldboard plow, MP) and five N rates (0 kg ha^{-1}, 45 kg ha^{-1}, 90 kg ha^{-1}, 135 kg ha^{-1}, and 180 kg ha^{-1}). Soil and tissue samples from the years 1995 and 2005, and 2015 were analyzed. The concentration of soil total N was significantly greater under the DP (1.10 g kg^{-1}) than under the MP (1.03 g kg^{-1}). Consistent decline of soil total sulfur (S) under MP at all N rates (except 90 kg N ha^{-1}) were observed, whereas DP maintained the levels of soil S over these years. However, comparison of DP plots to nearby undisturbed grass pasture (GP) revealed decline of soil total N (14%), SOC (34%), Mehlich III extractables P (32%), K (6%), Ca (86%), and Mg (77%) in the top 10 cm soil. Higher N rates increased the total concentrations of N, K, Ca and Mg in wheat straw and the concentration of grain N. The results indicate DP is better than MP or SW regarding macronutrients dynamics. Higher soil nutrients content of DP than MP could be attributed to the lower amount of soil aggregate disturbance and greater amount of residue cover left after tillage under DP than under MP.

Keywords: Long-term Experiment, Magnesium, Nitrogen, Phosphorus, Potassium

Abbreviations: disk plow, DP; sweep, SW; moldboard plow, MP.

Introduction

Soil degradation is considered a serious problem for a sustainable agriculture because of its direct impact on crop productivity (Rasmussen et al., 1998c). Soil degradation is manifested through erosion, soil organic matter (SOM) and nutrient depletion, soil acidity, and decreased microbial activity (Bezdicek et al., 2003). It is of utmost importance to recognize the direction of changes in soil quality indicators such as SOM and the status of plant essential nutrients before it is too late to correct. Nutrient availability and SOM can be maintained or increased if the lands are cropped every year (vs crop/fallow), crop residues or nutrients are returned to the soil, and erosion is kept to minimum; practices that are not common in the drylands of the inland Pacific Northwest due to the low precipitation in most areas (PNW) (Rasmussen et al., 1998a). Winter wheat- 14 months fallow (WW-F) rotation in combination with the low precipitation limits the biomass production and annual return of the crop residue in the PNW. Fallow conditions have negative impacts on the SOM and nutrient availability, and hence risk the sustainability of soil nutrients (Rasmussen et al., 1998a). In the last decades, there has been increasing interest on the impact of soil management practices on SOM and nutrient cycling all over the world (Bhupinderpal-Singh et al., 2004; Dalal et al., 2011). However, knowledge on how soil management practices, such as different tillage systems and N fertilization, affect the status of plant essential macronutrients in the drylands of PNW over the long-term periods, is limited (Murphy, 2015).

Tillage affects SOM (Havlin et al., 2013), pH (Blevins et al., 1977), and nutrient availability (Edwards et al., 1992). Due to reduced disturbance of soil, coupled with crop residues retention, conservation tillage such as disk plow tillage (DP) and subsurface sweep (SW) have shown positive effects on crop productivity which was reported to increase soil water content and nutrient availability (Seddaiu et al., 2016). On the other hand, more traditional tillage, such as moldboard plow tillage (MP) enhances SOM and nutrients depletion due to the increased accessibility of larger volume of SOM to microbes, greater amount of soil disturbance, faster mineralization, and greater residue incorporation/less residue cover of the soil (Obour et al., 2017). The effect of tillage on faster mineralization is aggravated in semiarid environment because decomposition is enhanced by burying residue in the moist soil profile; otherwise it would have been very slow due to dryness of the soil surface in the semiarid environment.

Previous research has shown tillage impacts on N, C, P, K, S, Ca, and Mg in the different soil depths. Dick (1983) reported higher concentration of organic P and K in the upper soil depths under no tillage than under reduced and conventional tillage. Similarly, Sarker et al. (2018) reported significantly greater SOC, extractable N, P, and S under conventional and reduced tillage than under no tillage and perennial pasture under wheat-fallow cropping system in semiarid environment of Australia, but, suggested that the effect may be reversed with time. However, Edwards et al. (1992) observed greater amount of P, K, Ca, and Mg in top surface under reduced tillage than under conventional tillage.

The other important management practice that affect SOM and nutrient availability is N fertilization. Increased SOM and total N has been reported from N fertilization due to increased plant biomass production (Blevins et al., 1983). On the other hand, increased N application to soil enhances mineralization and may subsequently contribute to increased N loses through leaching and gaseous emissions (Malhi and Lemke, 2007).

In addition to the macronutrient status, tillage and N fertilization affect soil pH, which is a key factor influencing the nutrient availability. In conservation tillage, such as DP and SW, N fertilizer is often banded close to seed in the topsoil layers, which results in greater acidification of the topsoils than under conventional tillage (MP) (Obour et al., 2017). Also, the mixing of SOM with the larger volume of soil under conventional tillage contributes to maintain higher pH than under conservation tillage (Mahler et al., 1985; Rasmussen and Rohde, 1989). However, in conventional tillage there is increased chance of losing base cations through mineralization, and eventually resulting in increased acidity than under conservation tillage.

Nutrients in wheat grain and straw are another important aspect of crop production as nutrient content is directly related to crop quality for human consumption, price determination, and crop residue quality and decomposition. Soil management practices play a crucial role in the uptake of nutrients by the crop because the availability of soil nutrients is one of the key factors that determines the crop’s end product (López-Bellido et al., 2001). For example, grain protein content is the prime measure of wheat grain quality which is directly related to the availability of N (López-Bellido et al., 2001). However, Gürsoy et al. (2010) reported little or no correlation between wheat grain protein and tillage systems. Contrasting to this, López-Bellido et al. (2001) found higher grain protein content under MP than under reduced tillage, as moisture stress tends to increase grain protein in wheat. These types of inconsistent and site-specific results require examination of the results from a long-term study for a specific region. In addition, assessments of crop nutrient uptake, along with crop yield, also determine the optimal fertilization practices (Yousaf et al., 2017). This is critical because over-fertilization decreases nutrient use efficiency and may cause environmental and economic issues (Yousaf et al., 2017).

Many previous studies in this region were mainly focused on C and N because of their larger global impact (Ghimire et al., 2017; Gollany et al., 2011; Rasmussen and Rhode, 1988). Most of the previous studies on the LTEs compared two time periods or compared a period of time with an undisturbed nearby perennial grass pasture (GP). This study compared the treatment effects with GP and included three-time periods (1995, 2005, and 2015), which makes the data more robust and minimizes uncertainty, that may have occurred between sampling and storing of the archived samples. The combination of different tillage practices and fertilizer management were found to affect soil chemical properties at different depths (Blevins et al., 1983). Hence, this study investigated plant essential macronutrients in wheat and soil at four soil depths under three tillage systems and four N application rates. To this date, no studies had examined the dynamics of other than C and N essential macronutrients in crops or soil under WW-F rotation in the PNW. The objective of this study was to quantify the effect of different tillage systems and N application rates on plant essential macronutrients (C, N, P, K, S, Ca, and Mg) in soil and in tissue (wheat grain and straw) following 75 years of treatments. Also, this study explored the trends in soil pH, soil C:N, and macronutrients dynamics in archived soil samples in 1995, 2005 and 2015 as influenced by the treatments. Furthermore, this study revealed the current macronutrients status of soil manifested by tillage and N fertilization over time by comparing it with GP. The hypothesis was that (i) in a long -term, conservation tillage (DP or SW) and N fertilization will maintain or reduce the decline of soil and crop macronutrients, soil pH, and soil C:N due to lower volume of soil aggregate disturbance and higher percentage of residue cover left under DP/SW than under MP; and (ii) tillage and low N application rates will significantly decrease soil macronutrients over time while higher N application rates plots will be less affected

Materials and methods

Site description and experimental design

This long-term study was conducted at tillage- fertility (TF) plots of the Columbia Basin Agriculture Research Center (CBARC), near Pendleton, OR (45°42’ N, 118°36’ W, elev. 438 m) on a well-drained Walla Walla silt loam soil (coarse-silty, mixed, superactive, mesic Typic Haploxeroll) in a 2-4% slope (Gollany et al., 2005). The site receives an average annual precipitation of 420 mm, with 90% of precipitation between November and June (Gollany, 2016). This is one of the ongoing long-term experiments at CBARC. It was established in 1940 as a randomized block, split-plot tillage by fertility experiment with three replications under dryland winter wheat-14 months fallow (WW-F) cropping system. Main plots were three primary tillage systems [moldboard plow (MP), disk plow (DP) and subsurface sweep (SW)] with the size of 35 by 40 m each. Subplots comprised of five N application rates (0, 45, 90, 135, and 180 kg N ha^{-1}) and were 5.8 by 40 m in size. The MP, DP, and SW differed in the tillage depth and in the percentage of residue cover left on the soil surface at the time of seeding. The tillage depth of MP, DP, and SW were 23 cm, 10 cm, and 15 cm respectively leaving 7%, 34%, and 43% soil surface covered by residue, respectively. Earlier studies on TF had reported 20% clay, 68% silt, 1.1% organic C kg^{-1}, and 16 cmolc kg^{-1} cation exchange capacity (CEC) at the upper 30 cm of the soil (Ghimire et al., 2017; Rasmussen and Rohde, 1989).

The primary tillage treatments were carried out in late March on undisturbed stubble left after wheat harvest with field a cultivator. The plots were rod weeded two to four times between April and October to control weeds. Nitrogen fertilizer (Urea ammonium nitrate) was added to a depth of 10 cm every other year (during crop year) using Viper Coulter (Yetter Manufacturing Inc. Colchester, IL) during the first week of October. Wheat was seeded at 72 ± 5 kg seed ha^{-1} with 25 cm between row spacing after a week following the N application. Before 2002, JD8300 drill (Deere and Company, Moline, IL) was used to sow wheat and thereafter Case IH 5300 disk drill (Klamath Basin Eq. Inc. Klamath Falls, OR) has been used. The wheat variety grown during the 1995-2005 period was Malcolm, and after that Stephens was used. These are semi-dwarf winter wheat varieties. Weeds within the growing season were controlled using late-fall or early-spring herbicide application. Wheat was harvested in late July.

An undisturbed (since 1931) nearby perennial grass pasture (GP) was used as the reference to detect the changes manifested by cultivation practices of this study. The GP was a cropland between 1881 and 1931, then was converted back to pasture in 1931, and comprises blue- bunch wheatgrass (*Agropyron spicatum L.* Pursh) and Idaho fescue (*Festuca idahoensis L.* Elmer) as dominant grasses.

Soil sampling and analysis

We used the soil cores of four depths (0-10, 10-20, 20-30, and 30-60 cm) from 1995, 2005 and 2015 in this study. The archived samples of soil and wheat grain and straw samples were from 1995 and 2005. In addition, soil samples were collected in the summer of 2015 after the wheat harvest. A truck-mounted Giddings Hydraulic Probe (Giddings Machine Company, Inc., Windsor, CO) and a steel sampling tube (internal diameter 3.6 cm) were used to sample the soils. The samples were homogenized and brought to the Central Analytical Lab (CAL, Oregon State University) to determine the soil total N, C, S, and Mehlich III-extractable P, K, Ca, and Mg. The concentration of soil and plant C, N and S was determined by dry combustion method in a Vario Micro Cube combustion analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). Mehlich III extraction method (Mehlich, 1984) was used to extract P, K, Ca, and Mg from soil samples whereas dry ash method was used to extract nutrients from the grain and straw samples. The extracts were run on an inductively coupled plasma-optical emissions spectroscopy (ICP-OES, Model #2100 DV, Waltham, Massachusetts, USA). The data of soil pH from 1995, 2005, and 2015 were provided by the CBARC, and were determined with pH electrodes using 10 g sample size in a 1:2 soil to 0.001M $CaCl_2$ solution.

Statistical analysis

Data were subjected to ANOVA as a split-plot design using the mixed-model of JMP© version 13 (SAS Institute Inc, 2014). Tillage system, N rates, year, and soil depths were considered the fixed effects while replications and their interactions were considered the random effects. The adjusted Tukey method was used for multiple means comparisons. Letter groupings were generated using a 5% level of significance.

The ANOVA of the soil pH were determined by converting the soil pH data to H^+ concentration (μmol L^{-1}) before analysis because the pH scale is a logarithmic and a small difference in pH represent significant differences. However, the mean comparisons of soil pH represent the original pH data.

Results and discussion

The concentration of total N, total C, total S, Mehlich III extractable phosphorus, potassium, calcium, and magnesium will be designated with N, C, S, P, K, Ca, and Mg; respectively, hereafter while discussing soil, unless otherwise stated. The total carbon of this TF plot is organic only, was confirmed as such by the soil pH in previous studies on this plot (Ghimire et al., 2017; Rasmussen et al., 1998a).

Tillage effects on soil macronutrients

Long-term effect of different tillage systems was observed for soil N and S only. The rest of the studied macronutrients in this experiment were influenced largely by the interaction between treatments and depth (Table S4.1). Disc tillage (DP) had significantly higher total N (1.10 g N kg^{-1}) than moldboard plow (1.03 g N kg^{-1}) (Fig. 4.1). The concentrations of total N under DP and SW were similar. This result was consistent with previous study by Rasmussen and Rhode (1988) of the same plot 30 years ago, and with the study from central Italy (Mazzoncini et al., 2011) study. The latter authors suggested that the higher amount of residue cover and the lower volume of disturbed soil may have contributed to the higher N under DP and SW than under MP. The MP exposed more otherwise protected organic matter, increased aeration, temperature, and thereby, enhanced microbial decomposition rates resulting in the release of inorganic N along with other nutrients (Prasad and Power, 1997; Rasmussen and Rhode, 1988). In this study, the MP treatment had a lower percentage of crop residue than the DP and SW.

This study revealed greater soil total S under MP (0.48 g kg^{-1}) than under SW (0.39 g kg^{-1}) and DP (0.40 g kg^{-1}) (Fig. 4.1). In a long-term, enhanced decomposition, such as in MP, is expected to decrease the S in the plots as MP facilitates quicker decomposition (Bhupinderpal-Singh et al., 2004; Kopittke et al., 2017). However, the results from this study do not support this concept. Total S was greater in MP than in DP and SW even after the 75 years of cultivation (Fig. 4.1).

Nitrogen fertilization effects on soil macronutrients

Different N application rates also affected soil total N and S. In general, soil total N increased with higher N rates. This trend was not evident with total S, which was significantly higher in the 0 kg N ha^{-1} (0.45 g kg^{-1}) than in 45 kg N ha^{-1} (0.41 g kg^{-1}); the rest were not different (Fig. 4.1). Previous studies have shown positive correlation between N application rates and soil total N (Mazzoncini et al., 2011; Rasmussen and Rhode, 1988; Sainju et al., 2010). The possible reason for positive correlation of higher N fertilization rate and soil total N could be the higher crop biomass production resulting from N fertilizer application (Rasmussen et al., 1998a) and subsequently greater plant residue. Besides enhancing crop production, the higher N application rates are known to chemically stabilize SOM and make N available in a longer period at a steady rate (Mazzoncini et al., 2011).

Nitrogen fertilization effect on soil C/N ratio

The long-term application of inorganic N fertilizers (N rates) influenced the C/N ratio in this study (Fig. 4.2). The C/N of the soil was significantly higher in the 0 kg N ha^{-1} (9.7) than in 180 kg N ha^{-1} (9.0) plots and followed decreasing trend with increased N application rates (Fig. 4.2). In contrast, Ghimire et al. (2015) did not find any significant effect of N application rates on C/N over 80 years in another long-term study of the CBARC. The results of the latter authors were based on three N rates (0, 45, and 90 kg ha^{-1}) as compared to the five N rates in this study. In this study, N increased with the higher N application rates in all the tillage treatments, which may have played a role in C/N ratios with the increased N fertilizer rates.

Interaction effect of treatments on soil macronutrients

There was an interaction effect of tillage and soil depth for soil C, K, Ca, Mg, and pH; and also interaction effect of N application rates and soil depth for soil P, Ca, and pH (Table S4.1). In the 0-10 cm soil depth, soil C, K and Mg were significantly higher under DP and SW than under MP (Fig. 4.3). Earlier studies reported similar results for C (Rasmussen and Rhode, 1988), K (Franzluebbers and Hons, 1996; Ussiri and Lal, 2009), and Mg (Edwards et al., 1992). The higher C, K, and Mg in the surface soil layer in the DP and SW than in the MP is attributed to reduced soil-residue interaction in the DP and SW (crop residue was buried 10-15 cm deep under SW and DP vs. 23 cm under MP) and subsequently lowering the rates of SOM mineralization. The other plausible reason for higher K and Mg under DP and SW than under MP might be due to greater cation exchange sites provided by the higher SOM present under DP and SW.

Soil Ca in the 0-10 cm soil depth was higher under MP (0.33 g kg^{-1}) than under DP (0.28 g kg^{-1}) and SW (0.32 g kg^{-1}) (Fig. 4.3), which is in agreement with Blevins et al. (1983). However, Edwards et al. (1992) found greater Ca at 0-10 cm soil depth in the plots that were less disturbed compared with Ca in the soil under conventional tillage. In this study, K at the 0-10 cm soil depth was greater under DP and SW than under MP probably, because of the competition between K and Ca for exchange sites.

The interaction of N application rates and depth affected soil P and Ca in this study. In the 0-10 cm and 10-20 cm soil depths, P increased linearly with the increased rate of inorganic N application after 45 kg ha^{-1} (Fig. 4.4). The results from this study are in contrast with the ones of Franzluebbers and Hons (1996) and Burzlaff et al. (1968) who reported no effect of N application rates on soil P. Probably, the effect of increased acidity on P resulting from the higher N rates, was balanced by the higher biomass production and increased N availability in this study. Increased N availability facilitates microbial activity to decompose OM and a release of P. A reverse trend was observed with soil Ca that consistently decreased with the higher N rates in the studied soil depths except in 30-60 cm (Fig. 4.4). This result is in agreement with the study of Ai et al. (2017), however, other studies had different results (Franzluebbers and Hons, 1996; Obour et al., 2017). The availability of Ca is inversely related to the soil acidity and decreases with high N application rates. Acidic soils have high exchangeable aluminum (Al) and replace Ca on the exchangeable sites and depress Ca concentration (Prasad and Power, 1997).

Effect of tillage and N fertilization on soil pH

Soil pH was highly influenced by N application rates in the 0-10 cm and 10-20 cm soil depths only (Fig. S4.1). In these depths, pH was significantly higher in the 0 kg N ha^{-1}, 45 kg N ha^{-1}, and 90 kg N ha^{-1} treatments than in the 135 kg N ha^{-1} and 180 kg N ha^{-1} application rates (Fig. S4.1). These results are consistent with the results from previous long-term studies, which reported that N fertilizer application markedly decreased soil pH in the top layers only (Ghimire et al., 2017; Obour et al., 2017), suggesting that soil acidification resulting from N application did not move beyond 20 cm soil depth. This is significant because acidification is confined at upper layers and has limited effect on acidification of the subsoil, otherwise it would be detrimental to crop production. Mahler et al. (1985) reported that only high application rates of N (>100 kg N ha^{-1}) acidified soil in a study with 40 years of data. However, Ghimire et al. (2017) with 70 years of data, and this study with 75 years of data demonstrated that even low N application rates could acidify the soil in a long-term. Among the tillage system, MP was found to be the most detrimental with regard to soil pH. In the 10-20 cm and 20-30 cm soil depths, soil pH in MP (5.35 at 10-20 cm and 6.03 at 20-30 cm) was markedly lower than the soil pH under SW (5.52 at 10-20 cm and 6.30 at 20-30 cm) and DP (5.74 at 10-20 cm and 6.43at 20-30 cm) (Fig. S4.1). The results could be attributed to the higher volume of soil disturbance and mixing of crop residue with soil deeper in the profile under MP than under SW or DP treatments.

Trends in soil macronutrients, C/N and pH dynamics as observed from the 20 years' data

The soil pH and the concentrations of S had significant interaction with year. The N application rates largely affected the soil pH over time, and interestingly, the soil pH at 0 kg N ha^{-1} markedly increased from 1995 and 2005 in 2015 (Fig. S4.2). This could be attributed to less biomass and no ammoinical N fertilizer inputs in 0 kg N ha^{-1} plots. A three-way interaction of N rates, tillage and year was observed for soil total S. The soil S concentration declined greatly with increased N application rates under MP from 1995 to 2015 (Fig. 4.5). This could be due to higher amount of organic matter mineralization under MP because greater amount of soil is exposed to microbial decomposition, which is enhanced by increased aeration and temperature under this system. Under SW, at 45 kg N ha^{-1} and 90 kg N ha^{-1}, S declined significantly over time (Fig. 4.5). The soil total S under DP did not decline at any of the studied N rates over the 20 years (Fig. 4.5).

Tillage and N fertilization effect on soil macronutrients compared to nearby undisturbed grassland pasture (GP)

Soil organic C, total N, and total S: Among the tillage systems used in this experiment, disc tillage (DP) was more desirable than other tillage systems due to greater concentration of macronutrients for most of the nutrients. However, SW and DP were comparable for many of the macronutrients. Thus, we compared the DP system with nearby undisturbed grass pasture (GP) to detect the soil chemical changes manifested by tillage and inorganic N application over 75 years in dryland WW-F cropping system. The cultivation effect on macronutrients, expressed in percentage in Table 4.1 and 4.2, were calculated from the differences in the value of respective nutrients obtained from GP and the highest value obtained from the treatment within each soil depth.

High biological oxidation and absence of C input during the fallow year is the major driver of SOM loss in dryland wheat-fallow cropping system of eastern Oregon (Rasmussen et al., 1998a). In this study, all five N application rates decreased C and N in each of the studied soil depths (Table 4.1). Carbon and N had markedly declined by at least 34 % (14.4 g kg^{-1}) and 35 % (1.4 g kg^{-1}); respectively, when compared to GP (C: 21.8 g kg^{-1}; N: 2.1 g kg^{-1}) in the top 10 cm depth at all N application rates during the 75 years of treatments application (Table 4.1). According to Rasmussen et al. (1998a), the top 30 cm of the soil in these plots lost about 35% of C in the first 50 years after the soil was broken to cultivate in 1881, whilst under pasture following cultivation, C and N of soils increased with time (Rasmussen et al., 1998a). Furthermore, Bhupinderpal-Singh et al. (2004) reported that conversion of perennial pasture over time accumulates more C in the soil than the annually cultivated pasture. The protected SOM becomes more accessible to the soil microbes, and the soil environment becomes more conducive to mineralization in the cropland than in the undisturbed pasture and eventually enhancing the mineralization and increasing the probability of C and N loses in cultivated soils (Awale et al., 2017). The loss of nutrients become more severe in dryland wheat-fallow cropping system of the PNW because fallowing keeps the soil moist in the summer which permits much greater biological oxidation than would normally occur (Rasmussen et al., 1998a). In addition to this, perennial grasses contribute greater amount of C and N all year round through their dense and deep root systems than wheat-fallow cropping system (Wuest and Gollany, 2013). There was no significant loss of N in deeper soil profile (20-30 cm and 30-60 cm) at any N application rates. This is significant for agriculture because the long-term cultivation has not limited N availability in subsoil after 75 years of cultivation and suggest the mineralization enhanced by tillage as the major factor responsible for C and N loss in the 0-20 cm soil depths. Interestingly, the S concentration in the 20-30 cm soil depth increased significantly after cultivation than that of GP, and slightly (not significantly) increased at all N rates on rest of the studied soil depths than GP (Table 4.1). This result partially agrees with Sakadevan et al. (1993) who reported gradual decrease in S after many years of pasture improvement because mineralization becomes significantly greater source of S for perennial grasses. It has been reported elsewhere that greater amount of crop residues and roots exudates (which is in GP in our study) greatly affect oxidation of S and releases S in soil solution (Germida and Janzen, 1993). However, it is not quite clear what increased the S in cultivated soil more than under GP over the long-term. In 20-30 cm at 0 kg ha^{-1}(0.45 g kg^{-1}), S was 41% higher than that at GP (0.32 g kg^{-1}) (Table 4.1).

Mehlich III extractable P, K, Ca, and Mg: Mehlich III extractable P, Ca, and Mg clearly declined after 75 years of continuous cultivation under WW-F cropping system at all N application rates at each of the studied soil depths (Table 4.2). Extractable P declined by 32%, 33%, 39%, and 40% in the 0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm soil depths, respectively compared with P in the GP (Table 4.2). Similarly, extractable Ca decreased by 86%, 83%, 81%, 78%, and extractable Mg decreased by 77%, 84%, 89%, 85% in the 0-10 cm, 10-20 cm, 20-

30cm, 30-60 cm soil depths, respectively (Table 4.2). The effect of N application rates on extractable K was not significant in the top soils (0-10 cm, 10-20 cm, and 20-30 cm); however, obvious decline in K concentration was observed deeper in the soil (30-60 cm). At this depth, extractable K sharply declined by 31% when compared with that in GP (Table 4.2).

This study revealed significant decline in soil macronutrients during 75 years of cultivation, which is alarming for the sustainability of soil nutrients supplying capacity of this region. The loss of macronutrients in cultivated plots are primarily due to increased weathering of primary minerals with tillage and the nutrient removal by high yielding crops, whereas in the GP, aboveground biomass is sometimes clipped otherwise not removed from the plots. The nutrients concentration in the soil is the balance between nutrient removed and nutrient added to the soil. In our experimental plots, soil macronutrients were not returned to the soil (except N in N fertilization treatments and incorporating crop residue). Furthermore, the straw: grain ratio has decreased progressively over time (Rasmussen et al., 1998a) and thus, resulting in lower contribution to SOM. Under GP, SOM is higher than under cultivated plots (Elliott, 1986), resulting in higher CEC under GP, which in turn affect the nutrient retaining capacity of the soil. Thus, SOM, nutrient removal by crops, no input of minerals except N, and weathering of minerals could be the major factors responsible for macronutrients decline in this long-term study.

Soil pH was significantly lower in the DP plots than in the GP plots in the 0-10 cm and 10-20 cm soil depths at all the studied N application rates (Fig. S4.3). This is well within the line with other studies from this LTE (Ghimire et al., 2017; Rasmussen and Rohde, 1989).

Nitrification derived acidification barely moves to lower depths in drylands and is confined to the fertilization zone only (Rasmussen and Rohde, 1988). This could be attributed to the observed significantly lower soil pH only on top soils at all N application rates. Beside this, significant loss of base forming cations via crop removal over time may also have reduced soil pH markedly in the TF plots than in the GP.

Treatment's effect on wheat straw and grain macronutrients accumulation: Subsurface sweep tillage noticeably increased straw N accumulation than MP (Fig. S4.4). Similar to Malhi et al. (2006), in this study, there was no tillage effect on straw N and C accumulation. The concentration of N, K, Ca, and Mg in straw was prominently greater in higher N application rates (above 90 kg N ha^{-1}) than in the lower rates (0 kg N ha^{-1} and 45 kg N ha^{-1}) (Fig. S4.4 and S4.5). No interaction between tillage systems, N application rates and year was observed for nutrient accumulation in straw (Table S4.3).

The effect of N application rates on soil N was reflected in wheat straw and in wheat grain nutrients. The N application rates significantly interacted with year for N accumulation in wheat grain. The other macronutrients in grain were not affected by tillage systems or N rates and their interaction with each other or with year (Table S4.3). The wheat grain N accumulation was largely influenced by the N application rates in each of the studied year (Fig. 4.6). Higher N rates consistently increased N accumulation in wheat grain over all the studied years. Except at 180 kg N ha^{-1}, N accumulation increased significantly from 1995 over the time at all N rates of this experiment (Fig. 4.6). These results agree with the ones of Gao et al. (2009) who reported linear increase of grain N uptake (up to 120 kg N ha^{-1}). The results of grain N from this study suggest that N rates could be used as a management tool for manipulating wheat grain N because low N content is desired in soft wheat whereas high N content is desired in hard wheat.

Conclusion

Plots under MP lost more N at all soil depths, and also lost C, K, and Mg at the top 10 cm soil depth compared with the ones in the SW or DP tillage systems. Soil pH was similar under the three tillage systems in the top 10 cm and in the 30-60 cm soil depths, but at 10-20 cm and 20-30 cm soil depths, the MP had lower soil pH than the DP treatment. Similarly, higher N application rates decreased the C: N, increased the extractable P in soil, and increased the accumulation N, Ca, and Mg in grain. However, soil acidification was greater with higher N application rates. Total soil S decreased under the SW and the MP at four of the studied N rates over the 20 years period, but DP maintained soil S concentrations during this period. The 20-years of data suggest that DP and higher N application rates seemed superior to other tillage systems in regard to macronutrient dynamics. However, if the LTE treatments are compare with the GP, none of the treatments seemed better than the GP for maintaining macronutrients in soil. Unsurprisingly and alarmingly, 75 years of cultivation significantly reduced soil pH, C, N, P, Ca, and Mg in the top 20 cm soil depths at all N application rates. The results from this study demonstrated that 20 years (1995, 2005, and 2015) of data were not sensitive enough to detect the subtle changes in the dynamics of soil (except S), in crop macronutrients accumulation (except grain N with N rates), or in soil pH. However, a comparison with the nutrient status of GP revealed greater loss of macronutrients due to 75 years of continuous WW- F cropping system. This is a significant finding for further understanding of the sustainability of agriculture in this region and other semiarid regions, and had been possible only due to the long-term study. Any short-term study will mask the delicate changes occurring in soil which could become an irreversible problem in the future if not detected and corrected early enough.

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Table 4. 1 Impact of 75 years of inorganic N application rate (N rate) on total soil C, N, and S in dryland winter wheat-fallow cropping system under disc tillage management compared to nearby perennial grass pasture (GP).

Nutrients	Soil depth	N application rate (kg ha^{-1})						Cultivation effect[1]
		0	45	90	135	180	GP	
		---------------------------- g kg^{-1} ----------------------------						
Carbon (C)	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 (N)	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	3% ↓
	30-60	0.9a	0.9a	0.9a	0.9a	1.0a	1.1a	13%↓
Sulfur (S)	0-10	0.4a	0.4a	0.4a	0.5a	0.4a	0.4a	7% ↑
	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% ↑

Note: Means sharing the same letter within the rows are not significantly different at 0.05 probability level.

[1]Percentage obtained from the difference in the value from grass pasture (GP) and the highest value from the treatment within each soil depths. Downward and upward arrow indicates decline and incline from the soils of GP after cultivation respectively.

Table 4. 2 Impact of 75 years of inorganic N application rate (N rate) on Mehlich III extractable P, K, Ca, and Mg in dryland winter wheat-fallow cropping system under disc tillage management compared to nearby perennial grass pasture (GP).

Nutrients	Soil depth (cm)	N rate (kg ha^{-1})						Cultivation effect[1]
		0	45	90	135	180	GP	
Phosphorus (mg kg^{-1})	0-10	34.9c[2]	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	6% ↓
	10-20	0.6ab	0.5b	0.6ab	0.7ab	0.6ab	0.7a	3%↓
	20-30	0.5a	0.5a	0.6a	0.6a	0.6a	0.6a	2% ↓
	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% ↓

Note: Means sharing the same letter within the rows are not significantly different at 0.05 probability level.
[1]Percentage obtained from the difference in the value from grass pasture (GP) and the highest value from the treatment within each soil depths. Downward and upward arrow indicates decline and incline from the soils of GP after cultivation respectively.

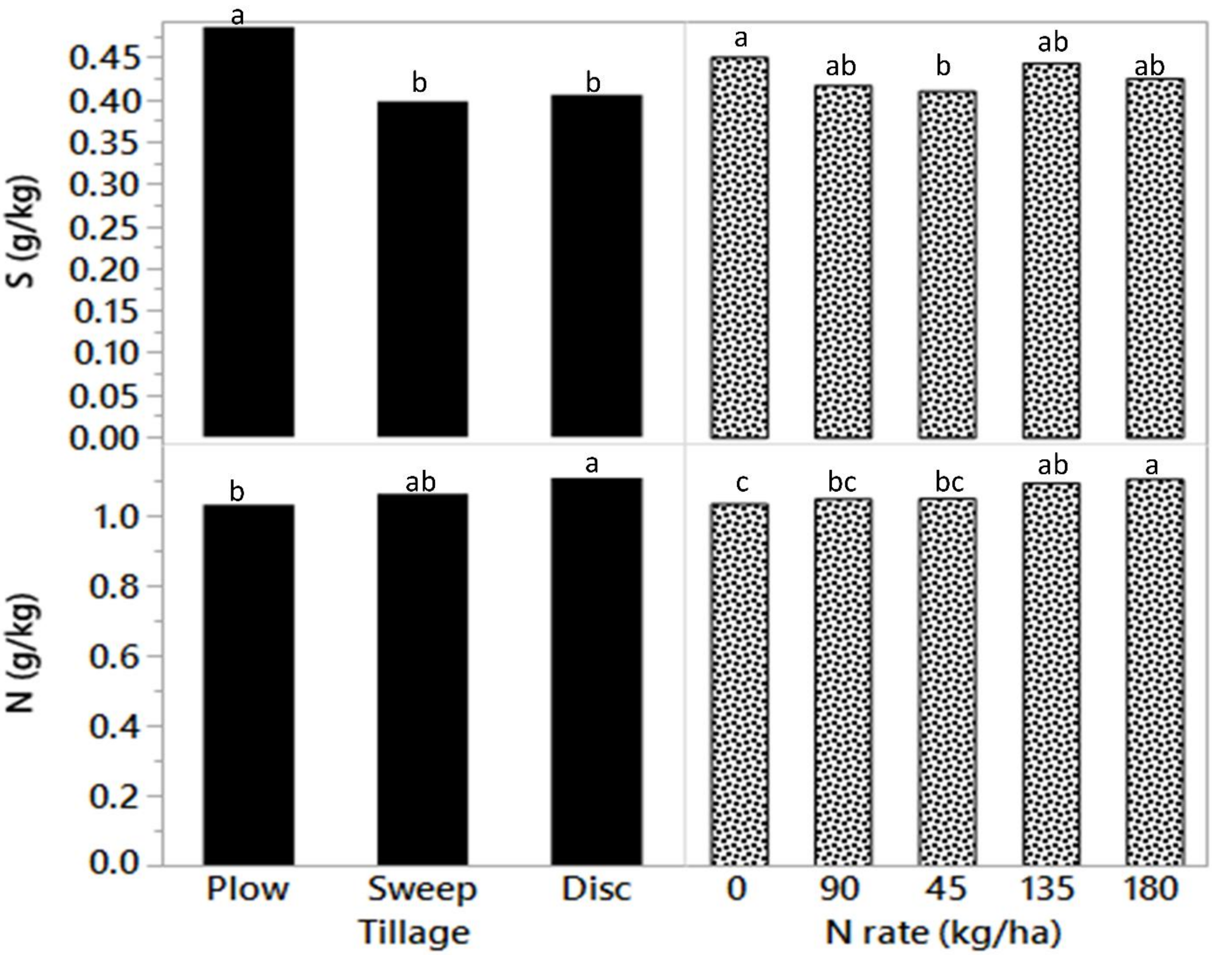

Fig. 4. 1 Long-term effect of tillage and N application rates on soil total N and total S in winter wheat-fallow system.

Plow: moldboard tillage; Sweep: subsurface sweep tillage; and Disc: disc tillage

Letters sharing the same letters above the bar within the treatments are not significantly different at 0.05 probability level.

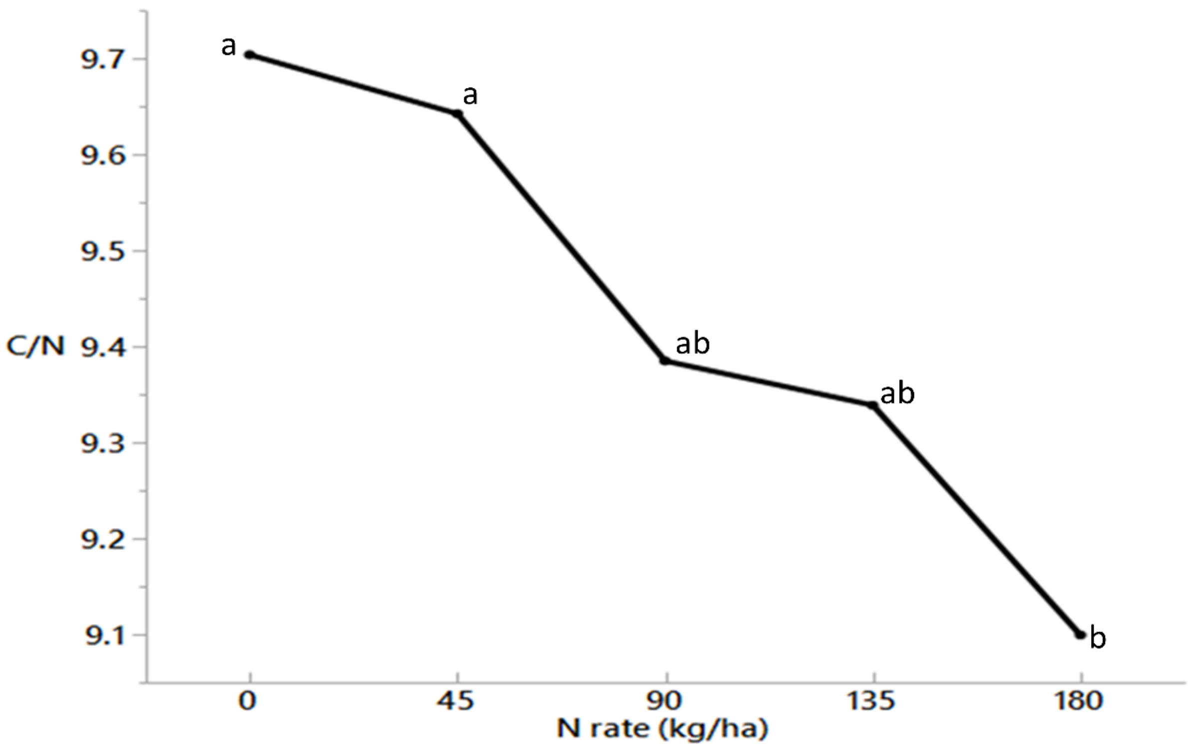

Fig. 4. 2 Carbon-nitrogen ratio (C/N) of soil as influenced by long-term inorganic N application in winter wheat-fallow system.

Letters sharing the same letters above a line are not significantly different at 0.05 probability level.

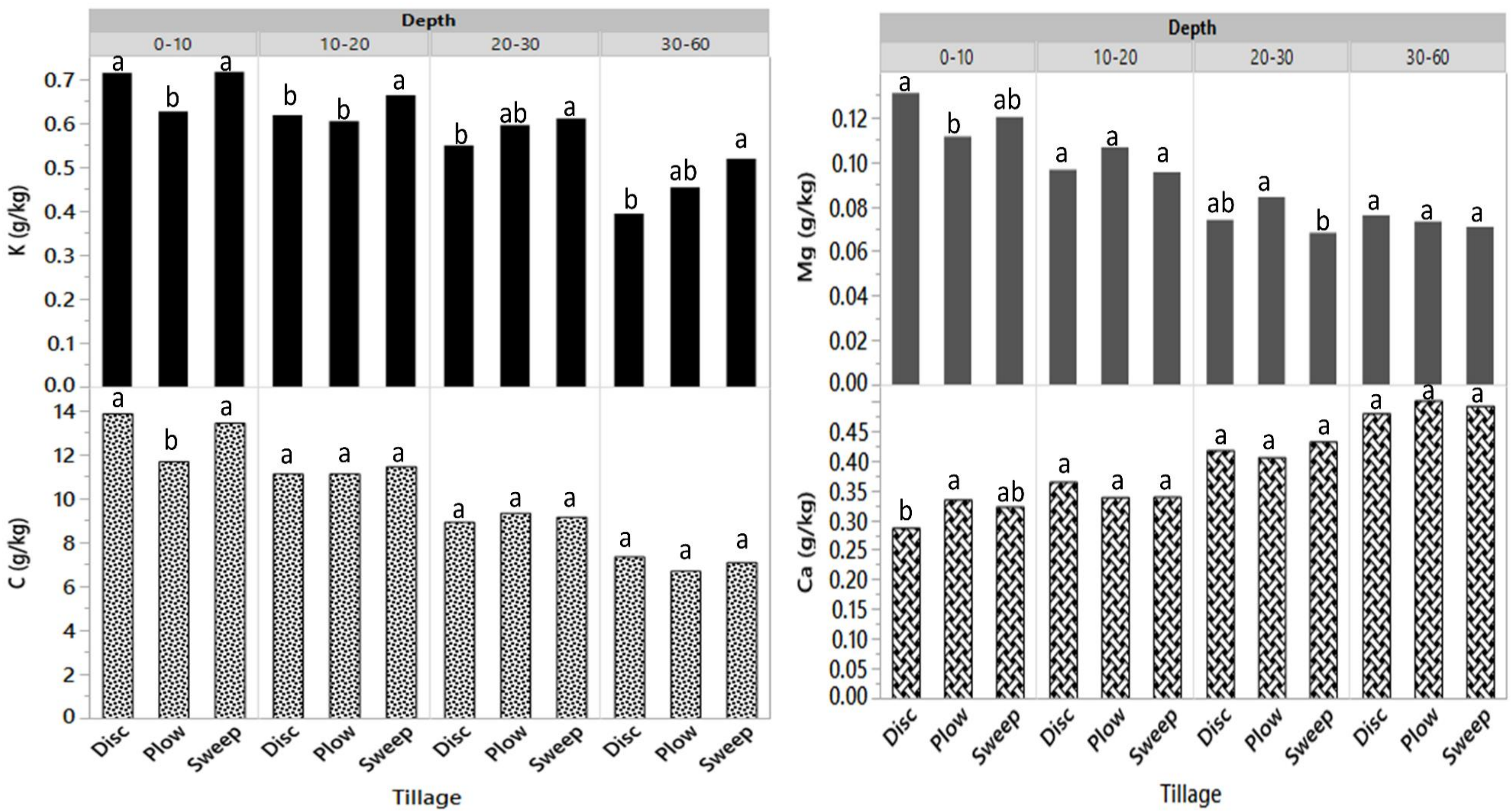

Fig. 4. 3 Long-term effect of tillage by depth (cm) on total soil organic carbon and on the Mehlich III-extractable cations in winter wheat-fallow system.
Plow: moldboard tillage; Sweep: subsurface sweep tillage; and Disc: disc tillage
Letters sharing the same letters above the bar within each soil depths are not significantly different at 0.05 probability level.

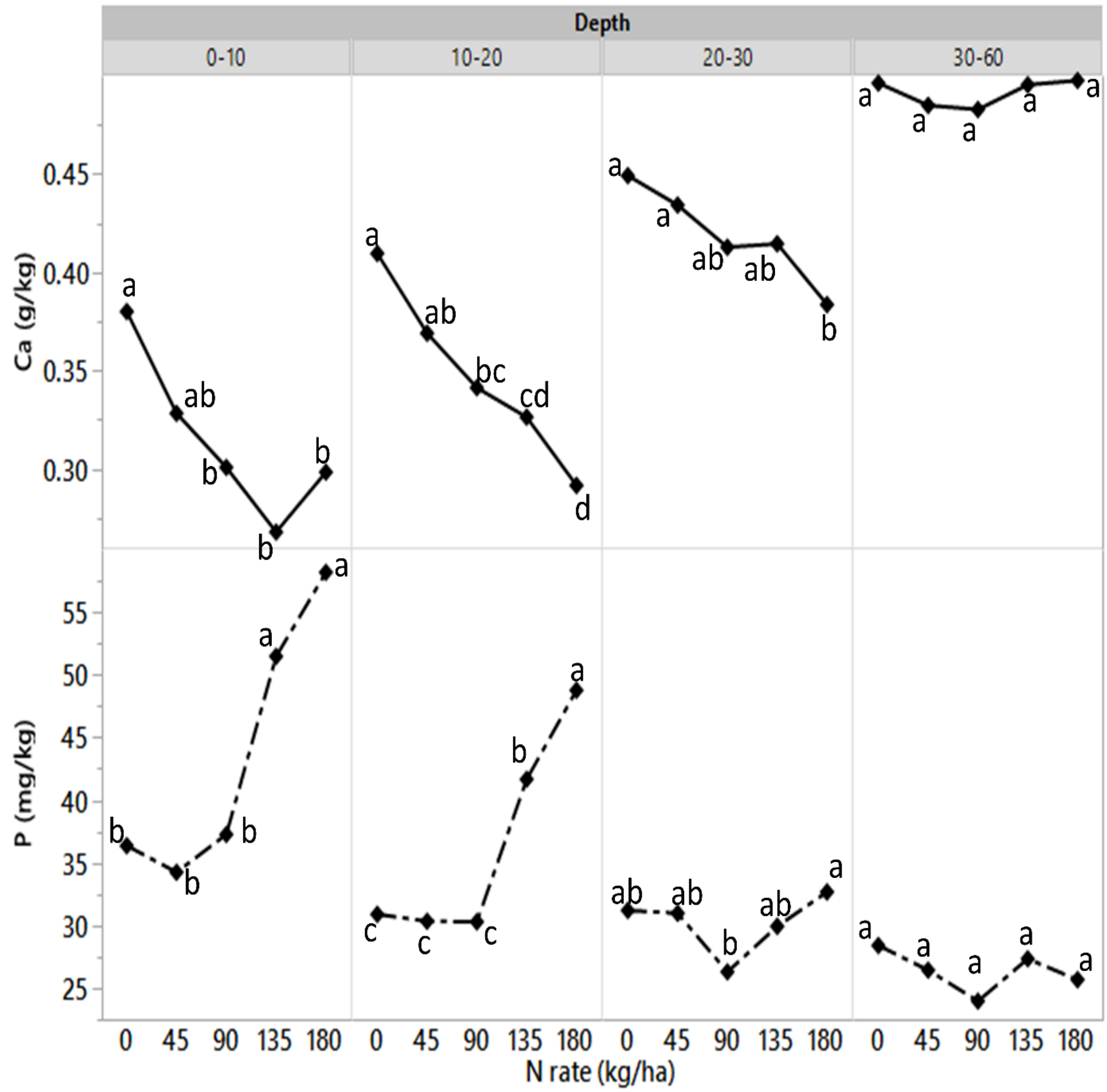

Fig. 4. 4 Soil depth (cm) distribution of Mehlich III-extractable P and Ca as influenced by long-term inorganic N application rates in winter wheat-fallow system.

Letters sharing the same letters above the bar within each soil depths are not significantly different at 0.05 probability level.

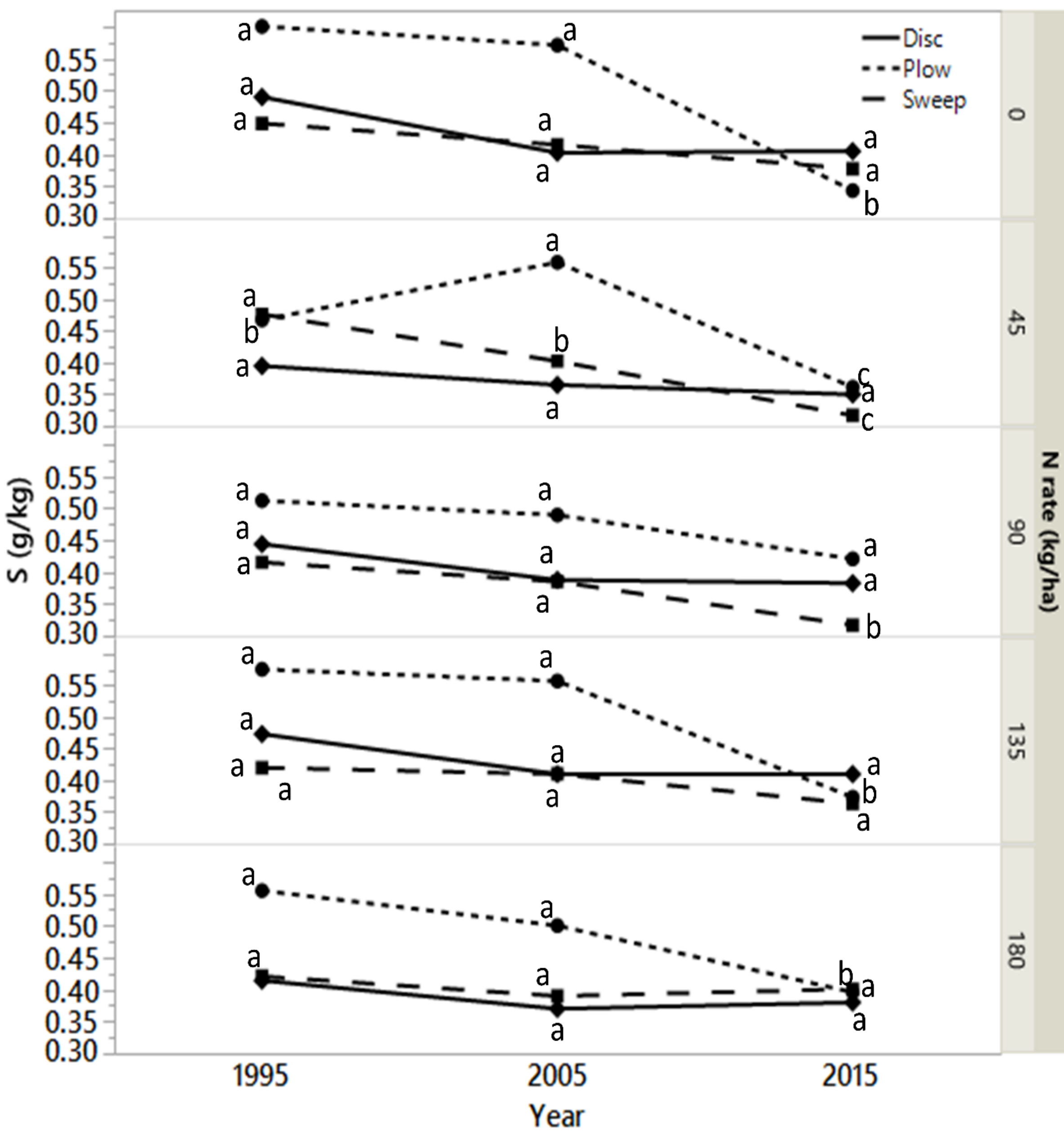

Fig. 4. 5 Effect of inorganic N application rates on total soil S over time (1995-2005-2015) under the different tillage system in winter wheat-fallow system.
Plow: moldboard tillage; Sweep: subsurface sweep tillage; and Disc: disc tillage
Letters sharing the same letters above the lines within each N rates are not significantly different at 0.05 probability level.

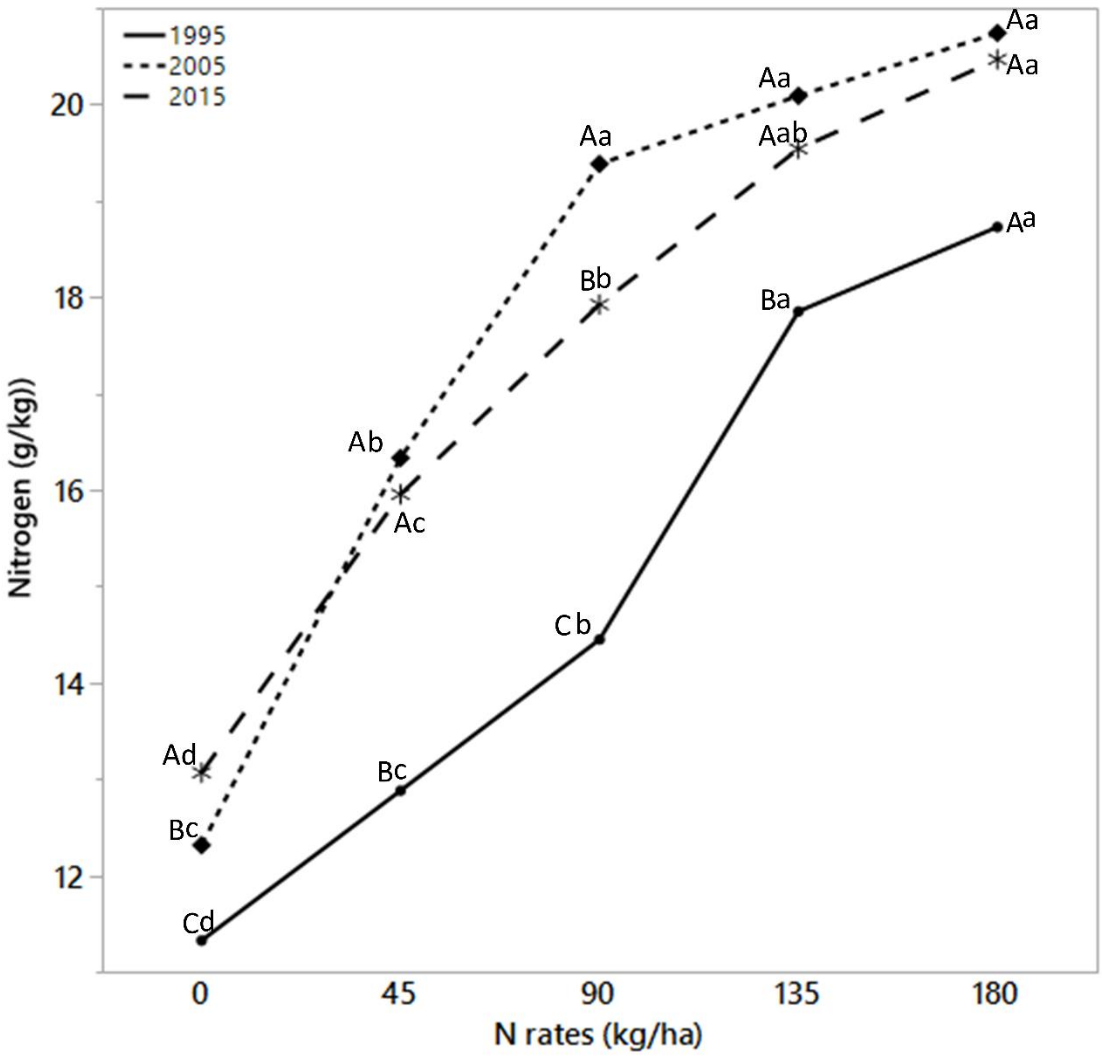

Fig. 4. 6 Effect of different N application rates and Year on wheat grain N in winter wheat-fallow cropping system.

Letters sharing the same uppercase letters within the N rates and same lowercase letters within the year are not significantly different at 0.05 probability level.

Table S4. 1 ANOVA for macronutrients in soil, soil C/N, and soil pH as influenced by 75 years of tillage, N rate, and depth.

Source of variation	N	C	S	P	K	Ca	Mg	C/N	pH
Tillage (T)	<0.01	<0.01	<0.01	0.07	<0.01	0.43	0.07	0.06	<0.01
Depth (D)	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
N rate (N)	<0.01	0.39	<0.01	<0.01	<0.01	<0.01	0.80	<0.01	<0.01
T x D	0.06	<0.01	0.06	0.11	<0.01	<0.01	<0.01	0.12	<0.01
N x D	0.22	0.06	0.61	<0.01	0.12	<0.01	0.61	0.42	<0.01
T x N	0.06	<0.01	0.60	0.07	0.09	<0.01	0.80	0.14	0.07
T x N x D	0.77	0.06	0.49	0.41	0.42	0.21	0.99	0.49	0.31

Table S4. 2 ANOVA for N, C, S, P, K, Ca, and Mg in wheat straw and grain as influenced by tillage, year and N rates.

Source of variation	N	C	S	P	K	Ca	Mg
				Wheat straw			
Tillage (T)	<0.01	0.18	0.22	0.37	0.33	0.44	0.53
Year (Y)	0.07	<0.01	0.51	0.37	<0.01	0.01	<0.01
N rate (N)	<0.01	0.17	0.24	0.41	<0.01	<0.01	<0.01
T x Y	0.07	0.16	0.21	0.41	0.32	0.31	0.31
N x Y	0.06	0.24	0.10	0.44	0.32	0.47	0.51
T x N	0.37	0.62	0.45	0.43	0.42	0.19	0.13
T x N x Y	0.67	0.11	0.06	0.46	0.30	0.23	0.18
				Wheat grain			
Tillage (T)	0.48	0.16	0.60	0.21	0.10	0.06	0.20
Year (Y)	<0.01	<0.01	0.33	<0.01	0.46	0.01	0.51
N rate (N)	<0.01	0.84	0.52	0.92	0.31	0.57	0.83
T x Y	0.06	0.17	0.07	0.36	0.51	0.57	0.36
N x Y	<0.01	1.00	0.73	0.53	0.91	0.59	0.61
T x N	0.16	1.00	0.61	0.95	0.25	0.83	0.76
T x N x Y	0.73	1.00	0.64	0.94	0.88	0.74	0.62

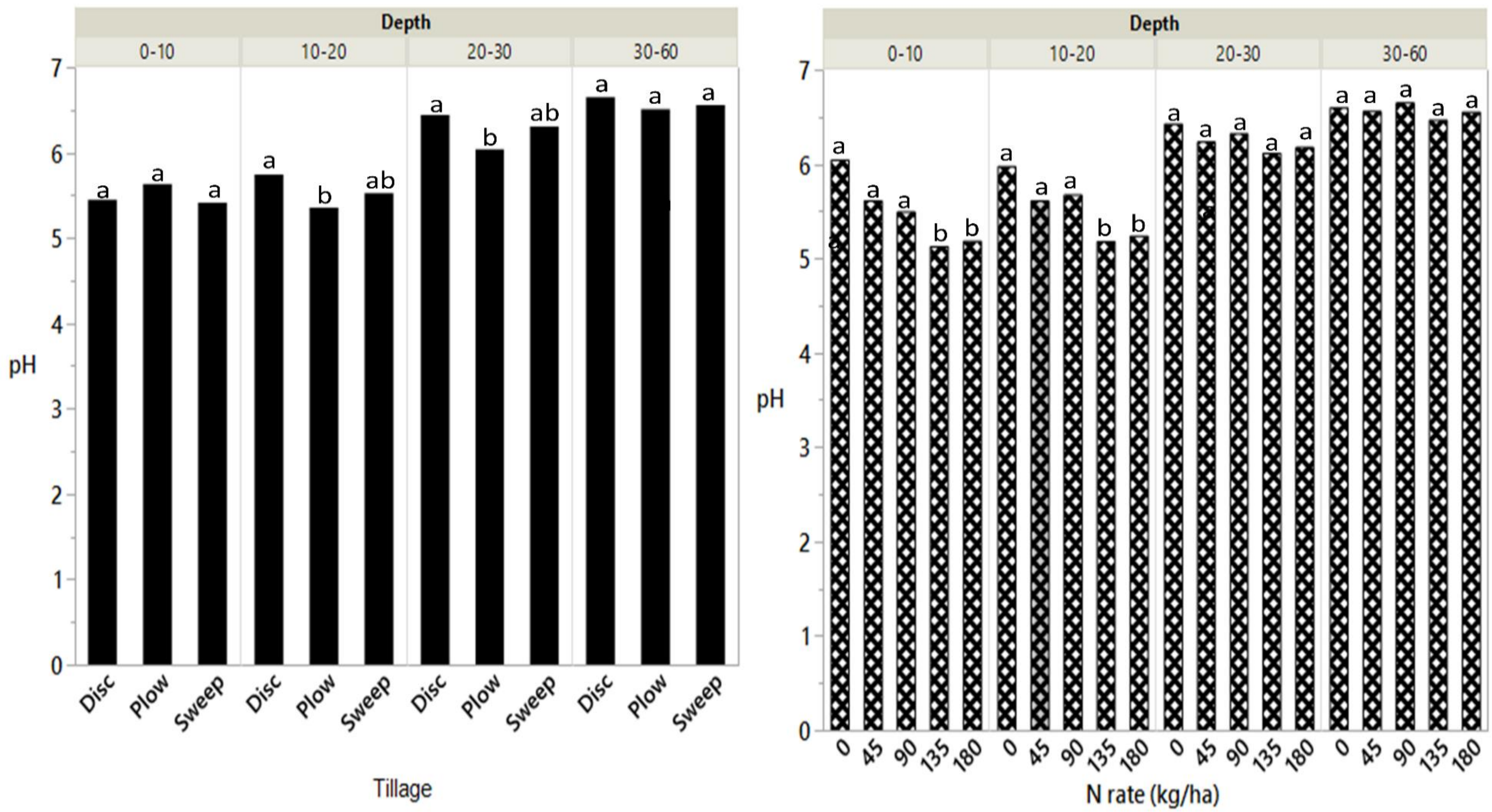

Fig. S4. 1 Long-term effect of tillage (left) and N application rates (right) on pH in four soil depths (cm) under winter wheat-fallow system.

Plow: moldboard tillage; Sweep: subsurface sweep tillage; and Disc: disc tillage

Letters sharing the same letters above the bar within each soil depths are not significantly different at 0.05 probability level.

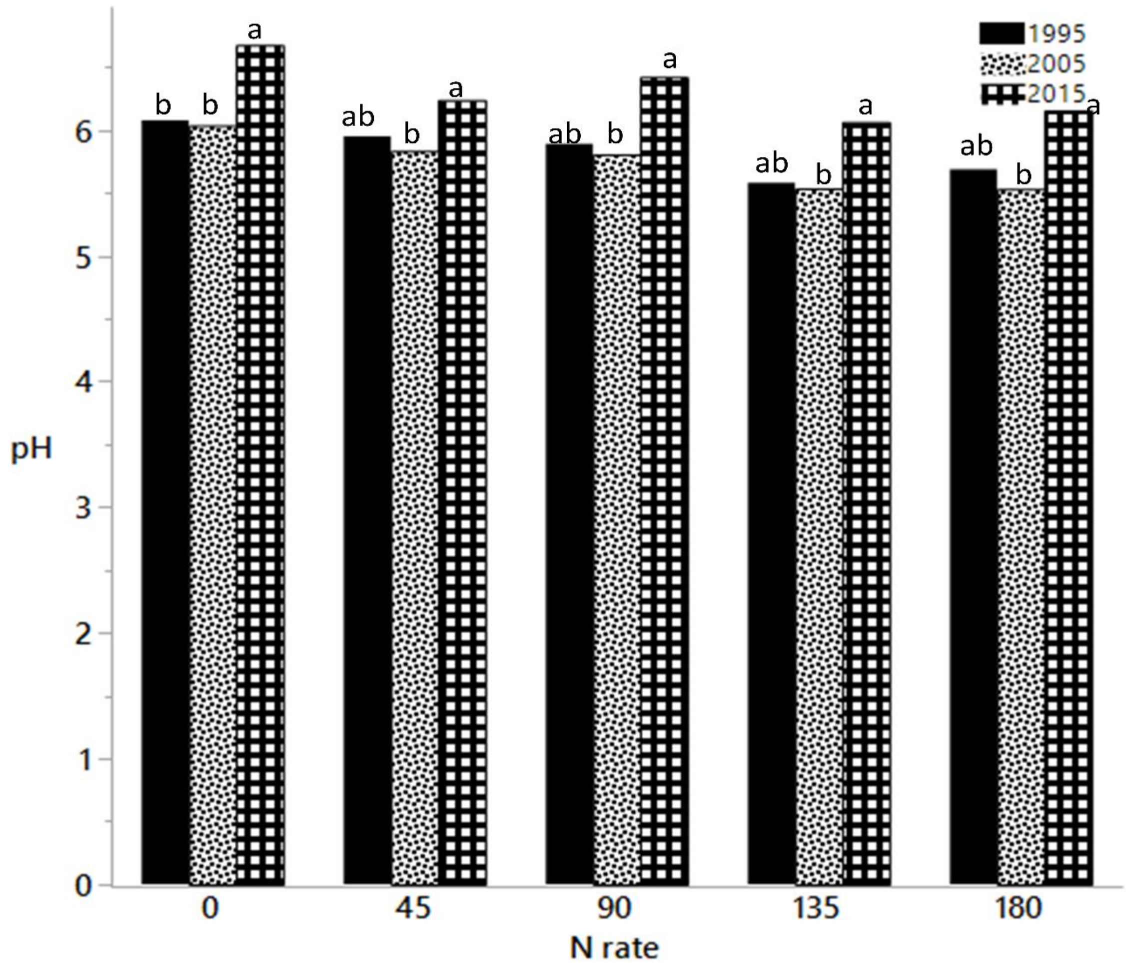

Fig. S4. 2 Effect of inorganic N application rates on soil pH over time (1995-2005-2015) in winter wheat-fallow system.

Letters sharing the same letters above the bar are not significantly different at 0.05 probability level.

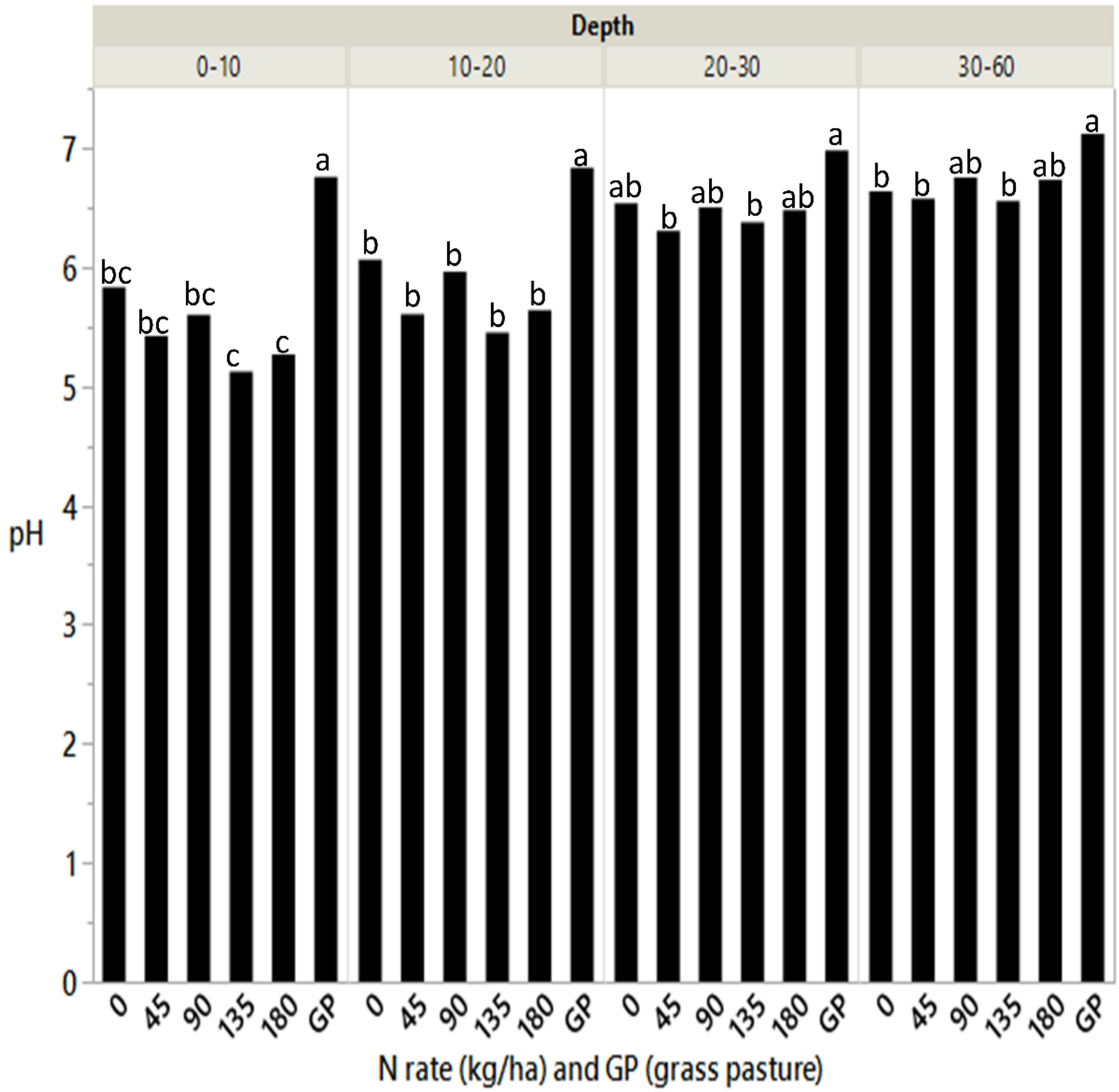

Fig. S4. 3 Changes in soil pH after 75 years of cultivation with different rates of inorganic N applications under disc tillage system compared with the soil pH of nearby undisturbed grassland pasture.

Letters sharing the same letters above the bar in each soil depths are not significantly different at 0.05 probability level.

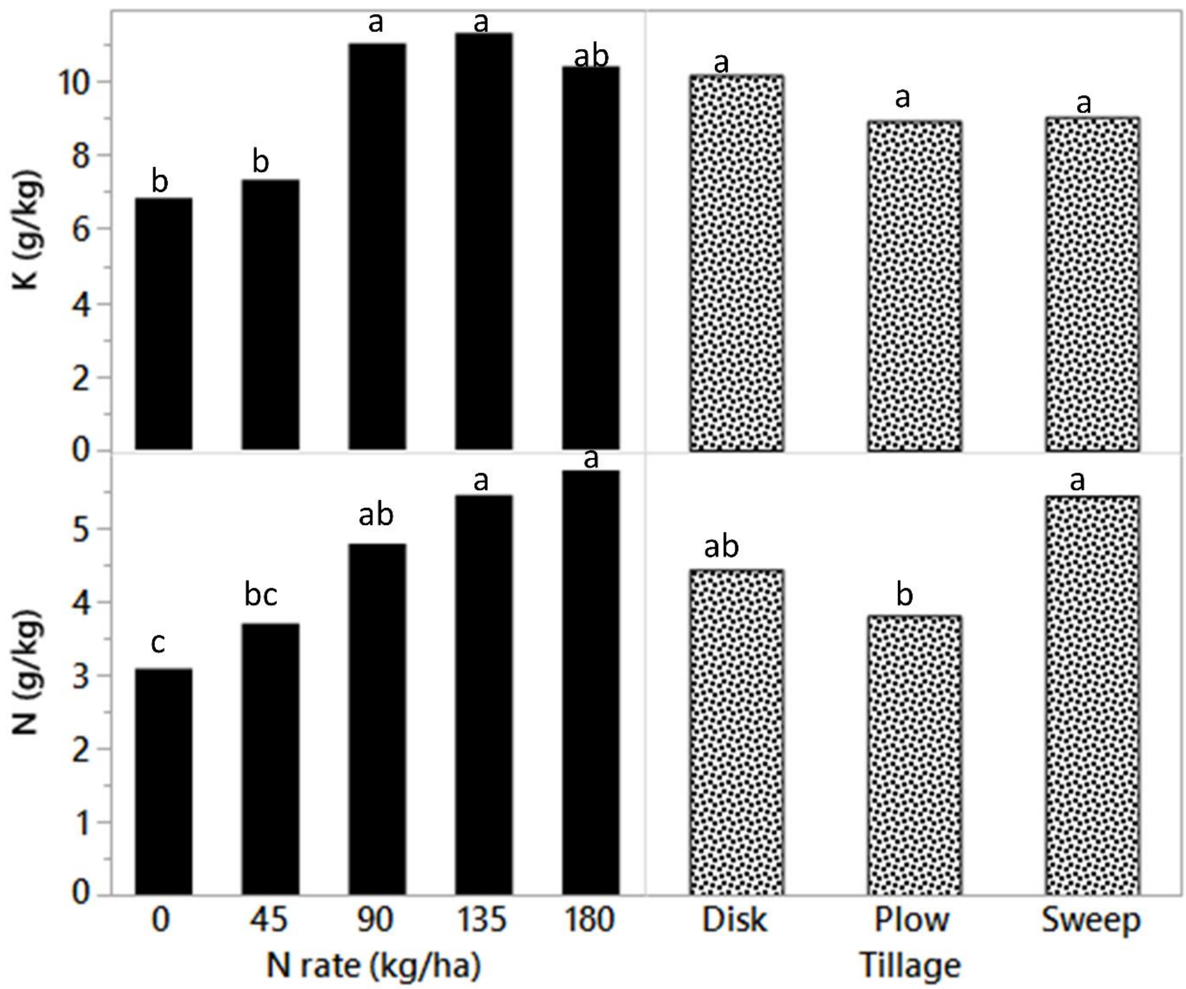

Fig. S4. 4 Effect of different inorganic N application rates and tillage systems on the accumulation of N and K in wheat straw in winter wheat-fallow cropping system in 2015.

Plow: moldboard tillage; Sweep: subsurface sweep tillage; and Disc: disc tillage

Letters sharing the same letters above the bar within the treatments are not significantly different at 0.05 probability level.

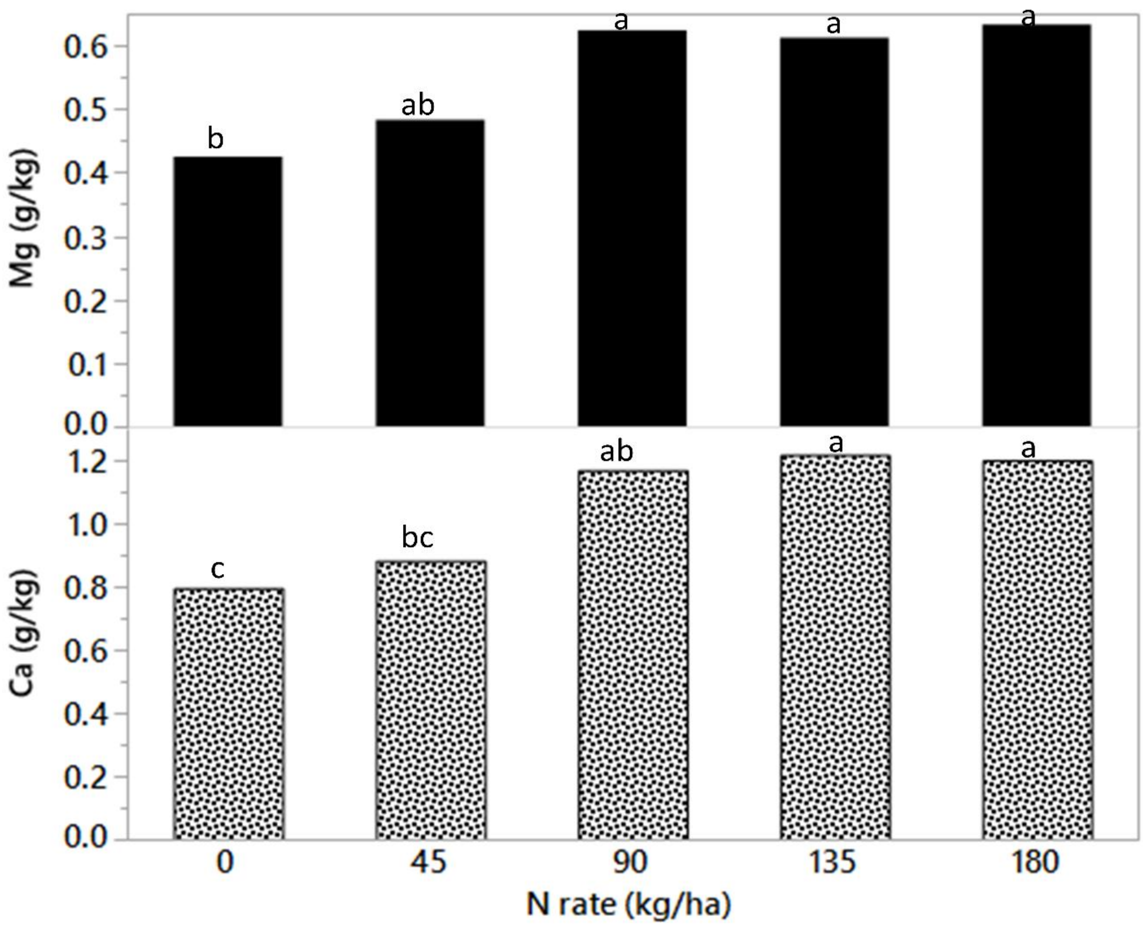

Fig. S4. 5 Effect of different rates of inorganic N applications on the accumulation of Ca and Mg in wheat straw in winter wheat-fallow cropping system in 2015.

Letters sharing the same letters above the bar within the treatments are not significantly different at 0.05 probability level.

Chapter 5

CHANGES IN SOIL AND WHEAT MICRONUTRIENTS AFTER 75 YEARS OF TILLAGE AND NITROGEN FERTILIZATION IN DRYLAND WINTER WHEAT-FALLOW SYSTEM

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Hero T. Gollany

Abstract

Tillage and nitrogen fertilization (N) can alter some of the soil properties such as pH and organic matter. These properties affect the micronutrients dynamics of the soil and the nutrients content in the plant. A study was conducted to determine the effect of 75 years of tillage and N application rates on the distribution of Mehlich III extractable Mn, Cu, Zn, B, and Fe in soils and accumulation of the same nutrients in wheat grain and straw. Tillage systems included moldboard (MP), disk (DP), and subsurface sweep (SW) and the N application rates were 0, 45, 90, 135, and 180 kg N ha^{-1}. Tillage and N application effects on soil micronutrients were compared with that of nearby undisturbed grass pasture (GP) to detect the changes in 75 years. The concentration of soil Mn was greater under DP (131 mg kg^{-1}) than under MP (111 mg kg^{-1}) whereas soil Cu was greater under MP (1.13 mg kg^{-1}) than under DP (0.79 mg kg^{-1}). The concentration of soil Cu, Mn, Zn, and pH had declined at the 0-10 cm soil depth in the cultivated plots compared to the ones in GP. The cultivated plots lost at least 43% and 53% of extractable Zn and Cu, respectively, in 75 years of continuous N fertilizer and tillage treatments. Increased N application rates increased Mn accumulation in wheat grain and straw. The results indicate that DP and inorganic N application have the potential to maintain the micronutrient status in soil and desirable nutritional quality of wheat grain. However, lack of proper adjustment of tillage methods and N application rates might potentially constrain the productivity of the dryland winter wheat-fallow cropping system.

Keywords: Boron, Copper, Iron, Manganese, pH, Zinc.

Abbreviations: soil organic matter (SOM);

Introduction

Tillage affects physical, chemical, and biological properties of soil, especially soil pH, organic matter (OM) and nutrient availability (Awale et al., 2017; Rasmussen and Rhode, 1988). The biological oxidation of OM is accelerated by tillage through changes in soil water, aeration, temperature, and nutritional environment (Thomas et al., 2007). Therefore, soil under no-tilled or reduced tilled plots would have a higher amount of soil organic matter (SOM) than soil under conventionally tilled plots. Furthermore, the distribution of OM is also affected by the tillage methods because of the differences in the soil inversions and mixing of soil (Thomas et al., 2007). Similarly, N fertilization also plays a significant role in the dynamics of SOM through increasing crop biomass. It is a well-established fact that SOM is the storehouse of plant essential macro and micronutrients because the accumulation of SOM will increase the amount of mineralizable plant essential organic nutrients (de Santiago et al., 2008; Kopittke et al., 2017). Furthermore, different tillage methods and fertilization are the main causes of stratification of OM (crop residues) and nutrients (Lavado et al., 1999). Hence, understanding the role of tillage and N fertilization in the availability and distribution of macronutrients and micronutrients is crucial in formulating and developing cropping system strategies for sustainable agriculture.

The chemistry of micronutrients availability is complex and is largely affected by tillage methods in cultivated plots (Mahler et al., 1985). It has been reported that even a slight soil disturbances or reduced tillage lead to increased chemical, and microbial activity and biomass (Feng et al., 2003). There have been disagreements between research reports regarding tillage effects on soil and crop Fe, Zn, Cu, and Mn. Mahler et al. (1985) observed higher extractable Fe and Mn under conventional and reduced tillage than under no-tillage in the soils of northern Idaho whereas other researchers reported the opposite in their studies (de Santiago et al., 2008; Edwards et al., 1992; Franzluebbers and Hons, 1996; Hargrove et al., 1982). Lavado et al. (1999) and Hickman (2002) reported unaffected extractable concentration of soil Cu and Zn by tillage system. However, Shuman and Hargrove (1988) observed lower Mn and Fe under no-tillage and reduced tillage than under conventional tillage due to the shift of exchangeable forms of Mn and Fe from inorganic?? to organic forms under no-tillage or reduced tillage. Under reduced and no-tillage, the availability of some micronutrients become higher in the upper surface due to the metal complexation by OM, and thus will be in readily available forms (Grčman et al., 2001). Additionally, higher OM increases microbial exudates, which supply additional micronutrients, especially Fe (Shenker et al., 1999), Cu, Mn, and Zn (Tao et al., 2003a) to the soil. A similar effect of OM on B has been reported by Sarkar et al. (2014).

The other key player for micronutrients availability in plants and soils is N and its availability. Since N is the most common limiting nutrient in the plant growth and development (Vitousek and Howarth, 1991), most of the N fertilization experiments were focused on developing strategies for agricultural management to alleviate N limitations (Bai et al., 2010; Granath et al., 2009). In addition to altering the dynamics of N, N fertilization greatly influence micronutrients concentrations availability in soils and plants (Malhi et al., 1998; Wang et al., 2017). Earlier results had shown that the concentrations of some micronutrients increased with high N application rates whereas other nutrients were negatively correlated to N application rates. For example, Fan et al. (2008) found greater concentrations of Zn and Fe in wheat grain while some studies observed a decline in Zn and Fe in wheat grain with high N rates (Cakmak et al., 2010; Kutman et al., 2010). Inconsistency in effect of varying N application rates on soil micronutrients dynamics were also reported previously. Previous studies indicated that N fertilization significantly increased the availability of Cu, Mn, and Fe (Malhi et al., 1998; Wang et al., 2017); however, Malhi et al. (1998) reported that high N fertilization rate decreased the concentration of available Cu and Zn in soils. The application of N fertilizers is largely controlled by crop demands while the input of micronutrients is less regulated. Therefore, there is a need to further investigate how N application rate impacts the concentration of micronutrients.

The plant requires micronutrients, such as Mn, Cu, Fe, B, and Zn in very small amount but the limitation on any of these nutrients will affect the plant's life cycle and productivity. The plant essential micro and macronutrients are necessary for the maintenance of certain physiological processes (Havlin et al., 2013). For example, Mn plays a key role in photosynthesis; Cu plays essential role in carbohydrate and N metabolism through the enzyme involved in the electron transport chain; Fe is necessary for oxidation-reduction reactions and maintenance of the structure of the chloroplast; Zn plays important role in the enzyme synthesis and is involved in the regulation of gene transcription; and B plays a key role in the cell wall formation and maintenance of structural and functional integrity of biological membranes (Prasad and Power, 1997; Srivastava and Gupta, 1996). Thus, given the roles played by Mn, Cu, Fe, B, and Zn in crop growth and metabolism, the evaluation of the concentrations of these nutrients should not be ignored when developing sustainable agriculture strategies. The knowledge on the dynamics of plant essential micronutrients as a function of tillage methods and N application rates becomes more important because the available literature is limited and inconsitnet. These results further confirm that the response of micronutrients to the crop and soil management depends on other factors as well, such as the plant species, climate, and soil properties (Tian et al., 2016). Currently, available the literature describing the impacts of tillage methods and N fertilization rate is inconsistent and relatively insufficient. Therefore, this study was undertaken with the objective to investigate: (i) the long-term effect (75 years) of continuous tillage and N fertilization rates on Mn, Cu, B, Fe, and Zn in soil and wheat grain and straw, (ii) 20 years' trend in the dynamics of Mn, Cu, Fe, B, and Zn in soil and plants, (iii) distribution of Mn, Cu, Fe, B, and Zn in soils as affected by long-term effect of tillage and N application rates. We formulated the following hypothesis:

i. The concentrations of extractable micronutrients are greater under conservation tillage [disk plow (DP) and subsurface sweep (SW)] than under conventional tillage [moldboard plow (MP)]. The base of this hypothesis is that the greater amount of crop residues left and lower volume of soil disturbance under SW and DP will accumulate and conserve more SOM than under MP. Soil OM is the storehouse of plant essential nutrients, and;

ii. The plots with higher N application rates will have a greater concentration of micronutrients than the one in the zero or low N rates application plots. This hypothesis is based on the well-established fact that the N enhances higher crop root biomass and increase SOM.

Materials and methods

Study sites and experimental design

The study was conducted at the tillage- fertility (TF) long-term experiment (LTE) plots of Columbia Basin Agriculture Research Center (CBARC), near Pendleton, OR (45°42’ N, 118°36’ W, elev. 438 m a.s.l.). The slope of the experimental area is 2-4% and has a well-drained Walla Walla silt loam soil (coarse-silty, mixed, superactive, mesic Typic Haploxeroll). The mean annual temperature is 10°C, ranging from -1°C in January to 21°C in July, and mean annual precipitation is 437 mm. The soil properties of the top 30 cm soil depths are 20% clay, 68% silt, 1.1% organic C kg^{-1}, and 16 $cmol_c$ kg^{-1} cation exchange capacity (CEC) (Rasmussen and Rohde, 1989).

This TF experimental plot was established in 1940 as a randomized block, split-plot tillage and fertility experiment with three replications under dryland winter wheat- 14 months fallow (WW-F) cropping system. Each block was divided into three main plots as tillage treatments and each main plot was divided into five subplots as nitrogen (N) fertilization treatments. The three tillage systems are moldboard plow (MP), disk plow (DP) and subsurface sweep (SW)] with the size of 35 by 40 m each. Subplots comprised of five N fertilization rates

(0, 45, 90, 135, and 180 kg N ha^{-1}) and were 5.8 by 40 m in size. The percentage of residue cover left by MP, DP, and SW were 7%, 34%, and 43% respectively, and the tillage depths were 23 cm, 10 cm, and 15 cm, respectively.

A nearby grass pasture (GP), which is undisturbed since 1931, was used as the reference for this study to detect the changes by treatments of this study over time. The dominant grasses in this pasture are blue-bunch wheatgrass (*Agropyron spicatum* L. Pursh) and Idaho fescue (*Festuca idahoensis* L. Elmer).

Field operations and soil sampling

After the wheat harvest in late July, the stubble was left undisturbed until the primary tillage operations in late March. The plots were rod weeded two to four times between April and October to control weeds and to maintain seed zone moisture. During the first week of October, N fertilizer was added to a depth of 10 cm using Viper Coulter (Yetter Manufacturing Inc. Colchester, IL). Urea ammonium nitrate supplied the inorganic N in the plots. A week after N fertilization, wheat was seeded at the rate of 72 ± 5 kg seed ha^{-1} in 25 cm rows spacing. JD8300 drill (Deere and Company, Moline, IL) was used to sow wheat before 2002 and thereafter Case IH 5300 disk drill (Klamath Basin Eq. Inc. Klamath Falls, OR) has been used to sow the seed. The variety of seed was Malcolm during the 1995-2005 period, and after that Stephens was used; both were semi-dwarf varieties of winter wheat. Weeds within the growing season were controlled using herbicides.

After the wheat harvest in the summer of 2015, the soils were sampled by compositing the cores of north-central and south-central sides of each plot whereas the wheat grain and straw samples were collected from the center of the plot. The soils were sampled from four depths (0-10, 10-20, 20-30, and 30-60 cm) in this study using a truck-mounted Giddings Hydraulic Probe (Giddings Machine Company, Inc., Windsor, CO) and a steel sampling tube (internal diameter 3.6 cm). In this study, the soil and plant samples from 1995 (archived samples), 2005 (archived samples) and 2015 cropping season were used. The ground soil samples were brought to the Central Analytical Lab (CAL, Oregon State University) to determine the extractable Mn, Cu, Fe, B, and Zn. Mehlich III extraction method (Mehlich, 1984) was used to extract available Mn, Cu, Fe, B, and Zn from the soil samples, whereas dry ash method (reference needed) was used to extract the total concentration of these nutrients from the grain and straw samples. An inductively coupled plasma-optical emissions spectroscopy (ICP-OES, Model #2100 DV, Waltham, Massachusetts, USA) were used to measure the nutrients in soil and plant tissue extracts (solutions). Soil pH data for 1995, 2005, and 2015 were provided by the CBARC, and were determined with a pH electrode using 10 g samples in a 1:2 soil to 0.001M $CaCl_2$ solution.

Statistical analysis

Three-way ANOVA with a split-plot design was used to test the effect of the treatments on the concentration of Mn, Cu, Fe, B, and Zn using the mixed model procedure of JMP© version 13 (SAS Institute Inc, 2014). Tillage system, N rates, year, and soil depths were considered the fixed effects while replications and their interactions were considered the random effects. Multiple comparisons with Tukey methods were performed to determine differences in nutrients and letter groupings were generated using a 5% level of significance.

The data of soil pH were converted to H^+ concentration (µmol L^{-1}) before ANOVA was performed. The pH scale is a logarithmic and a small difference in pH represent huge differences. However, the mean comparisons of soil pH represent the original pH data.

Results and discussion

Tillage effect on soil micronutrients

The magnitude of soil disturbance was lower under DP (10 cm), followed by SW (15 cm) and MP (23 cm) in this study. In addition to this, the tillage systems differed in the percentage of residue cover left in the field. It is well documented that the availability of soil micronutrients is associated with the SOM (de Santiago et al., 2008; Mahler et al., 1985; Prasad and Power, 1997; Srivastava and Gupta, 1996). In this study, soil Cu was influenced by the tillage methods, and soil Mn was affected by the interaction between tillage methods and the soil sampling depth (Table S5.1). The DP (131 mg Mn kg^{-1}) had greater Mn in the upper 10 cm depth than under MP (111 mg Mn kg^{-1}), whereas MP had greater Mn (84 mg kg^{-1}) in the 20-30 cm depth than under SW (68 mg kg^{-1}) (Fig. 5.1). The Mn under DP and SW significantly declined with the increasing soil depth while MP declined beyond the 20-30 cm soil depth (Fig. 5.1). Our results agree with previous studies, which also reported that the extractable Mn was greater in the 0-10 cm soil depth under tillage system that promoted accumulation of plant residues on the soil surface and resulted in poor soil mixing (de Santiago et al., 2008; Edwards et al., 1992; Lavado et al., 1999; Obour et al., 2017). In this study, the DP and SW were used as a conservation tillage practices.

The MP (1.13 mg Cu kg^{-1}) had greater Cu than under DP (0.79 mg Cu kg^{-1}) in the 0-

10 cm soil depth (Fig. 5.1), which is in line with some previous reports (Franzluebbers and Hons, 1996; Lavado et al., 1999). However, Hargrove (1985) and Mahler et al. (1985) observed lower concentration of extractable Cu in MP than under reduced tillage, while Edwards et al. (1992) did not find significant effect of tillage on soil Cu. The extractable soil Cu significantly increased with increase in the soil depth under all tillage systems (Fig. 5.1). This result partially agrees with Franzluebbers and Hons (1996) who reported increased Cu concentration until 30 cm depth whereas, in this study, Cu increased beyond the 30 cm soil depth. This behavior of soil profile distribution of Cu can be explained by its chemical relation with SOM. The Cu forms strong bonding with SOM and migrates into subsoil because the SOM acts as a carrier for Cu by forming soluble metal-organic complexes (Li et al., 2007). The concentrations of extractable Cu under DP were 0.79 mg Cu kg^{-1}, 1.63 mg Cu kg^{-1}, 2.06 mg Cu kg^{-1}, and 2.35 mg Cu kg^{-1} at the 0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm soil depths, respectively (Fig. 5.1).

The concentration of Zn was largely influenced by the tillage methods in this study and was significantly greater under DP (1.92 mg kg^{-1}) than under SW (1.38 mg kg^{-1}) but was comparable with Zn under MP (1.56 mg kg^{-1}) (Fig. 5.2). Several studies reported higher concentration of extractable Zn under conservation tillage than under MP tillage (Edwards et al., 1992; Mahler et al., 1985; Shuman and Hargrove, 1988).

N fertilization effect on soil micronutrients

In this study, only Cu was found to be affected by N fertilization rates and declined with the application of N fertilizer (Fig. 5.2). Extractable Cu was significantly greater at the

0 kg N ha^{-1} than in the plots with N application. Inorganic N fertilization 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; Srivastava and Gupta, 1996).

Trend of soil micronutrients dynamics over 20 years (1995-2015)

Interestingly, the concentration of Cu increased over the years and was the highest in 2015 (Fig. S5.3). The Cu concentration was greater under DP (1.76 mg kg^{-1}) than under MP (1.46 mg kg^{-1}) and SW (1.38 mg kg^{-1}) in 1995, whereas it was comparable between MP and DP in 2005 and in 2015. The MP (2.17 mg kg^{-1}) had significantly higher Cu than that under SW (1.76 mg kg^{-1}) in 2015. A three-way interaction of N rate, tillage and year were observed for extractable Zn, Fe, and B in this study (Table 5.1). However, we did not observe any consistent trend of micronutrients change over the 20-years time period. Overall, the extractable Zn, Fe, and B were significantly greater in 2005 than in 1995 and 2015 in most of the treatments (Table 5.1).

Soil micronutrients after continuous use of N fertilizer and tillage for 75 years

Since DP was the best tillage in maintaining micronutrient compared to the other tillage treatments in this study, we compared the N fertilization effect of DP with the reference (GP) of this study to detect the effect of the treatments over a time period of 75 years. Iron was not tested in the soils of GP and B was detected only at 20-30 cm depth in GP.

Extractable Mn, Zn, and Cu and soil pH significantly declined after 75 years of continuous use of N fertilizer in the upper 10 cm soil depth at all the tested N rates (Table 5.2). It is a well-documented that N fertilization lowers soil pH and this enhances the availability of micronutrients (Fan et al., 2012; Rutkowska et al., 2014; Singh et al., 2010b). It was evident that the soil pH had decreased after 75 years of cultivation (Table 5.2). However, this acidifying condition in the TF plots did not increase micronutrients availability over the time of this study, suggesting that the continuous removal through crop harvest and meager contribution through crop residue has depleted micronutrients in the soil resource. The other plausible reason for the significant decline of Mn, Cu, and Fe in the upper 10 cm soil would be due to the presence of a higher percentage of OM (crop residue) in the upper 10 cm soil than deeper in the soil profiles. The availability of these nutrients in the soil solution decrease with the higher OM, as these elements have high affinity for OM that result in stable bonding (Rutkowska et al., 2014). The concentrations of Zn and Cu had pronounced decline than other nutrients; extractable Zn decreased by at least 43% and Cu decreased by at least 53% in the upper 10 cm soil depth compared with their respective concentrations in GP (Table 5.2). The concentrations of Mn and Zn at the 20-30 cm and 30-60 cm soil depths were comparable to these of GP. At the 20-30 cm soil depth, N fertilization contributed to decrease in extractable Cu when compared with GP. Similarly, at the 30-60 cm soil depth, Cu decreased markedly in plots that received N fertilizer above 45 kg N ha-^{1}.

Treatments effect on micronutrients in wheat grain and straw

The Mn concenration in wheat straw was largely influenced by the N application rates, whereas Cu, Fe, and B were influenced by the interaction of tillage systems and year (Table

S5.3). The straw Mn linearly increased with the increased application rates of N (Fig. 5.3). The concentration of straw Mn was 27 mg kg^{-1}, 32 mg kg^{-1}, 44 mg kg^{-1}, 47 mg kg^{-1}, and 50 mg kg^{-1} at 0, 45, 90, 135, and 180 kg N ha^{-1}, respectively. However, the concentrations of Cu, Fe, and B in the straw declined over the 20-year period (1995-2015) under all the tillage systems (Table 5.3).

Except for the concentration of Mn, none of the micronutrients in wheat grain were affected by the TF treatments (Table S5.3). The grain Mn increased with the increasing rate of N fertilizer, but no increment increase was observed beyond 135 kg N ha^{-1} (Fig. 5.3). The concentration of grain Mn were 41 mg kg^{-1}, 44 mg kg^{-1}, 48 mg kg^{-1}, 54 mg kg^{-1}, and 52 mg kg^{-1} at 0, 45, 90, 135, and 180 kg N ha^{-1}, respectively. Contrasting to these results, Hamnér et al. (2017) reported that N fertilization did not influence grain Mn in their study; however, the same authors found increased concentrations of Fe, Zn, and Cu in the wheat grain as a function N fertilization. The relationship between N fertilization and micronutrients is unclear but ample studies indicated the relation of N to the movement of micronutrients within plants (Distelfeld et al., 2007; Shi et al., 2010; Uauy et al., 2006).

Conclusion

The findings of this study are significant in that the information on the effect of 75 years of tillage and N fertilization on the distribution of Mehlich III extractable soil Mn, Cu, Fe, Zn, and B and in wheat (grain and straw) revealed how different tillage systems and N application rates affected micronutrients over long term. Furthermore, the study demonstrated the declining trend in the concentrations of extractable soil Mn, Cu, and Zn in cultivated plots (cultivation effect) when compared to the ones in GP. From this study, it is now evident that the continuous cultivation with N fertilization and tillage over time could significantly decrease the concentration of plant essential nutrients in cultivated plots. We found that DP and higher N application rates were more favorable than the other treatments of this study, hence, some modification on these agricultural practices could help in reducing the micronutrients' decline rate over time.

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Table 5. 1 Three-way interaction effect of tillage system, N application rate, and year on extractable zinc, iron, and boron in soil.

	1995			2005			2015		
N rate (kg ha^{-1})	MP[1]	SW	DP	MP	SW	DP	MP	SW	DP
				Zinc (mg kg^{-1})					
0	0.14a[2]	0.48a	0.40a	4.95a	4.61a	5.36a	0.48a	0.90a	0.54a
45	0.14a	0.42a	0.34a	5.52a	2.31b	3.45ab	0.47a	0.41a	0.46a
90	0.32a	0.37a	0.31a	4.50b	3.44b	7.32a	0.34a	0.35a	0.77a
135	0.16a	0.23a	0.51a	3.39ab	4.89a	2.01b	0.72a	0.28a	0.72a
180	0.09a	0.34a	0.38a	1.90b	1.31b	5.96a	0.20a	0.32a	0.64a
				Iron (mg kg^{-1})					
0	142a	151a	147a	316a	337a	364a	145a	138a	128a
45	143a	140a	157a	350a	382a	268b	141a	156a	166a
90	163a	143a	126a	341a	352a	341a	162a	152a	139a
135	153a	161a	165a	342a	310a	302a	167a	181a	173a
180	164a	172a	157a	330a	293a	320a	192a	199a	181a
				Boron (mg kg^{-1})					
0	8.5a	9.1a	9.0a	8.6a	8.5a	8.5a	2.2b	2.4ab	2.5a
45	8.8a	8.1a	7.7b	13.1a	8.9b	8.4b	2.8a	2.1c	2.5b
90	8.4a	8.3a	8.6a	8.9a	8.8a	7.9b	2.5b	2.3b	2.8a
135	8.8a	8.6a	8.9a	8.4a	8.5a	8.5a	2.3b	2.2b	2.6a
180	8.7a	8.1b	8.3b	8.1a	8.3a	8.3a	2.2b	2.1b	2.4a

[1]MP: moldboard plow; DP: disk plow; and SW: subsurface sweep

[2]Means followed by the same letter in a row indicate no significant differences between tillage systems within each year at 0.05 probability level.

Table 5. 2 Impact of 75 years of inorganic N application rate (N rate) on soil micronutrients and soil pH in dryland winter wheat-fallow cropping system under disc tillage management compared to nearby undisturbed grass pasture (GP).

Nutrients	Soil depth (cm)	N rate (kg ha^{-1})						Cultivation effect[2]
		0	45	90	135	180	GP	
		---------------------- mg kg^{-1} --------------------------------------						
Manganese	0-10	124b[1]	120b	134ab	138ab	139ab	166a	16% ↓
	10-20	103ab	84b	88b	104ab	103ab	130a	21% ↓
	20-30	77a	74a	73a	67a	75a	94a	18% ↓
	30-60	85a	74a	76a	72a	71a	95a	11% ↓
Zinc	0-10	2.6b	1.7b	3.5b	1.8b	1.4b	6.0a	43% ↓
	10-20	2.0a	2.2a	2.3a	1.4a	3.1a	2.8a	11% ↑
	20-30	1.5a	0.5a	2.3a	0.2a	3.2a	1.1a	49%↓ 43%↑
	30-60	2.3a	1.2a	3.1a	0.4a	1.6a	1.0a	28%↓ 63%↑
Copper	0-10	1.1b	0.9b	0.7b	0.6b	0.6b	2.3a	53% ↓
	10-20	1.5b	1.9b	1.6b	1.5b	1.6b	2.6a	28% ↓
	20-30	2.4bc	2.2bc	2.1bc	1.7c	1.9bc	2.8a	15% ↓
	30-60	2.6ab	2.5ab	2.1b	2.2b	2.4b	3.1a	11% ↓

Boron	0-10	6.6a	6.2a	6.5a	6.7a	6.1a	0.0b	ND
	10-20	6.7a	6.2a	6.4a	6.5a	6.2a	0.0b	ND
	20-30	1.3a	0.7a	1.9a	0.2a	2.4a	1.1a	34%↓17%↑
	30-60	6.6a	6.3a	6.4a	7.0a	6.3a	0.0b	ND
pH	0-10	5.8b	5.4b	5.6b	5.1b	5.3b	6.8a	14% ↓
	10-20	6.1b	5.6b	5.9b	5.4b	5.6b	6.8a	11% ↓
	20-30	6.5ab	6.3b	6.5ab	6.4ab	6.5ab	7.0a	06% ↓
	30-60	6.6b	6.6b	6.8ab	6.6b	6.7ab	7.1a	05% ↓

[1]Means sharing the same letter within the rows are not significantly different at 0.05 probability level.

[2]Percentage obtained from the difference in the value from grass pasture (GP) and the highest value (if GP is greater) or the lowest value (if GP is lower) from the treatments within each soil depths, so that minimum deviation from the GP is calculated in either case. The downward and upward arrow indicates decline and incline from the soils of GP after cultivation respectively. The column with both upward and downward in the same cell indicates that respective soil depth has some treatments that have greater value than GP and has some treatments with lesser value than GP.

Table 5. 3 Interaction effect of tillage system and year on total concentrations of copper, iron, and boron accumulation in wheat straw.

Nutrients	Tillage	<------------------------Year--------------------->		
		1995	2005	2015
		---------------------- mg kg^{-1} ----------------------		
Copper	Moldboard	2.0aB[1]	3.4aA	0.6aC
	Sweep	2.4aA	1.7bA	0.6aB
	Disk	1.7aA	2.3abA	0.5aB
Iron	Moldboard	48aA	52aA	32aB
	Sweep	50aA	30bB	29aB
	Disk	48aA	49aA	30aB
Boron	Moldboard	3.7aB	5.8aA	2.3aC
	Sweep	3.4aA	4.2abA	2.0bB
	Disk	3.4aAB	3.1abA	2.3aB

[1]Means followed by the same uppercase letter in a row indicate no significant differences between years for each tillage system and means followed by same lowercase letters in a column indicates no significant differences between tillage system in each year at 0.05 probability level.

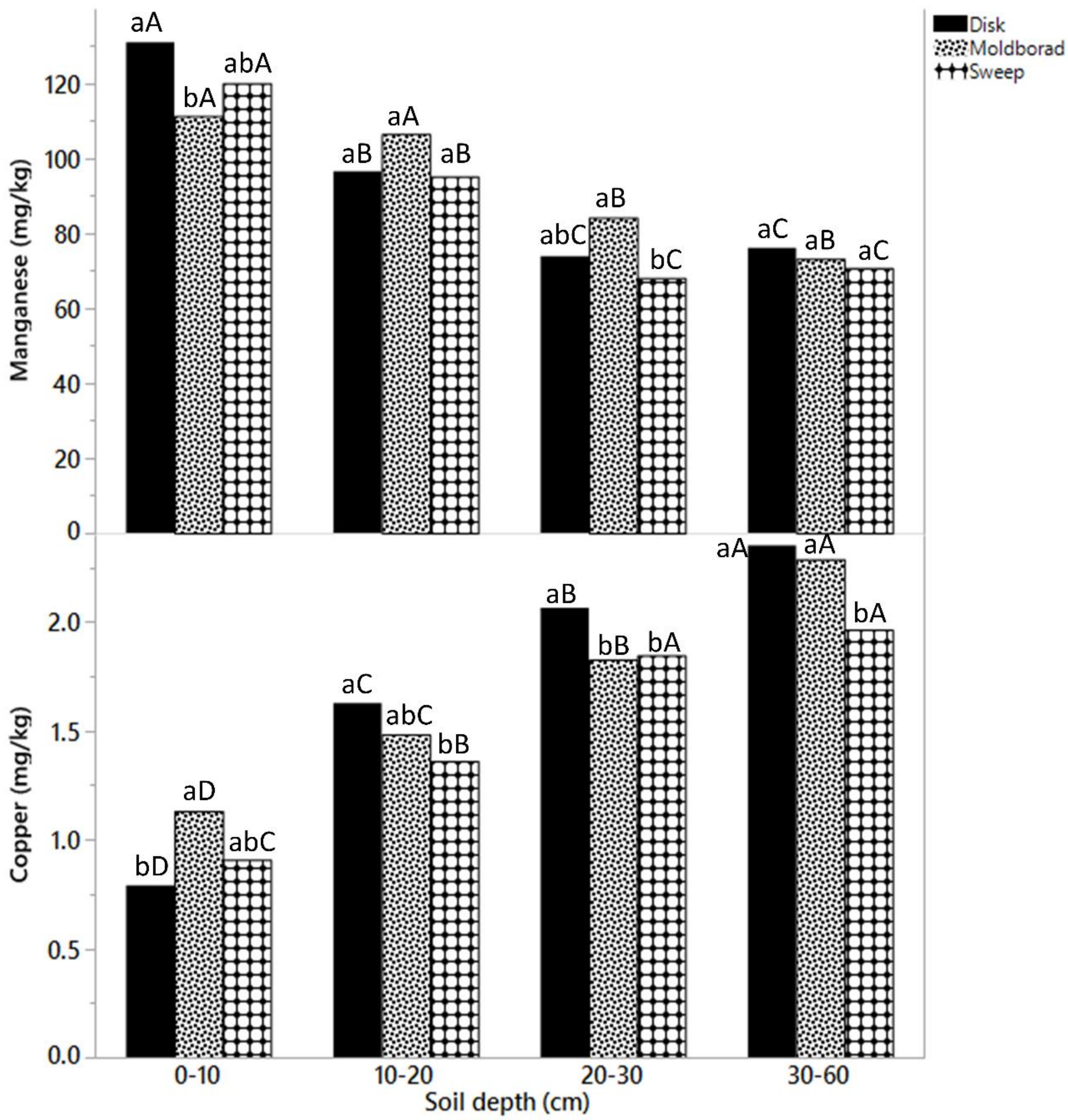

Fig. 5. 1 Mehlich III extractable soil copper (bottom) and manganese (top) as influenced by the interaction of tillage system and soil depth in 2015.

Means sharing the same letters are not significantly different at 0.05 probability level. Lowercase letters are comparison of tillage system within each soil depth, and uppercase letters are comparison of tillage system across the four soil depths.

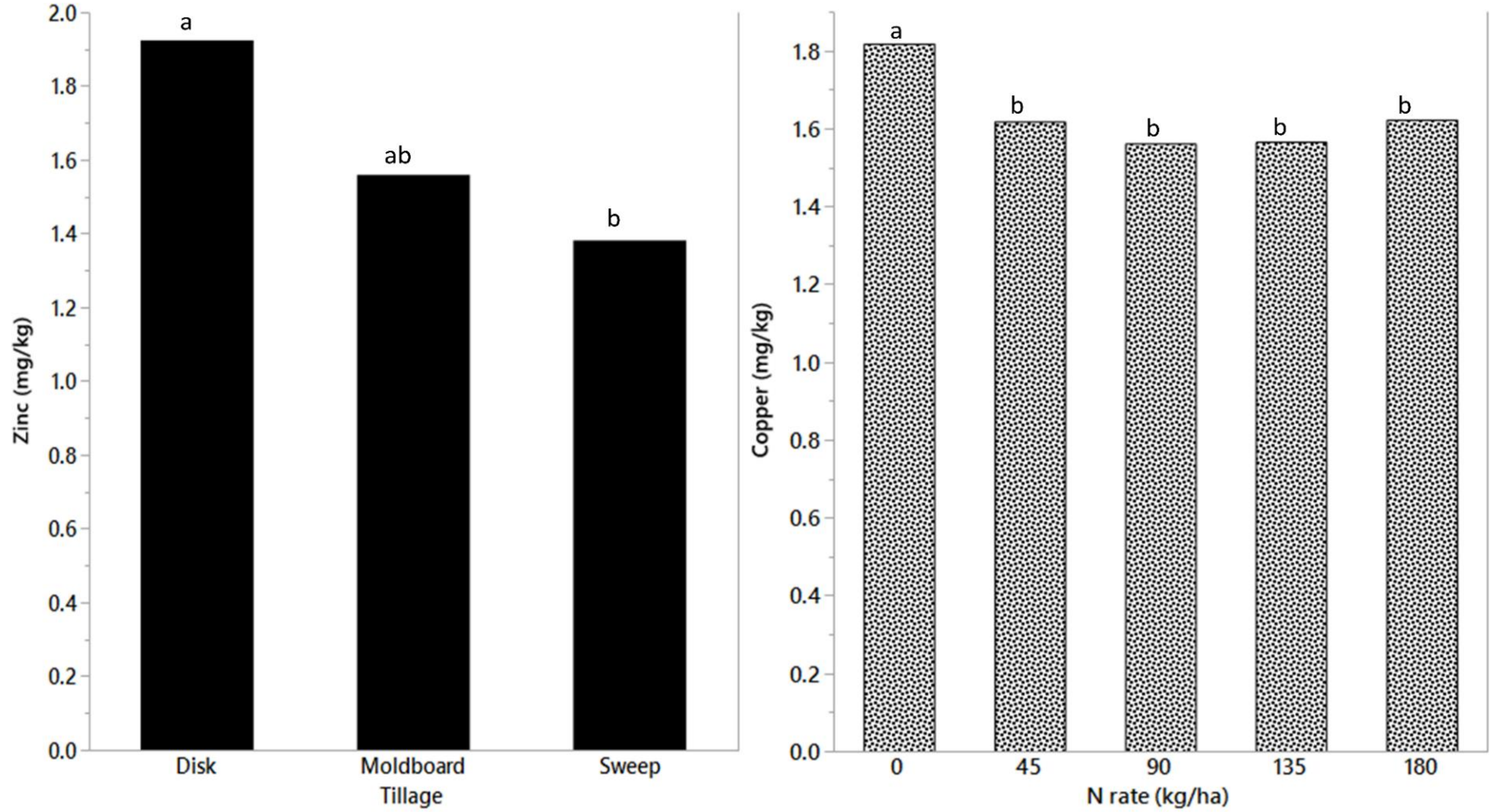

Fig. 5. 2 Mehlich III extractable soil zinc (left) and copper (right) as influenced by tillage system and N application rates in 2015 respectively.

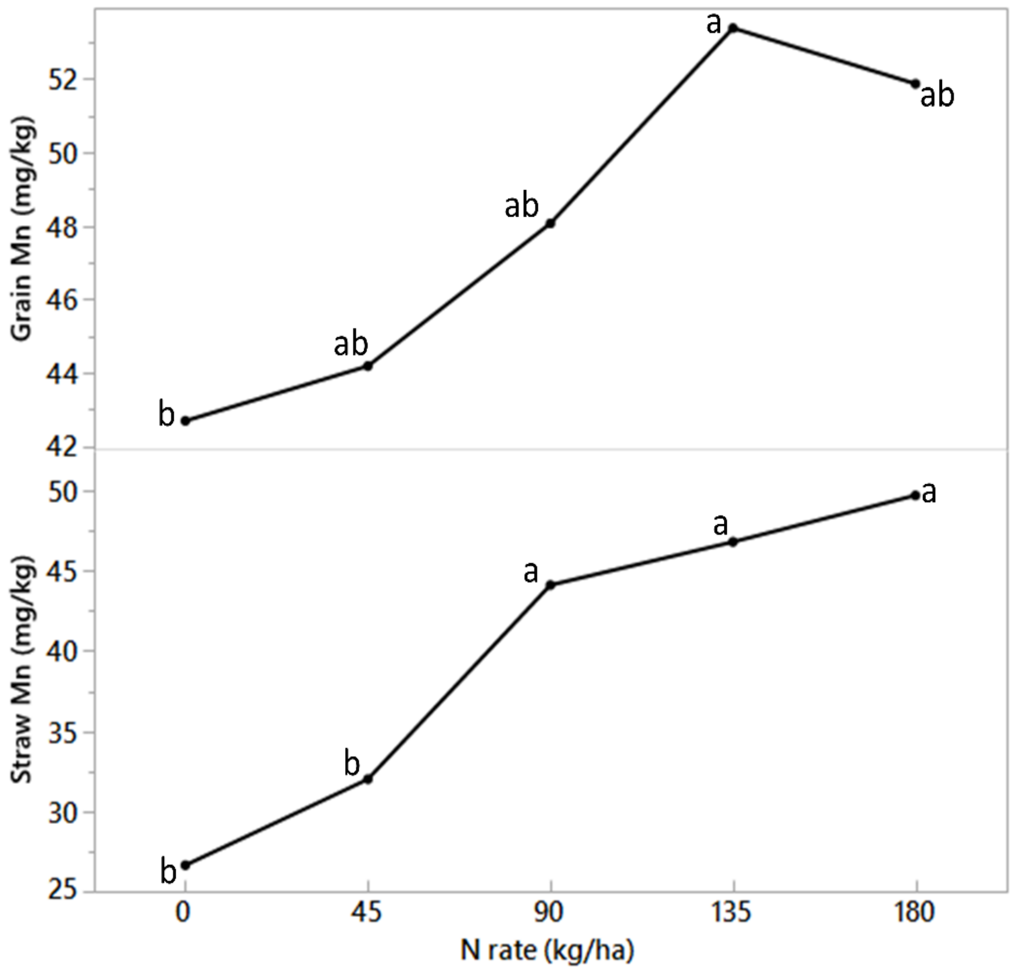

Fig. 5. 3 The long-term (75 years) effect of N application rates on wheat straw manganese (bottom) and grain manganese (top).

Letters sharing the same letters above line indicates no significant differences between treatments at 0.05 probability level.

Table S5. 1 ANOVA for extractable micronutrients in soil as influenced by tillage, N rate, and depth.

Source of variation	Manganese	Copper	Zinc	Iron	Boron
Tillage (T)	0.12	<0.01	0.05	0.61	0.44
Depth (D)	<0.01	<0.01	0.17	<0.01	0.96
N rate (N)	0.94	<0.01	0.06	0.78	0.68
T x D	0.01	<0.01	0.88	0.44	1.11
N x D	0.68	0.91	0.87	0.67	1.01
T x N	0.81	0.09	0.06	0.97	0.58
T x N x D	1.0	0.87	0.07	1.01	1.13

Table S5. 2 ANOVA for total concentrations of manganese, copper, zinc, iron, and boron in wheat straw and grain as influenced by tillage, year and N rates.

Source of variation	Manganese	Copper	Zinc	Iron	Boron
			Wheat Straw		
Tillage (T)	0.25	0.03	0.69	0.02	<0.01
Year (Y)	<0.01	<0.01	<0.01	<0.01	<0.01
N rate (N)	<0.01	0.94	0.61	0.15	0.12
T x Y	0.76	<0.01	0.94	<0.01	<0.01
N x Y	0.96	0.91	0.72	0.15	0.43
T x N	0.43	0.35	0.95	0.45	0.16
T x N x Y	0.55	0.09	0.98	0.97	0.26
			Wheat Grain		
Tillage (T)	0.67	0.86	0.31	0.91	0.13
Year (Y)	0.01	<0.01	<0.01	<0.01	<0.01
N rate (N)	0.03	0.58	0.58	0.86	0.37
T x Y	0.71	0.41	0.69	0.55	0.11
N x Y	0.45	0.56	0.71	0.81	0.78
T x N	0.37	0.89	0.61	0.87	0.52
T x N x Y	0.27	0.88	0.56	0.83	0.76

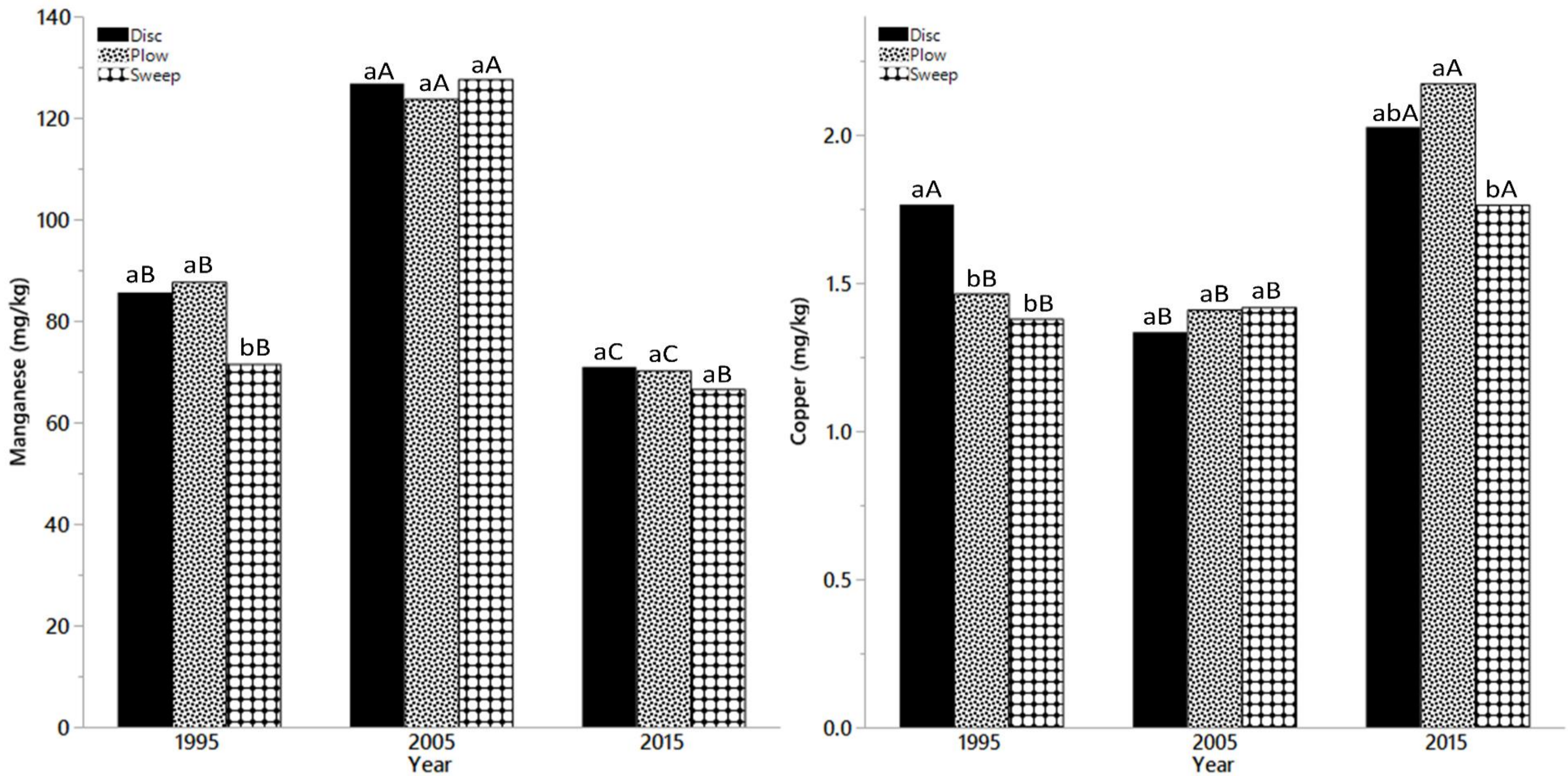

Fig. S5. 1 Mehlich III extractable manganese (left) and copper (right) in soil as influenced by the interaction of tillage system and year in soil.

Means sharing the same letters are not significantly different at 0.05 probability level. Lowercase letters are a comparison of tillage system within each year, and uppercase letters are a comparison of tillage system across the year.

Chapter 6

TILLAGE AFFECTS MACRONUTRIENTS IN SOIL AND WHEAT OF A LONG-TERM DRYLAND WHEAT- PEA ROTATION

Santosh Shiwakoti, Valtcho D. Zheljazkov, Hero T. Gollany, Baoshan Xing

Abstract

Tillage is known to significantly affect crop residue decomposition and soil nutrient dynamics, but their impacts on soil and plant macronutrients content with time have not been reported. This study was conducted to assess tillage timing and intensity influence on soil and wheat (*Triticum aestivum* L.) macronutrient content of winter wheat-dry pea (*Pisum sativum* L.) rotation (WW-P) under a dryland cropping system, and to compare macronutrients in the tillage treatments with a nearby long-term grass pasture (GP). The tillage treatments were fall tillage (FT), spring tillage (ST), no-tillage (NT) and disk/chisel tillage (DT/CT). Soil and wheat (grain and straw) samples from 1995, 2005, and 2015 were analyzed to determine soil organic carbon (SOC), total N and S, extractable P, K, Ca, and Mg, and soil pH. The impact of tillage on soil macronutrients was evident after 52 years of WW-P. In 2015, SOC in the 0-10 cm soil depth was greater under NT (18.9 g kg^{-1}) than under FT (14.0 g kg^{-1}) or ST (14.2 g kg^{-1}). Greater extractable P, S, and K levels were determined under NT than under FT or ST. The WW-P plots lost 28, 46, and 67% of SOC, Mg, and S, respectively, in the top 10 cm of soil compared with GP plots, whereas NT plots were the only plots in WW-P to maintain P (99 mg P kg^{-1}) comparable with GP plots (102 mg P kg^{-1}) at the same depth. The lack of mechanical soil mixing and decaying of crop residues near the soil surface leads to greater soil macronutrients under NT than under other tillage methods.

Keywords: Calcium, Magnesium, Nitrogen, No-tillage, Soil organic carbon, Sulfur

Introduction

Winter wheat-summer fallow (WW-SF) cropping system is a common dryland practice in the inland Pacific Northwest (PNW) (Ghimire et al., 2015; Schillinger and Papendick, 2008). Annual precipitation of approximately 420 mm has led to the wide adoption of WW-SF cropping system in this region (Payne et al., 2000). However, WW-SF is not sustainable due to its deleterious effects on soil physical and chemical properties (Rasmussen and Parton, 1994). 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 (Machado et al., 2008). 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, and nutrient cycling (Payne et al., 2000). However, the benefits of winter wheat-pea (WW-P) rotation in the inland PNW can be exploited to its full extent only if appropriate tillage methods at appropriate times are implemented.

Long-term conventional tillage (CT) such as moldboard plowing (MP) causes significant soil organic matter (SOM) depletion (Six et al., 2000) and can reduce soil organic carbon (SOC) levels by up to 70% (Lal and Bruce, 1999). The soil aggregation disrupting mechanism of MP increases the accessibility of SOM to soil microbes that increases the mineralization rate and reduces SOM (Obour et al., 2017). On the other hand, conservation tillage, such as reduced tillage (RT) and no-tillage (NT), maintains SOM or reduces the severity of SOM loss by improving the soil aggregate stability (Jacobs et al., 2009), increasing the residue accumulation and decreasing the rate of decomposition (Seddaiu et al., 2016). Conservation tillage is defined as tillage that leaves at least 30% of residue cover after tillage (Prasad and Power, 1997). Plant essential macronutrients like N, P, K, S, Ca, and Mg have been shown to be affected by tillage methods. Sarker et al. (2018) reported greater C, N, P, and S under CT and RT than under NT in the semi-arid region of Australia, whereas Dick (1983) showed greater P and K in topsoil under NT than under CT and RT in Ohio. Similarly, more P, K, Ca, and Mg were found in the upper soil profile under RT than under CT (Edwards et al., 1992). Tillage also plays a key role in soil pH. Fertilizer is banded close to the seed in RT and NT, which eventually leads to lower soil pH in the upper soil layers than under CT (Obour et al., 2017). Under CT, soil is mixed with a larger volume of calcareous dryland subsoil, which can also lead to higher soil pH than NT and RT (Rasmussen and Parton, 1994).

In addition to tillage intensities, tillage timing may also affect the availability of plant essential nutrients due to its role in soil water conservation and erosion control, especially in dryland systems and steep slopes. The importance of tillage timing is recognized in dryland PNW farming because of long, steep slopes and predominant winter precipitation falling on frozen soil (Pikul et al., 1993). Thus, primary tillage during the fall could be detrimental in this region because fall plowing (FP) will leave the soil bare during the high precipitation period (November-June; Gollany, 2016), making it vulnerable to erosion, and reducing soil water storage efficiency. Spring tillage (ST) leaves crop residue on the soil surface during winter, protecting the soil from raindrop impact, reducing runoff from frozen soil and its loss of plant available nutrients, increasing water infiltration and storage, and reducing evaporation compared to FT (Machado et al., 2008). Despite the negative impacts of FT in the dryland PNW, it is the typical tillage practiced in this region for winter wheat-dry pea rotation (Machado et al., 2008).

The physical and chemical properties of soil largely impact the quality of wheat. Agricultural practices that impact soil properties, such as crop rotations and tillage, have been documented to influence wheat grain quality (Šíp et al., 2013; Park et al., 2015). Negligible effects of tillage on N content and grain protein were reported by Rieger et al. (2008), whereas López-Bellido et al. (2001) reported greater protein content under CT than under RT or NT due to water stress under rainfed conditions. Generally, water stress increases grain protein content (Robinson et al., 1979). Trethowan et al. (2012) demonstrated that wheat grain and straw quality were affected by the tillage interaction with genotype and suggested that conservation tillage practices could be developed to attain the desirable market quality of wheat. Further research is needed to determine the impact of tillage methods on grain and straw quality such as macronutrient accumulations in tissue (Soane et al., 2012).

Tillage and crop rotation systems alter soil properties and wheat quality. However, the effects of tillage intensities and timing on macronutrient dynamics in the WW-P rotation cropping system have not been thoroughly studied in the dryland PNW. Therefore, we hypothesized that: (i) concentration of nutrients in soil and wheat tissues will decline in FT and ST due to the greater soil disturbance and soil inversion, while NT will maintain the nutrients supply over time unless the straw is removed, and (ii) the decline of soil and crop nutrients would be greater under FT than under ST due to differences in tillage timing. The objectives of this study were to (i) quantify the effects of different tillage methods on soil and wheat tissue macronutrients under the dryland WW-P cropping system, and (ii) compare the soil macronutrients in WW-P with the nearby undisturbed grass pasture (GP) to detect any changes after 52 years of cultivation. This study is significant for the dryland PNW region because it provided insight into the dynamics of plant essential macronutrient under different tillage methods in WW-P cropping system over time rather than determining the dynamics of SOC and N only as in earlier studies.

Materials and Methods

Site description

The study was conducted on winter wheat-dry pea rotation of long-term experiments (WP-LTE) at the Columbia Basin Agricultural Research Center (CBARC) in Adams, Oregon (45°42' N, 118°36' W, elev. 438 m asl). This WP-LTE is one of the several long-term experiments at CBARC and was established in the spring of 1962 on nearly level topography (0-1% slope). The soil is Walla Walla silt loam (coarse-silty, mixed, superactive, mixed mesic Typic Haploxerolls) derived from loess overlying basalt (Gollany et al., 2005). The average annual precipitation at the station is ~437 mm and more than 90% of that occurs during the November-June (Gollany, 2016). The site has a semi-arid climate with cool wet winters and hot dry summers. The 85-year average temperature at CBARC is 8°C.

Experimental design and field operations

The experimental design was a split plot with four replications. Each replicate included eight plots (two crops and four tillage treatments to allow yearly data collection for wheat and peas) of 7.3 m by 27 m. The location of pea and wheat within a replicate alternated from year to year (Fig. A.1).

Winter wheat was grown once in a 2-year cycle in rotation with fresh pea in WP-LTE between 1967 and 1991. Dry pea was replaced with fresh pea in the rotation in 1992. Semi-dwarf soft white winter wheat (cv. 'Stephens') was planted in early October when soil moisture was sufficient for germination using a double disk drill with 18 cm row spacing, and harvested in late July of the following year. Dry pea (cv. 'Columbia') was sown in late March or early April and harvested in mid-July of the same year. All wheat plots received 90 kg N ha^{-1} as ammonium nitrate (34–0–0) broadcasted before seeding (from 1986 to 1995), and as Urea (32–0–0) shanked 12 cm deep from 1996 onward. Ammonium phosphate sulfate (16-20-0-14) was broadcasted in the pea plots at the rate of 22 kg N ha^{-1}.

The four tillage treatments varying in intensity and timing of tillage were:

(i) Fall tillage (FT): In this treatment, wheat stubble was moldboard plowed to a depth of ~20 cm after wheat harvest in fall. Before seeding pea, the plots were sprayed with glyphosate at rates ranging from 314 to 628 g acid equivalent (a.e.) ha^{-1} to control weeds in the spring and tilled with a spring-tooth harrow (John Deere CC, John Deere, Moline, IL) twice to a depth of ~10-15 cm. After seeding, a Dunham Culti-packer (Dunham Co., Dunham, OH) was used to roller-pack the plots. After pea harvest in July, pea vines were moldboard plowed to a depth of

~20 cm in the summer followed by a light disc harrow ~10 cm deep, and roller-harrowed to reduce clods. Weeds were controlled with glyphosate, when necessary. The residue cover in the fall after pea harvest was approximately 1%, and in the fall the residue cover after wheat harvest was approximately 5%.

(ii) Spring tillage (ST): Wheat stubble was left undisturbed in the fall after harvest and was moldboard plowed to a depth of ~20 cm in the spring. Secondary tillage and pea vine management were like that of FT. The residue cover in the fall after pea harvest was approximately 1%, and after wheat harvest was approximately 80%.

(iii) Disk/chisel tillage (DT/CT): After wheat harvest, wheat stubble was roto-tilled twice to a depth of 10 cm in the fall to break up wheat stubble. Plots were sprayed with glyphosate when necessary before pea was sown and swept with a 2.4-m V-shaped Noble sweep plow (Noble Farms Ltd., Nobleford, AB, Canada) to a depth of ~5 cm and rod-weeded. Plots were roller packed after sowing pea. Pea was harvested in July, immediately after harvest the pea vines were swept to stop pea vine growth and water use, followed by chisel plowing twice to a depth of ~20 cm in the fall. The residue cover in the fall after pea harvest was approximately 10%, and residue in the fall after wheat harvest was approximately 40%.

(iv) No-tillage (NT): The NT plots were under minimum tillage until 1995. During the implementation of minimum tillage, these plots were rotary-mowed to cut wheat stubble before skew-treading once or twice in the fall, swept once to a depth of ~5 cm, and rod weeded. A Dunham skewtreader (Dunham Co., Dunham, OH) was used two to three times in the summer to skew-tread in pea vines. The plots were rod weeded twice and sprayed with herbicides when

necessary in the spring. Under this treatment, the residue cover in the fall after pea harvest was approximately 20%, and in the fall after wheat harvest it was approximately 80%. The DT/CT and NT are the conservation tillage treatments in this study.

In addition to the treatments in WP-LTE, a nearby perennial grass pasture (GP) was included in this study to determine influence of tillage methods on soil macronutrient availability and wheat nutrient uptake over time. The GP has been undisturbed since 1931 and maintained under native grasses such as bluebunch wheatgrass (*Agropyron spicatum* Pursh) and Idaho fescue (*Festuca idahoensis* Pursh).

Soil and tissue sampling and analysis

Two soil cores from four soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm) of each plot were composited. We used archived samples of soil and wheat grain and straw from 1995 and 2005 and fresh samples for 2015. Soil samples were collected using a truck-mounted Giddings Hydraulic Probe (Giddings Machine Co., Inc., Windsor, CO) and a steel sampling tube (with internal diameter of 3.6 cm), while wheat tissue (grain and straw) was collected from the center of each plot and was finely ground. Plant samples were air dried in the greenhouse for three days and then oven dried at 60°C for 72 hours. Soil samples were oven dried at 105°C for 24 hours. The oven-dried samples were roller milled in a vial for four hours. This rotator used 60-mL capped round bottles with two steel rods inside. The dry combustion method was performed using a Vario Micro Cube combustion analyzer (Elementar Analysensysteme GmbH, Hanau, Germany) to determine total C, N, and S in soil and plant tissue samples. The Mehlich III extraction method (Mehlich, 1984) was used to determine the extractable (plant-available) macronutrients (P, K, Ca, and Mg) in soil, and the dry-ash method was used to determine the total nutrient concentrations in wheat grain and straw. The extracts were analyzed by inductively coupled plasma-optical emissions spectroscopy (ICP-OES Model #2100 DV, Waltham, MA). Soil pH data were provided by CBARC station and these were analyzed in a 1:2 soil to 0.01M $CaCl_2$ solution using pH electrodes after 30 min equilibrium time. Since the soil pH of this study was below 7.4, we considered the total C of this study to be organic. According to Schumacher (2002), total C in soils with pH < 7.4 is mostly SOC.

Data analysis

Grass pasture was included as one of the WP-LTE treatments so that statistical inference with WP-LTE treatments can be made. Repeated measures analysis (RMA) of a split-plot design with four blocks and year (1995, 2005, 2015) as the whole plot factor, treatment (five levels: GP, FT, ST, DT/CT and NT) as the subplot factor; and response variables measured repeatedly in space at 4 soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm) was conducted to determine the effect of these factors (year, treatment, and depth) on the concentrations of total N, S, and C and extractable P, K, Ca, and Mg. A split-plot design with four blocks where year (1995, 2005, and 2015) as a whole-plot factor and four tillage treatments (FT, ST, DT/CT, and NT) as a subplot factor was used for analysis of N, C, S, P, K, Ca, and Mg concentration for wheat grain and straw. The data were checked for normality and were verified by examining the residuals as described in Montgomery (Montgomery, 2013). These assumptions were met either in the original data or after applying appropriate (square root or natural log or box-cox) transformation. The transformed data were back-transformed to the original scale to facilitate easier reading of the results. The data were analyzed using the mixed model in "Repeated Measures" add-ins in JMP Pro 13 (SAS Institute Inc., 2014). Multiple means comparisons were computed for significant effects (*P*-value < 0.05) by comparing the least squares means of the corresponding treatment combinations. Tukey-Kramer HSD method was used to generate letter groupings using a 5% level of significance.

The units of pH are on a logarithmic scale; therefore, pH data were converted to H^+ concentration (µmol L^{-1}) before analyses. The ANOVA table of pH is based on analysis of H^+ concentration. However, original values of pH scale were used for multiple comparisons.

Results

Table S6.1 illustrates the ANOVA of the main and interaction effects of year, treatment, and depth on the concentration of soil total N, SOC, soil total S, Mehlich III extractable P, K, Ca, Mg, soil C: N ratio, and soil pH in the wheat-pea rotation long-term experiment (WP-LTE). A significant effect of the treatments (main effect) on the macronutrients were observed; however, two-way and three-way interactions overrode those main effects in this study (Table S6.1). Since the nearby undisturbed GP was the baseline for evaluating the changes in the cropping system of our experiments, any deviation of WP-LTE treatment values from the value of GP was considered the long-term effect of continuous cultivation (WP-LTE was initiated in 1963) under the respective treatment. The WP-LTE treatments results were compared with the closest values to those of the GP to show the anthropogenic changes over time.

Macronutrients in soil

Soil organic carbon (SOC): A three-way interaction was observed for SOC in this study. The treatment values of the WP-LTE were similar in the upper 10 cm of soil in 1995 and 2005, but differences were evident in 2015 at that depth. In 2015, SOC was greater under NT than under ST and FT in the 0 to 10 cm depth (Table 6.1). In contrast, SOC in the 10 to 20 cm soil depth in 2005 was markedly lower under NT than under ST and FT in all years (1995, 2005, and 2015). As expected, the SOC of GP in the 0-10 cm depth was greater than SOC under the WP-LTE treatments in 1995 and 2015 (Table 6.1). Compared to GP, the upper 10 cm of soil lost 28% SOC under NT by 2015. The SOC was significantly greater in the 0-10 cm depth than in the 10-20 cm under DT/CT, NT, and GP in all the studied years (Table 6.1).

Soil total N concentration: Interaction of treatments and depth affected the soil total N in this study. The WP-LTE treatments differed in N only in the 10-20 cm soil depth (Fig. 6.1). The FT and ST treatments had greater N than those under DT/CT and NT in that depth (Fig. 6.1). Overall, N decreased with increased soil depth in all treatments. The GP had significantly greater N than WP-LTE treatments at all studied soil depths. A remarkably greater percentage of N loss in the 0-10 cm soil depth was observed vs. any other soil depth. Compared to GP, the N decline in the upper 10 cm of soil depth for NT was 33% (Fig. 6.1).

Soil total S concentration: Like SOC, a three-way interaction was observed for total soil S concentration (Table 2). The WP-LTE treatments were similar in S in 1995 and 2005 at all soil depths but the treatment effects were observed in 2015 in the top 20 cm soil depth (Table 6.2). In

2015, NT had greater S than under FT and ST in the 0-10 cm depth, while ST had greater S than NT in the 10-20 cm soil depth. Concentration of S at the 0-10 cm soil depth significantly increased over time (1995: 0.12 and 2015: 0.16 g S kg^{-1}) under NT. The WP-LTE treatments had noticeably lower S than under GP in all studied years at all studied soil depths. The NT lost 67% S in the top 10 cm of soil by 2015, while the other treatments lost at least 71% when compared with the GP at the same soil depth.

Soil Mehlich III extractable P concentration: A three-way interaction of treatment, year, and depth was observed for P. The WP-LTE treatments did not differ in P at all studied soil depths in 1995; however, the effect of the treatments started to manifest in 2005 and 2015 in the upper soil profile (Table 6.3). In 2005, FT had greater P than under DT/CT and NT in the 10-20 cm soil depth, whereas in the 0-10 cm, greater P was found under NT than under ST, DT/CT, or FT by 2015. The GP had significantly higher P than the WP-LTE treatments in the 0-10, 10-20, and 20-30 cm soil depths in 1995; however, it had comparable P under NT and ST in 2005 and under NT only in 2015. The P under NT increased over time in the upper 10 cm of soil. A 2.7-fold increase in P in the 0-10 cm soil depth was observed under NT from 1995 to 2015.

Soil Mehlich III extractable K concentration: The concentration of K was also affected by the three-way interaction of treatment, year, and soil depth in this study. No significant differences were observed between WP-LTE treatments in 1995 at any studied soil depths. However, K in the 0-10 cm soil depth was significantly higher under NT than under FT or ST in 2015 (Table 6.4). The GP had significantly greater K than under FT or ST in 1995; was comparable to the one in all of the WP-LTE treatments in 2005 and was markedly greater than the one in all WP-LTE treatments in 2015 in the upper 10 cm soil depth (Table 6.4). The extractable K under NT had increased significantly by 18% in the 0-10 cm soil depth over the 20 years period (1995-2015) (Table 6.4). Similarly, GP also had greater K in the 0-10 cm and 10-20 cm soil depths of over 20 years and apparently, K concentrations had not reached equilibrium even after 84 years.

Soil Mehlich III extractable Ca concentration: Unlike the dynamics of other soil macronutrients in this study, extractable Ca under GP did not differ from that in WP-LTE treatments in the studied years and soil depths (Table S6.2). Also, the plots in the WP-LTE treatments had similar Ca in the studied years. Under DT/CT, Ca was noticeably greater in the upper 10 cm of soil than in the deeper soil profile (30-60 cm) in all the time frames in this study (Table S6.2). Overall, the deeper soil profile had modestly higher Ca than the topsoil in all treatments.

Soil Mehlich III extractable Mg concentration: The extractable Mg in the 0-10 cm soil depth was lower under NT than under ST and FT, whereas at the other soil depths, Mg was similar among the WP-LTE treatments (Fig. 6.2). The extractable Mg in WP-LTE treatments increased with soil depths and was greatest in the 30-60 cm. The GP had significantly lower Mg in the 30-60 cm soil depth. The WP-LTE treatments had lost at least 41, 37, 27, and 11% of Mg in the 0-10, 10-20, 20-30, and 30-60 cm soil depths, respectively, when compared with Mg in the corresponding soil depths of GP.

Soil CN ratio and soil pH: The soil C:N ratio was not affected by the treatments, whereas the soil pH was influenced by the interaction of treatments and soil depths over time. Soil pH was comparable among WP-LTE treatments at all depths; however, GP had higher soil pH than the WP-LTE treatments in all of the soil depths of the study (Fig. 6.3). The soil pH increased significantly with soil depth under both WP-LTE treatments and GP. The soil pH of GP, DT/CT, ST, FT, and NT in the 0-10 cm soil depth decreased by 0.4, 0.8, 0.8, 0.8, and 1 unit, respectively, compared to the soil pH in the 30- 60 cm soil depth (Fig. 6.3).

Nutrient accumulation in wheat straw and grain

Table A.3 presents the ANOVA of the main and interaction effects of year and treatment on the accumulation of total concentrations of N, C, S, P, K, Ca, and Mg in the wheat straw and grain of WP-LTE at Pendleton. No significant impact of the WP-LTE treatments on the accumulation of macronutrients in wheat tissue over time was observed except for K and Mg in straw and N in grain (Table S6.3).

Total concentration of K and Mg in wheat grain and straw: The concentration of K in wheat straw remarkably increased over time in 20 years under all tillage systems (Fig. S6.2). No-tillage and FT had significantly higher straw K in 2015 than in 1995. Soil P and S were higher in 0-10 cm in 2015 than in 1995 under NT (Tables 6.2 and 6.3) and were positively correlated with straw K (Table S6.4). Straw Mg was influenced by tillage and was greater under ST than under NT or FT (Fig. S6.3). Soil N was greater under ST than under NT in the 10-20 cm soil depth, and Table A.4 revealed that soil N had a strong positive correlation with straw Mg at that soil depth.

Total N in wheat grain: The concentration of N in wheat grain was significantly influenced by year and treatment. Grain N markedly increased over 20 years. Grain N did not differ between the WP-LTE treatments in 1995 and 2005 but greater grain N was observed under

FT than under DT/CT or NT in 2015 (Fig. 6.4). Table S6.5 shows the correlation of soil nutrients in the 0-10 and 10-20 cm depths with the nutrient accumulation in wheat grain.

Discussion

Crop rotations are not always feasible under rainfed semiarid environments where soil water is limited. However, the WW-P rotation has offered several significant advantages for drylands of the PNW such as erosion protection, increased organic residue and plant essential nutrients (Pikul et al., 1993). These advantages are largely controlled by tillage methods in any crop rotation system (Ball et al., 1998).

Soil organic carbon and macronutrients

The four tillage methods differed in the amount of reside cover. Crop residue cover was greater in NT followed by DT/CT, ST, and FT. Consequently, decomposition of crop residue and mineralization of SOM resulted in release of nutrients at different rates. No-tillage had greater SOC, S, P, and K than FT and ST in the 0-10 cm soil depth by 2015 (Tables 6.1- 6.4). Previous studies reported greater SOC and N under NT and conservation tillage than under conventional tillage (Edwards et al., 1992; Franzluebbers and Hons, 1996; Gürsoy et al., 2010). Greater concentration of macronutrients over time in the upper 10 cm soil depth under NT could be the result of greater amounts of crop residues on the soil surface, and less disturbance to soil aggregates that consequently led to accumulation of SOC and microbial biomass near the soil surface (Franzluebbers and Hons, 1996). Higher SOC concentration at the 0-10 cm depth under

NT than under ST and FT was most likely due to crop residue accumulation at the soil surface by 2015 (Table 6.1). Thomas et al. (2007) also reported that SOC at the 0-10 cm soil depth did not differ with the tillage methods in the early years of their study but differentiated later. Similarly, other researchers observed higher SOC and total N over time in topsoils under NT than under conventional tillage (Halvorson et al., 2002; Mazzoncini et al., 2011). The FT and ST plots had greater N than DT/CT and NT in the 10-20 cm soil depth (Fig. 6.1). This is most likely because of higher mineralization rate under these two tillage treatments and NO_3 leaching to the subsoil compared with NT.

Changes in some of the nutrients such as S took more than 20 years to be detectable. According to Schillinger et al. (2006) and Gollany et al. (2011), the anthropogenic effects on soil nutrients in the semiarid environment require decades to be detected. In 2015, NT had greater S in 0-10 cm depth than under FT and ST, while NT and ST were comparable to that in DT/CT (Table 6.2). However, ST had greater S in the 10-20 cm soil depth than NT. The concentration of S increased in ST with the addition of decomposed crop residue in the 20-30 cm depth with increased soil aggregates disturbance in a short-term (Sarkar et al., 2014). Total S concentrations in the WP-LTE treatments were lower than those under GP at all determined soil depths. Concentration of S decreased more in plots that enhance decomposition such as FT and ST, a result that was similar to the results reported by Kopittke et al. (2017).

The chemical nature of nutrients also plays a key role in nutrient status under different tillage methods at different soil depths. Under NT, a greater P accumulation at the upper soil profile was expected in the absence of soil mixing because P is less mobile in the soil compared with the other nutrients. Significant ($P \leq 0.05$) differences in P concentration were found between the 0-10 and 10-20 cm soil depth under NT from 2005 to 2015 but not in 1995, most probably because before 1995, NT was under minimum tillage. This was consistent with previous reports by Obour et al. (2017) and Thomas et al. (2007). However, under FT, ST, and DT/CT, the P distribution in depth was uniform, probably due to the soil mixing. Crop uptake and mixing of P with a larger volume of soil may also have contributed to the lower P under FT and DT/CT compared with P under NT in 2005 and 2015. Awale et al. (2017) reported that different tillage methods in the same WP-LTE plots significantly affected SOM of the upper soil layer. Since SOM is a storehouse of plant essential nutrients, changes in SOM can eventually lead to changes in the available nutrients. Contrastingly, Mg was lower in the upper 10 cm of soil under NT than under FT and ST in this study and increased with soil depth. This could be due to the relatively lower soil pH in the 0-10 cm soil depth under NT than under FT and ST. The other possible reason for greater Mg accumulation in deeper soil could be leaching. However, this reason can be ruled out because, in the semi-arid environment where average precipitation is approximately 437 mm, leaching of basic cations seldom occurs (Obour et al., 2017).

Under NT, the concentrations of most nutrients were significantly ($P \leq 0.05$) lower at soil depths greater than 10 cm, whereas other tillage methods did not differ in nutrient concentrations at the lower soil depths. This could be attributed to the lack of soil mixing and a greater amount of crop residue at the topsoil than in subsoil under NT, which could also be a reason for greater soil pH differences between the upper 10 cm and 30-60 cm soil depth under NT than under the other tillage methods. In addition, nitrification of applied N fertilizer and SOM mineralization occurs on the soil surface under NT that can result in a noticeable decrease in pH at the soil surface (Obour et al., 2017). Our pH results are consistent with previous findings that showed a significant decrease in upper soil surface pH under NT compared with other tillage treatments (Franzluebbers and Hons, 1996; Obour et al., 2017).

The WW-P plots lost at least 28, 46, and 67% of SOC, Mg, and S respectively in 2015 in the top 10 cm of soil compared to nearby undisturbed GP. The major mechanisms of nutrient loss in cultivated plots are enhanced biological oxidation and nutrient removal with harvest without nutrient replenishment. Both conditions are rare in undisturbed GP. Except for P in the 0-10 and 10-20 cm soil depths under NT, macronutrients and soil pH declined considerably under WP-LTE compared to GP. The reason for comparable P under NT and GP could be due to the lack of mechanical soil inversion and application of ammonium phosphate sulfate (16-20-0-14) every two years in this study.

Macronutrients in wheat straw and grain

No significant tillage effect on N content in the wheat straw was found, but grain N was affected by the tillage treatments in 2015. The observed increasing grain N content over time could be due to low rainfall during 2015 growing season (Fig. S6.4). These results contradict reported results by Malhi et al. (2006), that there was a significant effect of tillage on wheat straw N accumulation but no effect on the N content of wheat grain. Grain N increases with drought and decreases with abundant rainfall (López-Bellido et al., 2001). Greater straw Mg was found under ST than under NT. The extractable Mg and soil pH were greater under ST than under NT only at the 0-10 m soil depth, which suggested that the top 10 cm of soil plays a more significant role in the straw Mg accumulation than the deeper soil profile. A strong positive correlation between soil total N at the 10-20 cm soil depth and straw Mg were found, and ST had greater soil total N than NT. Therefore, soil pH and N content could be factors contributing to the greater straw Mg under ST than NT in this study.

Conclusions

This 52-year WP-LTE plots comparison with GP assessed the impacts of the most common tillage (FT and ST) and the less common tillage (DT/CT and 20 years of NT) under the winter wheat-dry pea rotation on macronutrient dynamics of soil and wheat nutrient content. The WW-P plots lost at least 28, 46, and 67% of SOC, Mg, and S respectively in the top 10 cm soil after 52 years of WW-P rotation compared with the nearby undisturbed GP. The NT plots have begun to reverse the decline of soil C, S, P, and K in the upper 10 cm over time. The results from this study suggest that NT, or DT/CT to some extent, could curb the declining status of macronutrients in soil and improve the wheat grain quality of the inland PNW over time. Occasional tillage in NT plots could be beneficial to uniformly distribute the nutrients throughout the soil profile and to increase the soil pH of upper soil profile.

Acknowledgments

This research was supported by the Oregon State University startup funds awarded to Dr. Valtcho D. Jeliazkov (Zheljazkov). We thank Mr. Karl Rhinhart and his crews for their help with the field soil sampling. Special thanks to Paul Rasmussen (retired) and coworkers for collecting and archiving long-term grass pasture and wheat-pea rotation soil and plant samples, and Chris Rogers (retired) and Joseph (Joe) St. Claire for the CNS analyses of the soil and tissue samples (USDA Agricultural Research Service, Columbia Plateau Conservation Research Center, Adams, OR).

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Table 6. 1 Mean concentration of soil total carbon (g kg^{-1}) obtained from the combinations of treatment, year, and depth in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton, Oregon.

Depth	Treatment				
(cm)	Fall tillage	Disk/chisel tillage	Spring tillage	No tillage	Grass pasture
1995					
0-10	B[1] 14.01 ab[2]	B 16.22 a	B 14.59 a	B 16.09 a	A 22.80 a
10-20	A 14.35 ab	BC 12.59 b	AB 13.94 a	C 11.62 b	AB 13.92 bc
20-30	A 9.94 cde	A 9.86 c	A 9.56 cd	A 8.83 bcd	A 9.62 cd
30-60	A 6.18 f	A 7.15 de	A 6.58 d	A 6.56 d	A 7.82 d
2005					
0-10	AB 15.25 a	B 13.55 b	AB 15.43 a	AB 16.25 a	A 16.83 b
10-20	A 13.50 abc	B 9.33 cd	A 13.45 ab	B 10.27 bc	B 10.45 cd
20-30	A 8.70 def	A 7.77 cde	A 8.96 cd	A 7.67 cd	A 8.97 cd
30-60	A 7.55 def	A 7.01 de	A 7.48 cd	A 8.14 dc	A 10.52 cd
2015					
0-10	C 14.03 ab	BC 17.30 a	C 14.23 a	B 18.86 a	A 26.15 a
10-20	B 14.17 ab	BC 13.16 b	AB 15.18 a	C 11.84 b	A 16.70 b
20-30	A 11.15 bcd	A 9.43 cd	A 10.46 bc	A 8.98 bcd	A 13.50 bc
30-60	B 6.72 ef	B 6.90 e	B 6.39 d	B 6.52 d	A 11.92 bcd

[1] Uppercase letters are a comparison of the five treatments within each year and depth, and [2] lower-case letters are a comparison of the 12 combinations of year and depth within each of the five treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Table 6. 2 Mean concentration of soil total sulfur (g kg^{-1}) obtained from the combinations of treatment, year, and depth in wheat-pea rotation long-term experiment (WP-LTE) at Pendleton, Oregon.

Depth	Treatment				
(cm)	Fall tillage	Disk/chisel tillage	Spring tillage	No tillage	Grass pasture
1995					
0-10	B[1] 0.11 ab[2]	B 0.12 a	B 0.11 abcd	B 0.12 bc	A 0.45 ab
10-20	B 0.12 ab	B 0.10 a	B 0.11 abcd	B 0.10 cd	A 0.36 cd
20-30	B 0.09 b	B 0.09 a	B 0.09 bcd	B 0.10 cd	A 0.33 cd
30-60	B 0.08 b	B 0.08 a	B 0.08 d	B 0.08 d	A 0.32 d
2005					
0-10	B 0.14 a	B 0.11 a	B 0.14 a	B 0.14 ab	A 0.40 bc
10-20	B 0.12 ab	B 0.10 a	B 0.12 ab	B 0.10 cd	A 0.39 c
20-30	B 0.08 b	B 0.08 a	B 0.09 bcd	B 0.09 cd	A 0.31 d
30-60	B 0.08 b	B 0.15 a	B 0.09 d	B 0.09 cd	A 0.38 cd
2015					
0-10	D 0.12 ab	BC 0.14 a	CD 0.12 abc	B 0.16 a	A 0.49 a
10-20	BC 0.12 ab	BC 0.12 a	B 0.14 a	C 0.11 bcd	A 0.37 cd
20-30	B 0.12 ab	B 0.10 a	B 0.11 abcd	B 0.10 cd	A 0.35 cd
30-60	B 0.08 b	B 0.09 a	B 0.09 cd	B 0.08 d	A 0.34 cd

[1] Uppercase letters are a comparison of the five treatments within each year and depth, and [2] lower-case letters are a comparison of the 12 combinations of year and depth within each of the five treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Table 6. 3 Mean concentration of Mehlich III extractable phosphorus (mg kg^{-1}) obtained from the combinations of treatment, year, and depth in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton, Oregon.

Depth	Treatment				
(cm)	Fall tillage	Disk/chisel tillage	Spring tillage	No tillage	Grass pasture
1995					
0-10	B[1] 36.89 abc[2]	B 38.83 ab	B 36.81 bcd	B 36.31 b	A 91.37 ab
10-20	B 37.28 abc	B 29.51 b	B 35.31 bcd	B 26.46 b	A 67.74 bcd
20-30	B 30.42 bc	B 30.68 b	B 31.43 bcd	B 30.64 b	A 55.07 cd
30-60	AB 30.82 bc	AB 35.81 ab	B 28.14 cd	AB 29.75 b	A 47.45 d
2005					
0-10	B 47.35 ab	B 40. 73 ab	AB 63.47 a	AB 66.84 a	A 82.46 abc
10-20	A 39.67 abc	C 23.34 b	AB 37.53 bcd	BC 26.24 b	AB 38.03 d
20-30	A 34.72 abc	A 29.04 b	A 27.78 cd	A 36.33 b	A 45.46 d
30-60	A 27.14 c	A 43.61 ab	A 27.14 cd	A 38.37 b	A 40.98 d
2015					
0-10	B 46.31 ab	B 58.14 a	B 46.21 abc	A 98.68 a	A 101. 88 a
10-20	AB 51.58 a	B 39.01 ab	AB 48.13 ab	B 30.41 b	A 81.43 abc
20-30	B 33.11 bc	B 27.14 b	B 29.43 bcd	B 27.32 b	A 54.91 cd
30-60	BC 26.82 c	B 36.33 ab	C 25.47 d	BC 29.57 b	A 51.51 cd

[1] Uppercase letters are a comparison of the five treatments within each year and depth, and [2] lower-case letters are a comparison of the 12 combinations of year and depth within each of the five treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Table 6. 4 Mean concentration of Mehlich III extractable potassium (g kg^{-1}) obtained from the combinations of treatment, year, and depth in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton, Oregon.

Depth (cm)	Treatment Fall tillage	 Disk/chisel tillage	 Spring tillage	 No tillage	 Grass pasture
1995					
0-10	B[1] 0.59 a[2]	AB 0.67 ab	B 0.59 abc	AB 0.60 bc	A 0.74 bc
10-20	A 0.57 ab	A 0.52 bcd	A 0.58 abc	A 0.56 bcd	A 0.61 cd
20-30	A 0.44 abc	A 0.44 cd	A 0.49 cde	A 0.44 cde	A 0.55 cd
30-60	AB 0.38 c	B 0.36 d	B 0.35 e	AB 0.38 e	A 0.53 d
2005					
0-10	A 0.64 a	A 0.54 abcd	A 0.69 ab	A 0.64 a	A 0.73 bc
10-20	A 0.62 a	AB 0.47 bcd	AB 0.53 bcd	B 0.45 cde	AB 0.60 cd
20-30	AB 0.49 abc	B 0.41 cd	AB 0.49 cde	B 0.43 de	A 0.58 cd
30-60	B 0.41 bc	B 0.42 cd	B 0.39 de	B 0.40 de	A 0.68 bcd
2015					
0-10	C 0.61 a	BC 0.76 a	C 0.62 abc	B 0.78 a	A 1.00 a
10-20	B 0.63 a	B 0.60 abc	AB 0.72 a	B 0.62 ab	A 0.86 ab
20-30	AB 0.56 ab	B 0.45 cd	A 0.60 abc	B 0.43 de	A 0.69 bcd
30-60	B 0.38 c	B 0.32 d	B 0.37 de	B 0.35 e	A 0.68 bcd

[1] Uppercase letters are a comparison of the five treatments within each year and depth, and [2] lower-case letters are a comparison of the 12 combinations of year and depth within each of the five treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

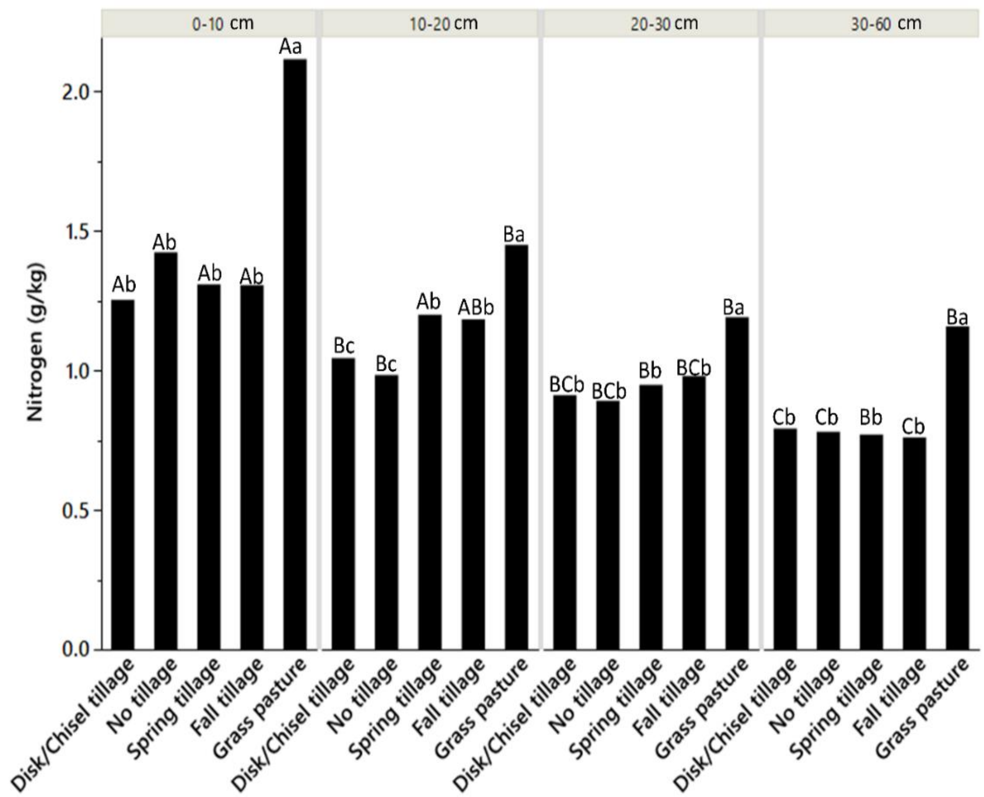

Fig. 6. 1 The long-term effect of four tillage methods and undisturbed grass pasture on the concentration of soil total nitrogen (g/kg) in different soil depths.

Uppercase letters are a comparison of each treatment across four soil depths, and lower-case letters are comparison of the treatments within each of the soil depths. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

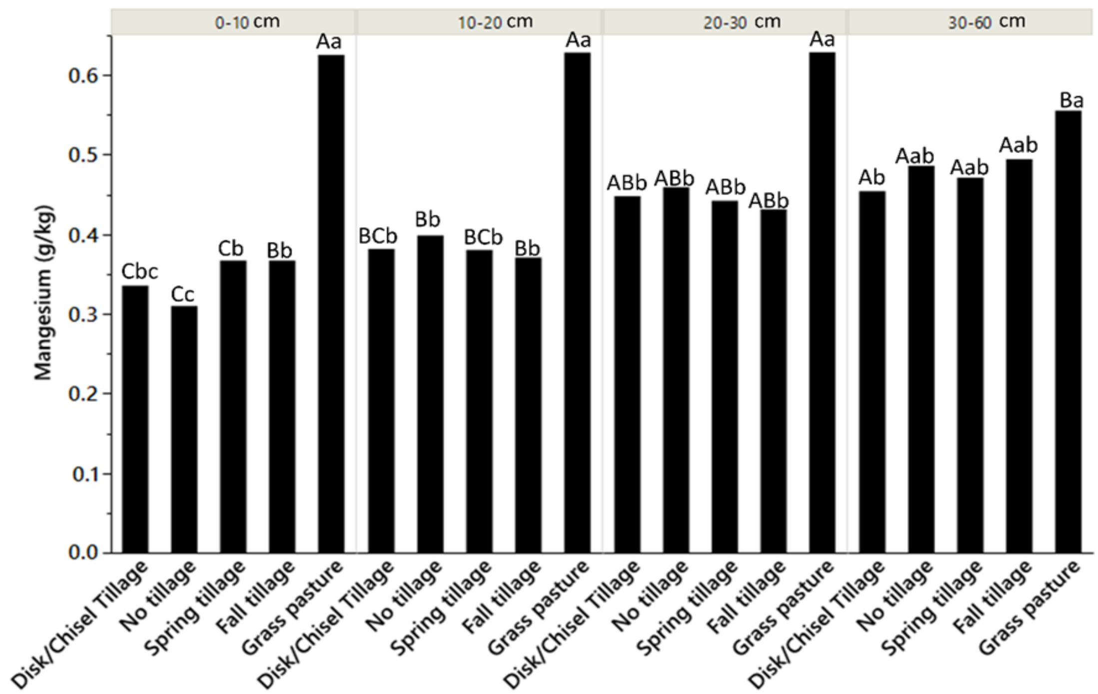

Fig. 6. 2 The long-term effect of four tillage methods and undisturbed grass pasture on the concentration of Mehlich III extractable magnesium (g/kg) in different soil depths (cm). Uppercase letters are a comparison of each treatment across four soil depths, and lower-case letters are a comparison of the treatments within each of the soil depths. Means sharing the same letter are not significantly different.

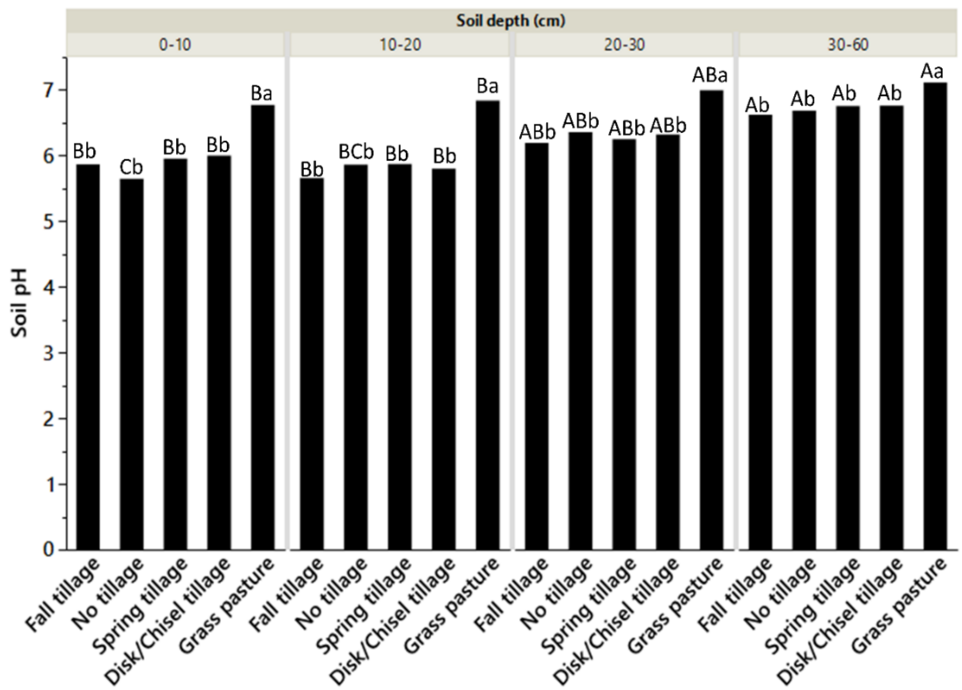

Fig. 6. 3 The long-term effect of four tillage methods and undisturbed grass pasture on soil pH in different soil depths (cm).

Uppercase letters are a comparison of each treatment across four soil depths, and lower-case letters are a comparison of the treatments within each of the soil depths. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

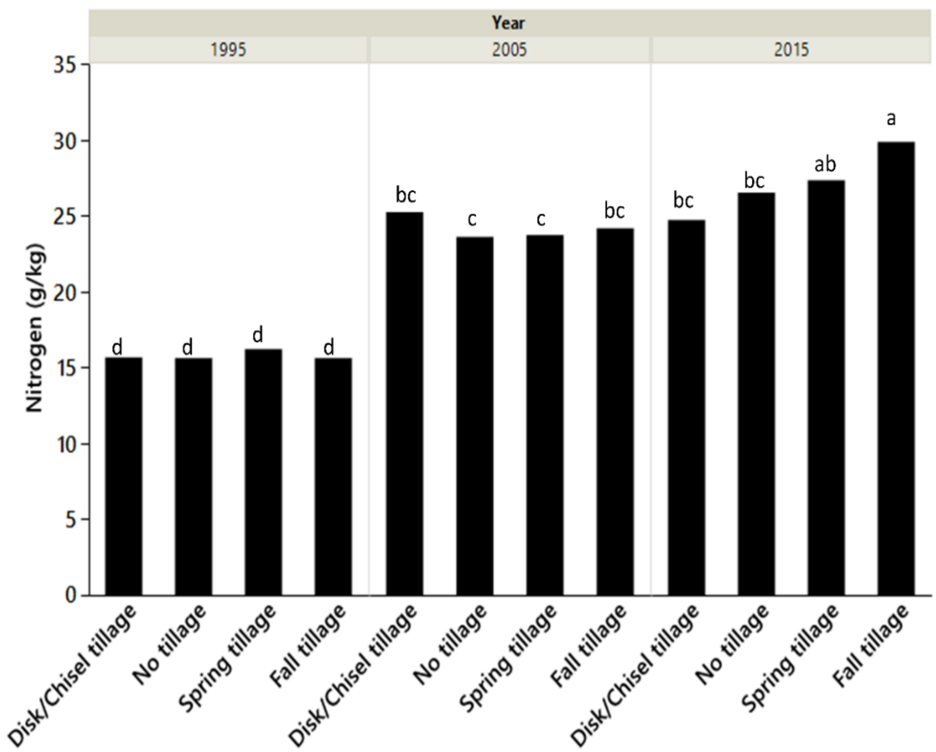

Fig. 6. 4 Effect of tillage methods on the concentration of grain nitrogen over 20 years.

Letters above the bars are a comparison of 12 combinations of treatment and year. Means sharing the same letter are not significantly different.

Table S6. 1 ANOVA table of the main and interaction effects of year, treatment, and depth on

Source of variation	**N**	**C**	**S**	**P**	**K**	**Ca**	**Mg**	**C:N**	**pH**
Year (Y)	0.03	<0.01	0.13	0.20	0.16	0.27	0.32	0.25	<0.01
Depth (D)	<0.01	<0.01	<0.01	<0.01	0.16	<0.01	<0.01	<0.01	<0.01
Tillage (T)	<0.01	<0.01	0.11	<0.01	<0.01	0.82	0.33	0.15	0.45
Y X D	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.07	<0.01	<0.01
Y X T	0.13	<0.01	0.37	0.10	0.72	0.78	0.35	0.30	0.93
D X T	**<0.01**	<0.01	<0.01	<0.01	<0.01	<0.01	**<0.01**	0.31	**0.03**
Y X D X T	0.06	**<0.01**	**<0.01**	**0.04**	**<0.01**	**<0.01**	0.89	0.77	0.18

the concentration of soil total N, SOC, soil total S, Mehlich III extractable P, K, Ca, Mg, soil C:N ratio and soil pH in the wheat-pea rotation long-term experiment.

Note: Significant treatment effects that require multiple means comparison are shown in bold.

Table S6. 2 Mean concentration of Mehlich III extractable calcium (g kg-1) obtained from the combinations of treatment, year and depth in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

Depth (cm)	Treatment				
	Fall tillage	Disk/chisel tillage	Spring tillage	No tillage	Grass pasture
1995					
0-10	A[1] 2.71 ab[2]	A 2.57 bcd	A 2.68 a	A 2.57 ab	A 2.39 a
10-20	A 2.48 ab	A 2.59 bcd	A 2.59 a	A 2.87 ab	A 2.31 a
20-30	A 2.83 ab	A 2.87 abc	A 2.91 a	A 2.82 ab	A 2.37 a
30-60	A 2.93 ab	A 3.31 a	A 3.23 a	A 3.07 ab	A 2.54 a
2005					
0-10	A 2.54 ab	A 2.71 bcd	A 2.37 a	A 2.32 ab	A 2.33 a
10-20	A 2.66 ab	A 3.0 abc	A 2.87 a	A 3.00 ab	A 2.35 a
20-30	A 3.00 ab	A 3.12 ab	A 3.34 a	A 3.19 ab	A 2.29 a
30-60	A 4.69 a	A 3.31 a	A 4.03 a	A 4.80 a	A 2.36 a
2015					
0-10	A 2.45 b	A 2.15 d	A 2.28 a	A 2.01 b	A 2.44 a
10-20	A 2.34 b	A 2.39 cd	A 2.33 a	A 2.57 ab	A 2.46 a
20-30	A 2.74 ab	A 2.83 abcd	A 2.68 a	A 3.01 ab	A 2.57 a
30-60	A 3.72 ab	A 3.28 a	A 2.85 a	A 3.30 ab	A 2.40 a

[1] Uppercase letters are a comparison of the five treatments within each year and depth, and [2] lower-case letters are a comparison of the 12 combinations of year and depth within each of the five treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Table S6. 3 ANOVA table of the main and interaction effects of year and treatment on the accumulation of N, C, S, P, K, Ca, and Mg in the grain and straw of wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

Source of variation	Nitrogen	Carbon	Sulfur	Phosphorous	Potassium	Calcium	Magnesium
				Wheat Straw			
Year	0.01	0.09	<0.01	<0.01	<0.01	<0.01	<0.01
Treatment	0.61	0.45	0.55	0.34	0.27	0.96	**0.03**
Year*Treatment	0.37	0.99	0.79	0.17	**<0.01**	0.31	0.63
				Wheat Grain			
Year	<0.01	<0.01	<0.01	<0.01	<0.01	0.15	<0.01
Treatment	0.08	0.38	0.16	0.70	0.65	0.06	0.13
Year*Treatment	**<0.01**	0.11	0.22	0.75	0.45	0.09	0.45

Note: Significant treatment effects that require multiple means comparison are shown in bold.

Table S6. 4 Correlation between nutrients in the soil (0-10 cm and 10-20 cm soil depths) and nutrients in wheat straw in wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

0-10 cm soil depth				**Wheat straw**			
	Nitrogen	Carbon	Sulfur	Phosphorus	Potassium	Calcium	Magnesium
Soil total nitrogen	0.19	**0.39**	0.25	0.18	0.27	0.07	0.02
Soil organic carbon	0.03	**0.36**	0.11	0.05	0.12	0.02	-0.03
Soil total sulfur	**0.30**	**0.38**	**0.38**	0.27	**0.39**	0.16	0.06
Extractable phosphorus	**0.34**	**0.30**	**0.37**	0.26	**0.40**	0.10	0.10
Extractable potassium	**0.29**	**0.29**	**0.37**	0.20	**0.33**	0.08	0.15
Extractable calcium	**-0.29**	-0.15	**-0.32**	-0.26	-0.28	-0.05	-0.05
Extractable magnesium	-0.13	-0.07	-0.11	-0.19	-0.14	-0.03	0.07
10-20 cm soil depth							
Soil total nitrogen	0.08	-0.04	0.11	-0.09	0.18	-0.19	**0.36**
Soil organic carbon	0.06	-0.06	0.07	-0.12	0.12	**-0.29**	**0.29**
Soil total sulfur	**0.28**	-0.11	**0.29**	0.07	**0.37**	-0.07	**0.37**
Extractable phosphorus	0.20	-0.08	0.15	0.13	**0.29**	-0.09	**0.31**
Extractable potassium	0.11	-0.11	0.06	0.04	0.13	-0.15	0.22
Extractable calcium	0.01	0.08	0.01	0.04	-0.08	0.02	-0.23
Extractable magnesium	-0.06	0.00	-0.14	0.14	-0.02	0.39	-0.27

Note: Significant correlations are shown in bold.

Table S6. 5 Correlation between nutrients in the soil (0-10 cm and 10-20 cm soil depths) and nutrients in wheat grain in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

0-10 cm soil depth				**Wheat Grain**			
	Nitrogen	Carbon	Sulfur	Phosphorus	Potassium	Calcium	Magnesium
Soil total nitrogen	0.27	0.19	**0.28**	0.12	**0.30**	0.07	-0.16
Soil organic carbon	0.18	0.22	0.21	**0.31**	0.15	-0.16	0.01
Soil total sulfur	**0.34**	**0.29**	**0.34**	0.20	**0.31**	0.05	-0.19
Extractable phosphorus	**0.48**	**0.47**	**0.48**	0.26	**0.39**	0.03	-0.22
Extractable potassium	**0.32**	0.20	**0.34**	0.24	0.22	-0.03	-0.02
Extractable calcium	**-0.33**	**-0.32**	**-0.30**	**-0.36**	-0.09	0.15	-0.14
Extractable magnesium	-0.15	-0.14	-0.14	-0.25	-0.03	0.06	-0.07
10-20 cm soil depth							
Soil total nitrogen	0.13	-0.04	0.08	0.17	-0.08	-0.21	0.09
Soil organic carbon	0.07	-0.11	0.07	0.14	-0.06	-0.17	0.07
Soil total sulfur	0.27	0.05	0.24	**0.30**	-0.13	-0.26	0.10
Extractable phosphorus	0.12	0.04	0.04	0.25	-0.09	**-0.40**	0.28
Extractable potassium	0.10	-0.07	0.03	-0.03	0.08	-0.26	0.24
Extractable calcium	-0.02	0.07	-0.07	-0.03	0.01	0.10	-0.11
Extractable magnesium	-0.14	0.07	-0.14	-0.10	-0.07	0.07	-0.14

Note: Significant correlations are shown in bold.

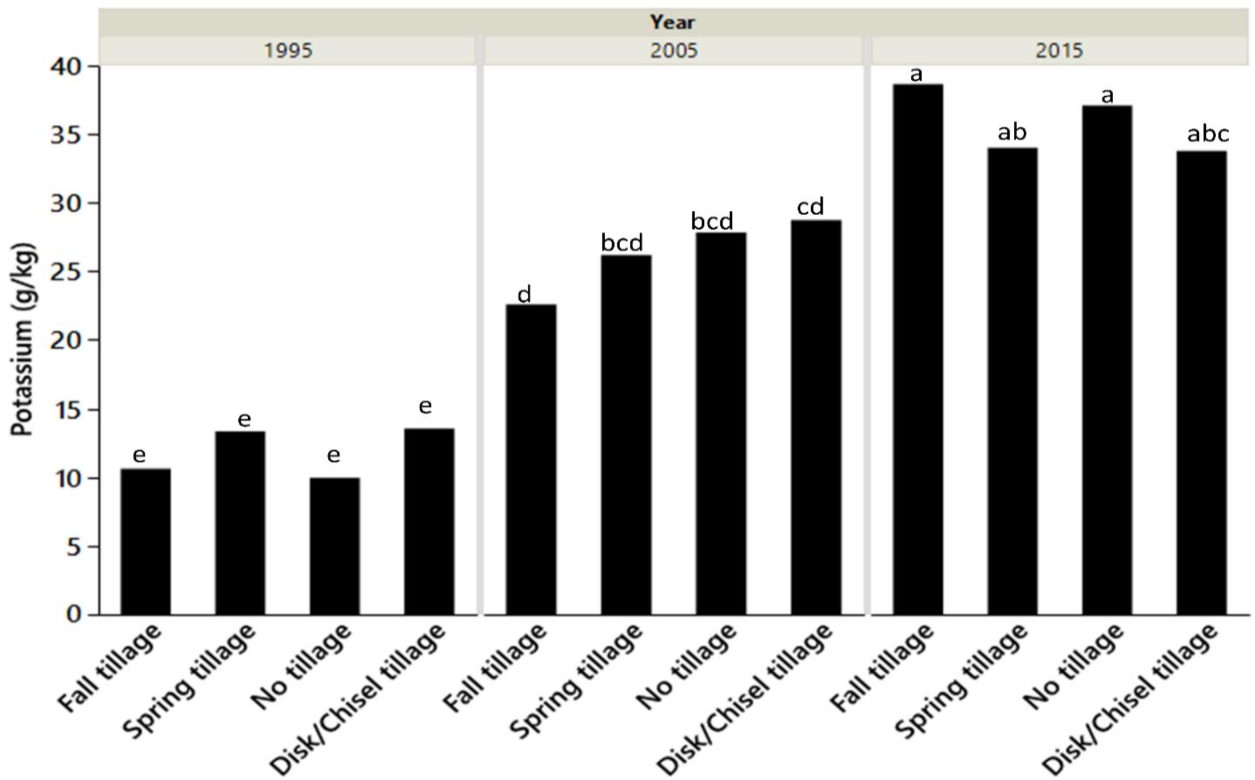

Fig. S6. 1 Effect of tillage methods on the concentration of potassium in straw over the 20 years' time. Letters above the bars are a comparison of 12 combinations of treatment and year. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

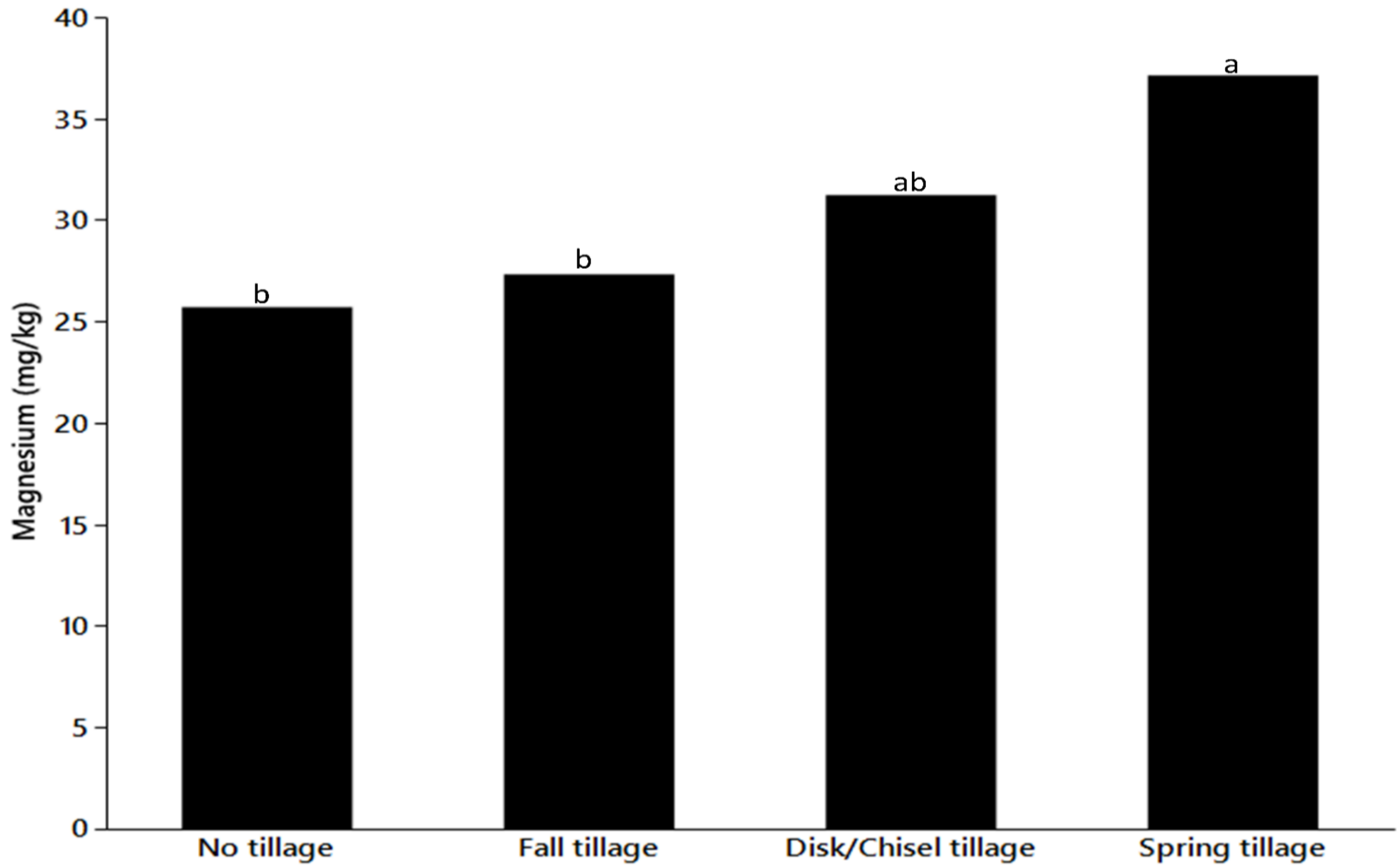

Fig. S6. 2 The long-term effect of tillage methods on the concentration of straw magnesium. Means sharing the same letter are not significantly different.

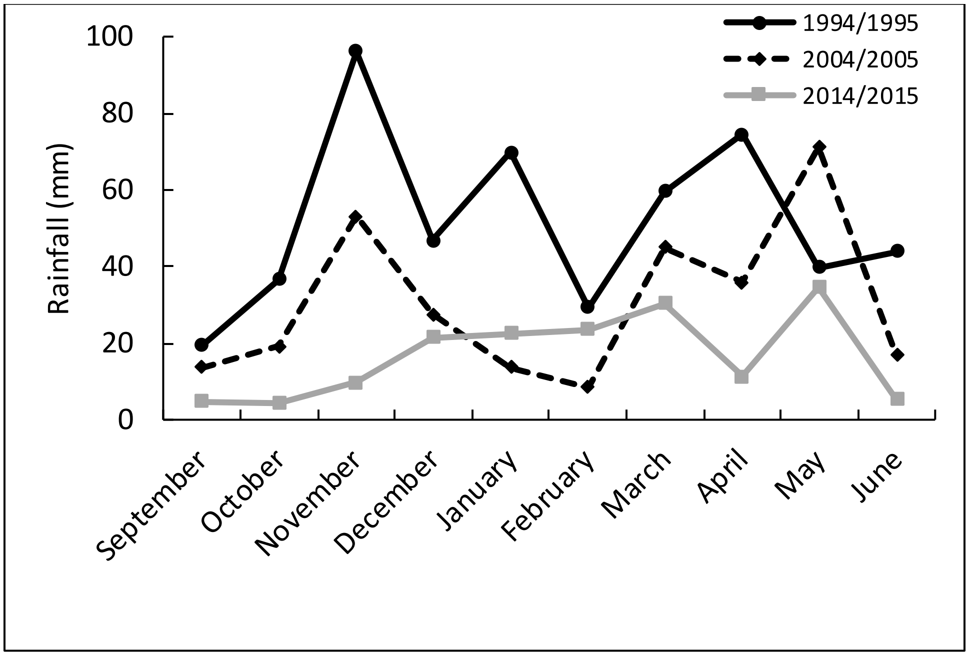

Fig. S6. 3 Rainfall in winter wheat growing season in Pendleton, Oregon.

Chapter 7

SOIL-PROFILE MICRONUTRIENT DISTRIBUTION AS AFFECTED BY TILLAGE AND 52 YEARS OF WINTER WHEAT-PEA ROTATION

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Submitted to Soil & Tillage Research

Abstract

Tillage plays a major role in nutrient dynamics under dryland cropping systems, but there remains uncertainty regarding the impacts of long-term continuous tillage on nutrient availability. The objectives of this study were to (i) examine the influence of tillage intensity and timing on soils and winter wheat (WW) (*Triticum aestivum* L.) micronutrient content under dryland winter wheat–pea (*Pisum sativum* L.) rotation (WW-P), and (ii) compare these treatments with the nearby long-term undisturbed grass pasture (GP). Soil and wheat (grain and straw) samples from 1995, 2005, and 2015 were analyzed from 52-years WW-P rotation under fall tillage (FT), spring tillage (ST), maximum tillage (MT), or no-tillage (NT). The concentrations of Mehlich III extractable B, Mn, Zn, Cu, and Fe in soil were unaffected by the tillage methods; however, a significant ($P < 0.01$) decline in extractable Zn in the top 10 cm soil was observed compared to GP (NT: 2.3 mg kg^{-1} vs. GP: 6.0 mg kg^{-1}). Similarly, in the top 10 soil depth after 52 years of WW-P, extractable Mn concentration was significantly lower in FT (97 mg kg^{-1}), ST (92 mg kg^{-1}), and MT (113 mg kg^{-1}) compared to GP (175 mg kg^{-1}) whereas NT (123 mg kg^{-1}) maintained the Mn concentration with that of GP at the same depth. Soil pH was lower in the upper 10 cm under NT than in the rest of the WW-P treatments. Increase in micronutrient availability under NT is expected over time due to decreased soil pH, lower soil organic matter (SOM) mineralization rate, and the greater amount of SOM within the surface soil of NT compared to other tillage methods.

Keywords: Boron, Grass pasture, Long-term experiment, Manganese, No-tillage, Zinc.

Introduction

The growing global population and demand for food has led to intensive agriculture production (Kopittke et al., 2017) and an increased percentage of dryland cultivation area (Huang et al., 2016). Agricultural practices impact the nutrient supplying capacity of soil (Li et al., 2007; Setia and Sharma, 2004; Wei et al., 2006), and these impacts are more evident in drylands than in irrigated lands (Schillinger and Papendick, 2008). However, there is uncertainty about how these practices affect soil nutrients in the long-term. Therefore, it is essential to assess the potential impact of agricultural practices, such as tillage and crop rotation in drylands, as such lands will be a crucial resource of future global food supply (Huang et al., 2016; Mueller et al., 2012).

Tillage intensities greatly influence SOM decomposition and soil microbial activity, which in turn, affect macro- and micronutrient availability in soil (Kennedy and Schillinger, 2006). The quantity of mineralizable organic forms of micronutrients and microbial activity both increase with accumulation of SOM, whereas nutrients become unavailable or decline when the SOM decreases (Carpenter-Boggs et al., 2003). Several researchers reported that metal complexation (Datta et al., 2001) and microbial exudates increase the availability of Fe (Kraemer, 2004), Mg, Zn, and Cu (Tao et al., 2003) to plants. Soil under conservation tillage (no-tillage, NT; or chisel plowing, CP) has a greater amount of SOM and microbial activity than soil under conventional moldboard plow tillage (Thomas et al., 2007). Consequently, greater concentrations of some soil extractable micronutrients, such as Mn and Zn were reported under NT methods than for conventional tillage (Follett and Peterson, 1988; Hargrove et al., 1982).

Other researcher reported that NT enhanced the conversion of Fe and Mn oxides to exchangeable forms compared to conventional tillage due to low soil pH and high amount of SOM in NT plots than in conventionally tilled plots (Shuman and Hargrove, 1988). On the other hand, Lavado et al. (1999) and Hickman (2002) reported that tillage system did not affect extractable concentrations of soil Cu and Zn.

Timing of tillage methods is another important factor in the dryland winter wheat (WW) cropping systems of the Pacific Northwest (PNW) because wheat is grown once in a 24-month period in the PNW (Rasmussen and Collins, 1991). In this traditional system, practiced over 100 years in the PNW, land is left bare for 14 months (if fallowed) or 10 months (if pea could be incorporated into the rotation, which depends on the amount of rainfall). Soils in this system are without crop or crop residue and exposed to wind and water erosion due to lack of cover during this long period (Rasmussen and Parton, 1994; Williams, 2004). If tillage is delayed and implemented in spring instead of fall, there will be residue cover to protect the soil from erosion, rainfall impacts can be reduced, water infiltration may increase, and evaporation may be reduced (Rasmussen and Parton, 1994). Consequently, the dynamics of SOM and soil microbial activities may be affected by tillage timing, which also impacts nutrient cycling.

The availability of micronutrients in soil significantly affects the productivity and quality of crops (Li et al., 2007). Therefore, changes in plant-available micronutrients in the soil are not only important for plant nutrition, but also for livestock and human nutrition. The importance of the connection between plant-human nutrition is evident in studies that have documented Zn as the most widespread micronutrient deficiency limiting crop production (Alloway, 2009). It was estimated that more than two billion people may have inadequate intake of Zn (Stein, 2014), and elevated CO_2 levels may exacerbate the problem with Zn and other nutrient deficiencies (Myers et al., 2014). Recent reviews reported that climate change and elevated CO_2 concentration will influence the quality of food, possibly decreasing Zn and Fe concentrations in cereals and legumes (Myers et al., 2017; Myers et al., 2015).

Most studies on tillage systems investigated changes in the soil C, N, and P (Motavalli and Miles, 2002; Ussiri and Lal, 2009; Wang et al., 2011). Few studies have examined changes in micronutrients as influenced by tillage systems in long-term experiments (Franzluebbers and Hons, 1996; Mahler et al., 1985). Furthermore, very few studies focused changes in micronutrients concentrations with soil depths over time. No-tillage and reduced tillage systems have been adopted in the PNW region; however, there is no information on micronutrient dynamics in the winter wheat-dry pea rotation (WW-P) cropping system.

The objectives of the present study were to: (i) examine the long-term impact of tillage timing and intensity on the concentration and distribution of plant essential micronutrients at four soil depths (0-10, 10-20, 20-30, and 30-60 cm), and in wheat grain and straw; and (ii) determine the change in plant essential micronutrients in soil after 52 years of continuous cultivation under WW-P, by comparing micronutrient data from WW-P plots with that of nearby undisturbed grass pasture (GP) under a dryland of eastern Oregon. We hypothesized the tillage that leaves a greater amount of residue for a longer period of time on on the soil surface, and causes less soil disturbance, will increase micronutrient levels, or at least reduce the severity of a nutrient decline compared with tillage that incorporates residue early in the season and makes a greater soil disturbance.

Materials and methods

Experimental site and design

A tillage experiment in field plots under a dryland winter wheat-dry pea rotation was established in 1962 at the experimental station of Oregon State University in Adams, eastern Oregon (458439 N, 1188 389W. elev. 490 m). The soil is a well-drained, coarse-silty, mixed, superactive, mesic Typic Haploxerolls soil derived from loess (Gollany et al., 2005). The average annual precipitation at the station is around 400 mm and 70% of its precipitation occurs during the winter (September- February). According to the Columbia Basin Agricultural Research Center (CBARC) report, the 85-year average temperature of the site is 8°C with hot dry summers and cool winters.

The winter wheat-pea long-term experiment (WP-LTE) is a randomized split-plot (7.3 m x 27 m plot dimension) design with four replications. Each replication consisted of eight plots (two crops × four tillage methods). The reason for including two crops in each replication was to allow yearly data collection for wheat and peas. The location of the wheat and peas alternated within a replication year to year and WW is grown once every two years. The wheat varieties grown were 'Nugaines' and 'Hyslop' during 1967 to 1974 and 1975-1978, respectively, and after that 'Stephens' was used. Fresh pea was included in the rotation until 1991 and then replaced by dry pea. Winter wheat received 45 kg N ha^{-1} between 1967 and 1981. The N rate was increased to 67 kg N ha^{-1} in 1982, and it was further increased to 90 kg N ha^{-1} after 1985. Ammonium nitrate (34-0-0) was broadcast applied as an inorganic N source until 1995, and urea ammonium nitrate (32-0-0) was shanked 12 cm deep before planting in WW phase after 1995. In pea phase, either ammonium sulfate (21-0-0-24) or ammonium phosphate sulfate (16-20-0-14) was broadcast applied at 22 kg N ha^{-1}.

The tillage treatments varied in timing and intensity as follows:

1. *Fall tillage (FT):* This is the standard tillage management in eastern Oregon for WW-P. After the wheat harvest in fall, the wheat stubble was moldboard plowed to a depth of ~20 cm. In the spring, the weeds were controlled by spraying with glyphosate at rates ranging from 314 to 628 g acid equivalent (a.e.) ha^{-1}. Before seeding pea, plots were tilled twice to a depth of ~ 10-15 cm using spring-tooth harrow (John Deere CC, John Deere, Moline, IL). A Dunham Culti-packer (Dunham Co., Dunham, OH) was used to roller-pack the plots after seeding pea. In the summer, pea vines were moldboard plowed again to a depth of ~20 cm, which was followed by disc harrowing to ~10 cm deep. The residue cover in the fall following pea harvest and in the fall following wheat harvest were approximately 1% and 5%, respectively.
2. *Spring tillage (ST):* Wheat stubble was left undisturbed until the spring and then it was moldboard plowed to a depth of ~20 cm. Secondary tillage and pea vine management were similar to that of FT. The residue cover in the fall following pea harvest and in the fall following wheat harvest was approximately 1% and 80%, respectively.

3. *Maximum tillage (MT):* Wheat stubble was roto-tilled to a depth of 10 cm in the fall after wheat harvest with the purpose of breaking up the wheat stubble. A V-shaped Noble sweep (Noble Farms Ltd., Nobleford, AB, Canada) was used to sweep the weeds after glyphosate spraying on the plots. After sowing pea, plots were roller packed. Pea vines were swept after pea harvest in July to stop pea vine growth and water use. In the following fall, a chisel plow was used twice to till to a depth of ~20 cm. The residue cover in the fall following pea harvest and in the fall following wheat harvest was approximately 10% and 40% respectively.
4. *No-tillage (NT):* This plot was under minimum tillage before 1995. Therefore, to the date of this study, the NT plot is "only" 20 years old (compared with 52 years for other treatments). The plots were rotary mowed to cut wheat-stubble in the fall and were swept once to a depth of ~5 cm before rod weeding until 1995 when it was under minimum tillage. Pea vines were sprayed with glyphosate, if necessary, in the spring and rod weeded twice. In the summer, pea vines were skew-treaded two to three times. Under this NT treatment, the residue cover in the fall following pea harvest and in the fall following wheat harvest was approximately 20% and 80%, respectively.

The WP-LTE treatments were compared to nearby undisturbed perennial grass pasture (GP) to evaluate the changes brought by tillage over time. The GP plot has been maintained since 1931 with native perennial grasses such as bluebunch wheatgrass (*Agropyron spicatum* Pursh) and Idaho fescue (*Festuca idahoensis* Pursh).

Soil and tissue sampling and laboratory analysis

Soil cores from 1995, 2005, and 2015 were used in this study. Archived soil and tissue (wheat grain and straw) samples from 1995 and 2005 were provided by the CBARC and samples were collected in the summer of 2015. Soil samples from four depths (0-10 cm, 10-20 cm, 20-30 cm, and 30- 60 cm) were used in this study. The soils were collected using a truck-mounted Giddings Hydraulic Probe (Giddings Machine Company, Inc., Windsor, CO) and a steel sampling tube (internal diameter 3.6 cm) after wheat harvest in summer. Soil samples from two sides of each plot were composited. The soil samples were oven dried for 24 hours at 105°C and were roller milled for four hours. Wheat grain and straw were removed from the center of each treatment and were ground.

The ground soil samples were analyzed for extractable B, Mn, Fe, Zn, and Cu; and tissue samples were analyzed for total B, Mn, Fe, Zn, and Cu concentration in grain and straw. The Mehlich III extraction method (Mehlich, 1984) was used to extract the micronutrients from the soil, whereas a dry-ash method (Pap and Harms, 1985) was used to extract the micronutrients from the tissue. The concentrations of micronutrients were determined by inductively coupled plasma-optical emissions spectroscopy (ICP-OES, Model #2100 DV, Waltham, Massachusetts, USA). The analyses were carried out in the Central Analytical Lab (CAL, Oregon State University). Soil pH was determined from 10 g samples in a 1:2 soil to 0.001 M $CaCl_2$ solution using pH electrodes after a 30 minute equilibrium time (Thomas, 1996).

Statistical analysis

Grass pasture (GP) was included as one of the treatments of WP. Data were analyzed as a Repeated measure analysis (RMA) of a split-plot design with four blocks where year (1995, 2005, 2015) was used as the whole plot factor, treatment (five levels: GP, FT, ST, MT, and NT) as the subplot factor and responses were measured repeatedly in space at 4 soil depths (0-10 cm, 10-20 cm, 20-30 cm, and 30-60 cm). Analysis of wheat grain and straw was conducted as a split-plot design with four blocks where year (1995, 2005, and 2015) was a whole-plot factor and tillage treatment (FT, ST, MT, and NT) was a sub-plot factor. The data were checked and verified for the model assumption (normality) using the residuals (Montgomery, 2013). The assumption was met either in the original data or by applying an appropriate transformation (square root or log or cubic). The data were back-transformed to their original values for easier reading of the results. We used the mixed model in "Repeated Measures" add-ins in JMP Pro 13 to analyze the soil data, whereas wheat grain and straw were analyzed by the mixed model procedure of JMP Pro 13 (SAS Institute Inc, 2014). Multiple means comparisons were carried out for the significant effects (p-value < 0.05) by comparing the least squares means of the corresponding treatment combinations. Letter groupings were generated by Tukey-Kramer HSD method using a 5% level of significance.

Since the units of pH are on a logarithmic scale, thus, we converted soil pH data to H^+ concentration (μmol L^{-1}) before analyses for ANOVA. However, the multiple comparisons consist of original values.

Results and discussion

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 (Fig. 7.1). This is in line with the findings of earlier studies (Edwards et al., 1992; Franzluebbers and Hons, 1996). However, soil pH under GP was higher than under the tillage treatments at 0-10, 10-20, 20-30 and even at 30-60 cm soil depths (Fig. 7.1). The NT had lowest soil pH in upper 10 cm soil than the rest of the treatments when compared across all studied soil depths (Fig. 7.1). Overall, the data from this study revealed a decline in soil pH in the top 20 cm soil depth after 52 years of continuous winter wheat- dry pea rotation cropping (Fig. 7.1). The removal of basic cations without replenishment could be a plausible reason for the higher acidity observed in cultivated plots than in GP. Greater decline in soil pH was observed in the top 20 cm of the soil profile than in the 30-60 cm depth (Fig. 7.1). The reason for high pH deeper in the soil profile may be due to the high $CaCO_3$ content of these soils with increasing depth, and moisture stress during summer (Unger, 1991) .

Soil pH affects micronutrient availability in soil (Shuman and Hargrove, 1988). Tillage is another factor responsible for the dynamics of micronutrients (Hargrove, 1985). In this study, tillage significantly affected Mehlich III extractable Mn and Zn (Table 7.1). Only significant treatment effects are discussed here.

Mehlich III extractable boron (B)

Over the 20-year period, B concentration was comparable among the WP-LTE treatments (Table 7.2). Boron in the WP-LTE treatments was in the range of 4.5 to 4.9 mg kg^{-1} in 1995 and 2005 at all studied soil depths (Table 7.2), whereas in 2015 it increased slightly to 4.8 to 5.5 mg kg^{-1}. In 2015, a significant redistribution in B was observed under FT deeper in the soil profile (20-30 and 30-60 cm) compared with the same depths in 1995 and 2005 (Table 7.2). This was likely due to the leaching of B or crop uptake over time (Table 7.2). Boron from GP was not included in the statistical analysis because B was only found in top 10 cm depth under GP. Previous research reported that SOM increased B fixation in soil (Gupta, 1968; Olson and Berger, 1947), while other reports disagreed (Diana et al., 2010; Mahler et al., 1985).

Mehlich III extractable manganese (Mn)

The concentration of Mn was influenced by the three-way interaction of tillage method, soil depth, and years (Table 7.3). Contrary to two previous reports (Franzluebbers and Hons, 1996; Hargrove et al., 1982) no differences in Mn were observed over time between tillage methods at any of the studied soil depths. However, this result was in agreement with a report by Edwards et al. (1992), who reported no differences between NT and moldboard tillage with respect to Mn. However, except for NT, Mn markedly declined under WW-P long-term cultivation when compared with Mn under GP (Table 7.3). Averaged over the years NT had greater Mn than under other treatments, but when compared with GP, NT lost Mn in the top 20 cm soil depth. Although NT was the best of the WP-LTE plots, it still lost ~ 22% Mn in 0-20 cm, after 20 years under continuous WW-P. Retention of crop residue and improved SOM in the topsoil under NT were shown to improve Mn availability (Srivastava and Gupta, 1996). Continuous loss of Mn from the soil through harvest removal and without replenishment could possibly be the reason for lower Mn under WP-LTE plots than under GP. Additionally, greater SOM and mineralization under GP could also have contributed to an increase of extractable Mn under GP than under WP-LTE plots.

Mehlich III extractable zinc (Zn)

T There was a soil depth and tillage interaction at 0-10 and 10-20 cm soil depth which influenced concentration of Zn in the soil, but Zn was comparable among the WP-LTE treatments within each soil depth (Fig. 7.2). The concentration of Zn in the top soil was lower under WP-LTE plots (1.5-2.4 mg kg^{-1}) than under GP (6.0 mg kg^{-1}), whereas Zn in the 10-20 cm soil depth, GP (2.8 mg kg^{-1}) was greater than under NT (1.0 mg kg^{-1}) and MT (0.96 mg kg^{-1}), and was comparable for FT (1.4 mg kg^{-1}) and ST (1.4 mg kg^{-1}). The Zn concentration was greatest near the soil surface and decreased with depth (i.e., 20-30 and 30-60 cm) under NT, ST, and GP (Fig. 7.2). This is in agreement with earlier reports on the influence of tillage on extractable Zn in the soil surface only, and was attributed to factors such as higher SOM levels and lower soil pH at the soil surface (Edwards et al., 1992; Franzluebbers and Hons, 1996). Furthermore, the immobility of Zn in soil could be another reason for greater Zn concentration near the soil surface than in deep soil profile (Prasad and Power, 1997).

Mehlich III extractable iron (Fe) and copper (Cu)

The influence of tillage systems on the concentration of Fe and Cu were not detected over the 20-year period. These results were in agreement with the reported Cu results by Edwards et al. (1992); however, Franzluebbers and Hons (1996) observed lower Cu and Fe under NT than under moldboard plow at the soil surface. This observation could be a result of less mineralization of SOM or soil pH.

Micronutrients accumulation in wheat straw and grain over time

Except for the concentration of B and Mn in wheat straw, no significant differences in micronutrients concentration of wheat straw were observed over time (Table 7.4). Similarly, micronutrient accumulations in wheat grain generally remained unaffected by the treatments over time (Table 7.4). Despite the relatively constant concentration of extractable soil B over time, tillage methods influenced the B concentration in wheat straw (Fig. 7.3). The straw B concentration was greater under FT (6.7 mg kg^{-1}) than under NT (5.6 mg kg^{-1}) and MT (5.7 mg kg^{-1}). The tillage methods did not affect straw Mn in 1995 and 2005; however, in 2015, NT and MT showed significantly ($P < 0.05$) greater straw Mn concentration than that in FT and ST (Fig. 7.4). Srivastava and Gupta (1996) reported that B uptake had an antagonistic impact on Mn uptake by plants as both compete for the common carrier molecule for nutrient translocation. This could be the reason for having lower straw Mn in the treatment with higher straw B in this study.

Summary and Conclusions

This study examined changes in plant essential micronutrients (i.e., B, Mn, Zn, Cu, and Fe) at four soil depths (0-10, 10-20, 20-30, and 30-60 cm), and in wheat grain and straw of the WP-LTE. There were no treatment main effects on concentration of micronutrients over time, however, interactions were observed. Although there were no significant differences between the treatments over the 20-year period, the Mehlich III extractable Mn, Zn, and soil pH declined after 52 years of continuous cultivation under WW-P when compared to GP. The effect of 20 years of NT on soil extractable Mn was manifested in 2015 and was comparable to GP in the upper 10 cm depth. Extractable B was also slightly increased in 0-10 and 10-20 cm under NT compared to other tillage systems. There were signs of a stratification effect of NT on the micronutrients. The effect of nutrient stratification in the soil profile under NT has yet to be seen over longer than 20-years period. The impact of tillage and long-term cropping on nutrient availability, its distribution at different soil depths, and in wheat straw suggest that tillage intensities can affect micronutrient availability. The greater amounts of crop residue and lower decomposition rates within the upper soil profile under NT compared to other tillage methods improved micronutrient availability in the topsoil due to stratification and decreased soil surface pH. Corrective measures such as liming may need to be considered in NT systems to maintain soil pH over time.

Acknowledgments

This research was supported by the Oregon State University startup funds awarded to Dr. Valtcho D. Jeliazkov (Zheljazkov). We thank Mr. Karl Rhinhart and his crews for their help with the field soil sampling.

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Table 7. 1 ANOVA table of the main and interaction effects of year, treatment, and depth on the concentration Mehlich III extractable B, Mn, Zn, Fe, and Cu in the wheat-pea rotation long-term experiment. Significant treatment effects that require multiple means comparison are shown in bold.

Source of variation	Boron	Manganese	Zinc	Iron	Copper
Year (Y)	0.05	0.73	<0.01	0.74	0.48
Depth (D)	<0.01	<0.01	<0.01	<0.01	<0.01
Tillage (T)	0.16	<0.01	<0.01	0.20	0.32
Y X D	0.94	<0.01	0.11	0.04	0.22
Y X T	0.45	<0.01	0.21	0.65	0.12
D X T	0.45	<0.01	**<0.01**	0.08	0.22
Y X D X T	**0.03**	**<0.01**	0.14	0.21	0.19

Table 7. 2 Mean concentration of Mehlich III extractable boron (B) obtained from the combinations of treatment, year and depth in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

Depth (cm)	Fall tillage	Maximum tillage	Spring tillage	No tillage
		Boron (mg kg^{-1})		
1995				
0-10	A[1] 4.61 b[2]	A 4.52 a	A 4.51 b	A 4.59 bc
10-20	A 4.51 b	A 4.51 a	A 4.50 b	A 4.58 bc
20-30	A 4.64 b	A 4.70 a	A 4.72 ab	A 4.85 abc
30-60	A 4.70 b	A 4.85 a	A 4.88 ab	A 4.89 abc
2005				
0-10	A 4.55 b	A 4.50 a	A 4.55 ab	A 4.54 c
10-20	A 4.83 b	A 4.67 a	A 4.51 b	A 4.80 bc
20-30	A 4.83 b	A 4.67 a	A 4.61 ab	A 4.80 abc
30-60	A 4.91 b	A 4.78 a	A 4.71 ab	A 4.93 abc
2015				
0-10	A 4.85 b	A 4.79 a	A 5.01 ab	A 5.06 abc
10-20	A 4.77 b	A 4.78 a	A 4.95 ab	A 5.12 abc
20-30	A 5.03 a	A 5.00 a	B 5.52 a	A 5.17 ab
30-60	A 5.45 a	A 5.06 a	A 5.04 ab	A 5.24 a

[1] Uppercase letters show a comparison of the four treatments within each year and depth, and [2] lower-case letters show a comparison of the 12 combinations of year and depth within each of the four treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Table 7. 3 Mean concentration of Mehlich III extractable manganese (Mn) obtained from the combinations of treatment, year and depth in the wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

Depth (cm)	Fall tillage	Maximum tillage	Spring tillage	No tillage	Grass pasture
			Manganese (mg kg^{-1})		
1995					
0-10	B[1] 108 abc[2]	B 121 a	B 107 abcd	B 127 ab	A 171 a
10-20	B 112 abc	B 110 a	B 111 abc	B 114 abcd	A 148 ab
20-30	A 84 bcd	A 82 a	A 80 bcd	A 84 bcd	A 90 d
30-60	A 69 d	A 76 a	A 74 cd	A 72 d	A 90 d
2005					
0-10	A 132 a	A 111 a	A 142 a	A 141 a	A 152 ab
10-20	A 124 ab	A 96 a	A 122 ab	A 104 abcd	A 90 d
20-30	A 102 abcd	A 87 a	A 97 abcd	A 92 abcd	A 80 d
30-60	A 81 cd	A 101 a	A 95 abcd	A 94 abcd	A 95 cd
2015					
0-10	B 97 abcd	B 113 a	B 92 abcd	AB 123 abc	A 175 a
10-20	B 104 abcd	B 89 a	B 91 bcd	B 96 abcd	A 157 a
20-30	A 81 cd	A 82 a	A 75 cd	A 73 d	A 121 bc
30-60	A 68 d	A 98 a	A 69 d	A 81 cd	A 104 cd

[1] Uppercase letters show a comparison of the five treatments within each year and depth, and [2] lower-case letters show a comparison of the 12 combinations of year and depth within each of the five treatments. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Table 7. 4 ANOVA table of the main and interaction effects of year and treatment on the accumulation of N, C, S, P, K, Ca, and Mg in the grain and straw of wheat-pea rotation long-term experiment (WP-LTE) at Pendleton.

Source of variation	Boron	Manganese	Zinc	Iron	Copper
			Wheat Straw		
Year	<0.01	<0.01	<0.01	0.29	<0.01
Tillage	**0.03**	<0.01	0.25	0.91	0.87
Year*Tillage	0.25	**<0.01**	0.37	0.73	0.46
			Wheat Grain		
Year	<0.01	<0.01	<0.01	<0.01	<0.01
Tillage	0.55	0.10	0.17	0.16	0.32
Year*Tillage	0.51	0.09	0.18	0.37	0.30

Significant ($P \leq 0.05$) treatment effects that require multiple means comparison are shown in bold.

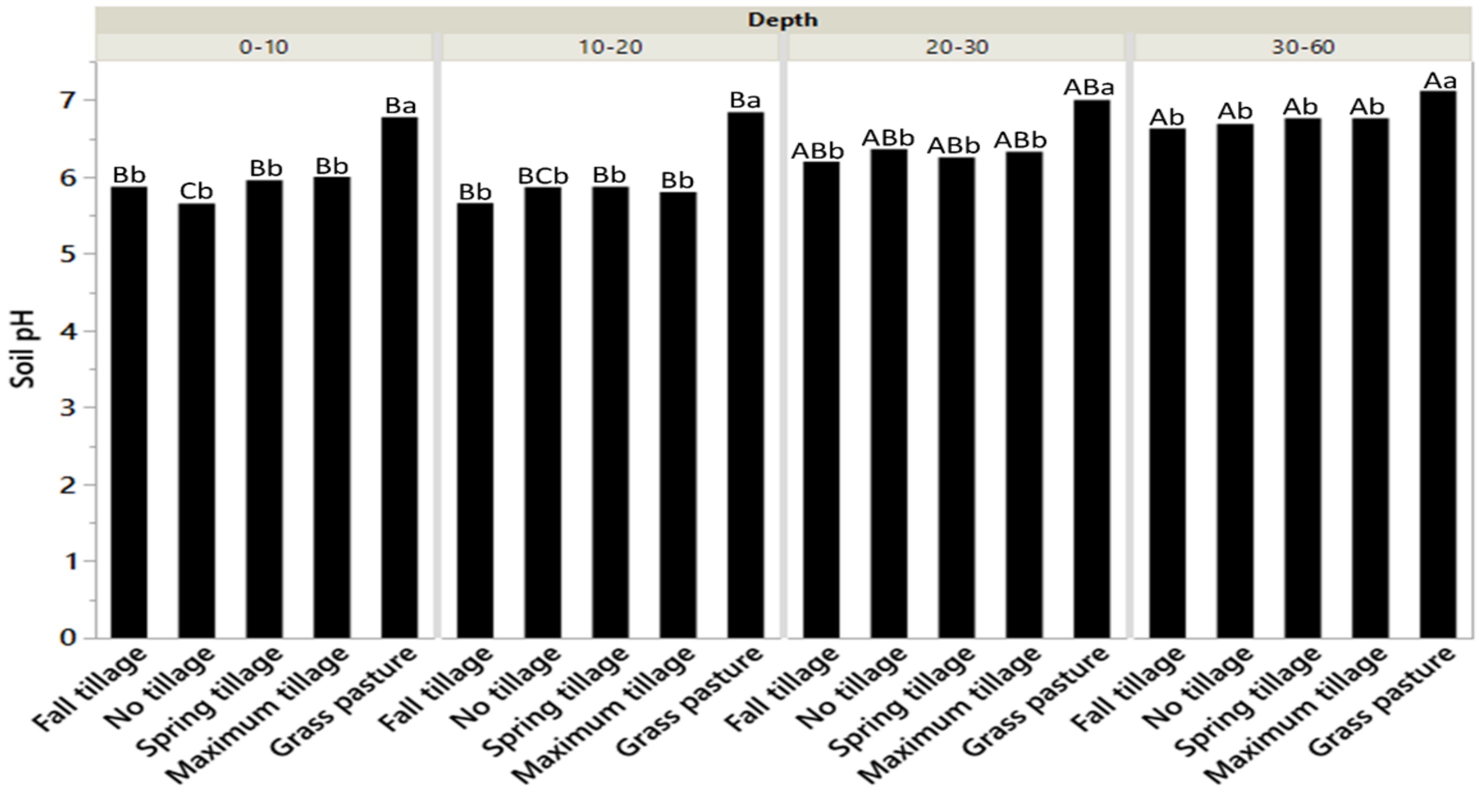

Fig. 7. 1 The long-term effect of four tillage methods and undisturbed grass pasture on soil pH in different soil depths (cm).

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 ($P \leq 0.05$) different.

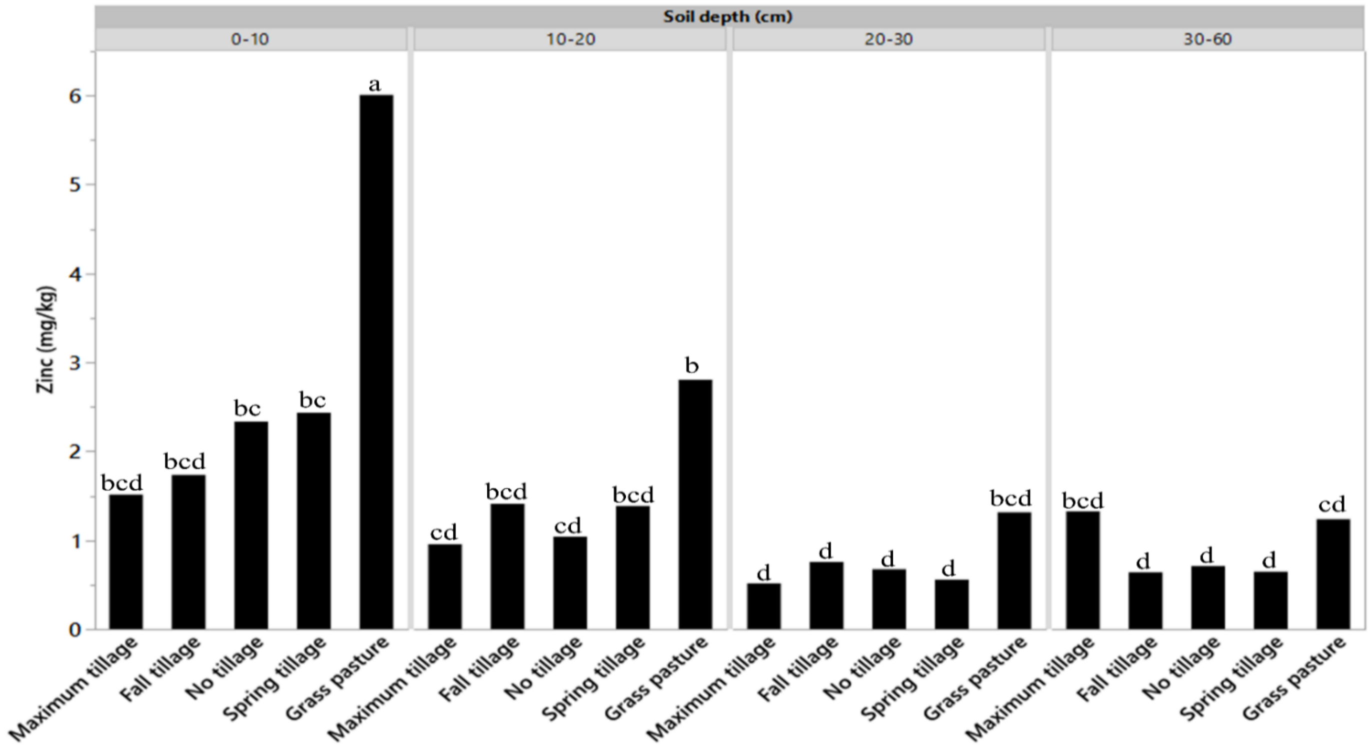

Fig. 7. 2 The long-term effect of four tillage methods and undisturbed grass pasture on Mehlich III extractable zinc (mg/kg) in different soil depths under winter wheat-dry pea rotation.

Letters above the bars show a comparison of 20 combinations of treatment and soil depths. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

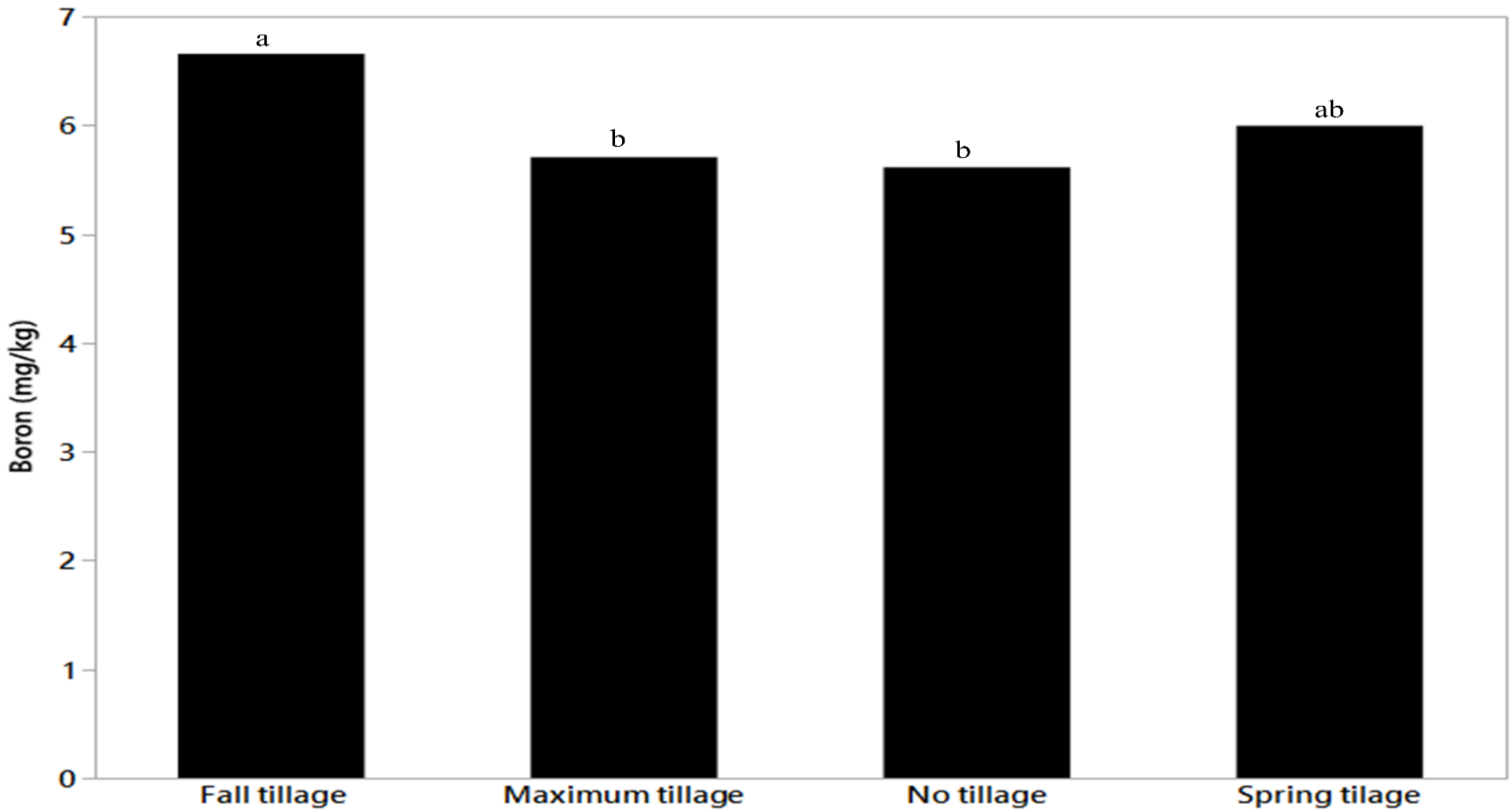

Fig. 7. 3 The long-term effect of tillage methods on the concentration of straw boron under winter wheat-dry pea rotation. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

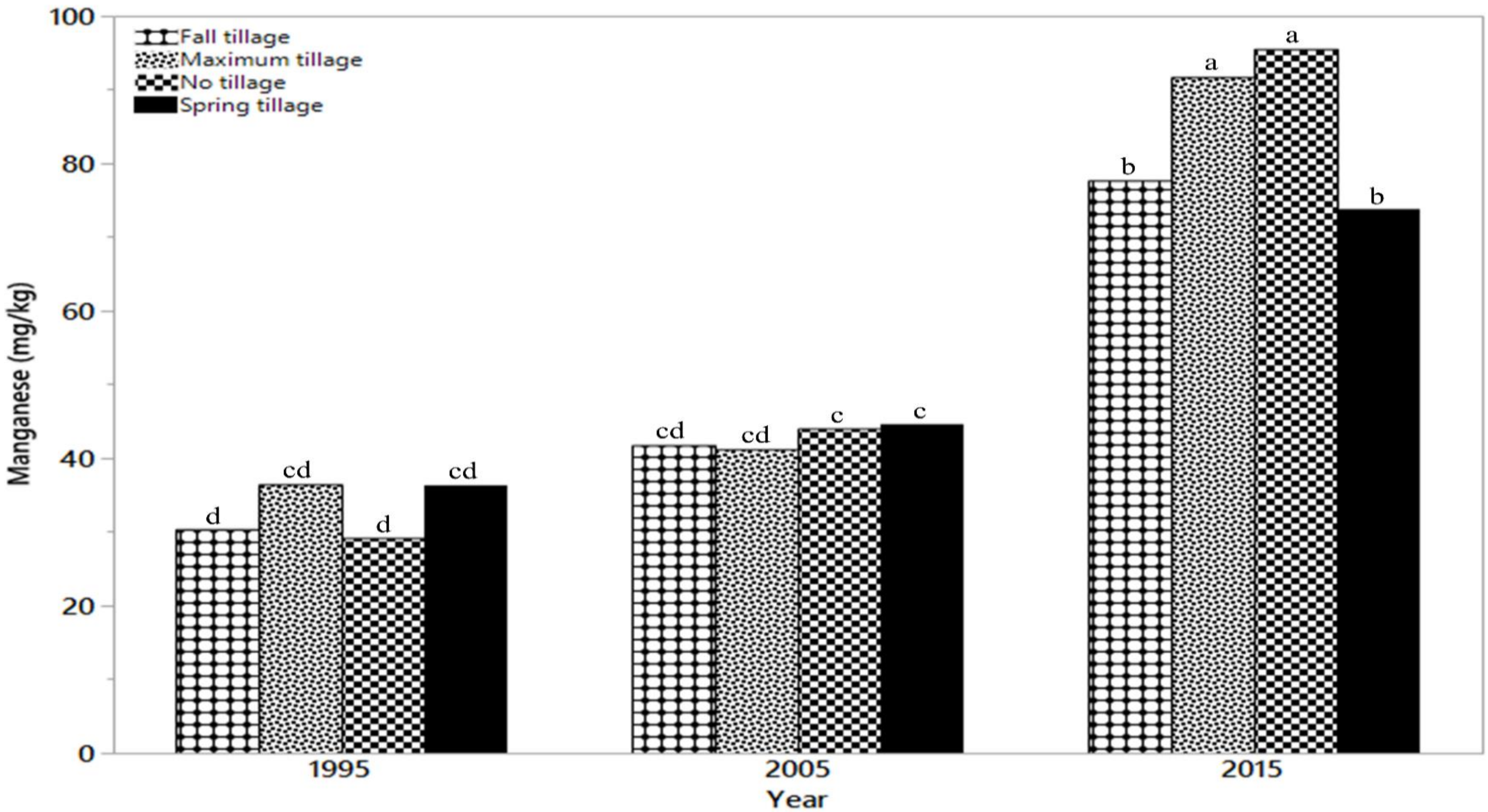

Fig. 7. 4 Effect of tillage methods on the concentration of straw manganese over the 20 years' time.

Letters above the bars show a comparison of 12 combinations of treatment and year. Means sharing the same letter are not significantly ($P \leq 0.05$) different.

Chapter 8

CONCLUSION

The objectives of this work: (i) assessment of at least 50 years' impact of common agricultural practices of winter wheat dryland cropping system of the inland PNW on plant essential macro and micro-nutrients (N, C, S, P, K, Ca, Mg, Mn, Fe, Zn, Cu, and B) in soil and wheat, (ii) twenty years trends of the nutrients dynamics as affected by the agricultural practices, and (iii) recommending the best management practices for sustainability of agriculture based on the quantification of the effect derived from this study were accomplished via Chapters 2, 3, 4, 5, 6, and 7.

In Chapter 2 and Chapter 3, I demonstrated the 84 years effect of different methods of crop residue management on plant essential macro and micronutrients under conventional tillage. We did not find the significant impact of residue burning on soil nutrients. However, unburned residue incorporation had smaller C/N ratio than burned residue incorporation. Among the treatments, farmyard manure (FYM) treatment had slowed nutrient decline in soil and in wheat over the time. Higher N rates acidified the soil, increased N (less protein content is desired in soft winter wheat) and decreased the P accumulation in wheat grain- all of which are not desirable. On the other hand, application of inorganic N increased Mehlich III extractable B in soil than that did not receive inorganic N. The results indicate that application of FYM is vital to reduce nutrient loss and can't be replaced by inorganic N application, however, pea vines incorporation can be replaced by inorganic N application. Earlier research in this plot has reported no yield increase after 45 kg N ha^{-1}. Thus, we suggest incorporation of judicious amount of FYM with unburned residue and inorganic N fertilizer at the rate of 45kg N ha^{-1} could be beneficial and viable for the maintenance of soil macronutrients and enhancing the economics in dryland WW-F farming system in a long run.

In Chapter 4 and Chapter 5, I studied the impact of different tillage methods and variable inorganic N rates application after 75 years of winter wheat-Fallow cropping. The plots under moldboard plow lost N, C, K, and Mg in top 10 cm soil depths than under sweep and disc tillage over the time. Over the twenty years (1995-2005-2015), total S significantly declined under sweep and moldboard tillage at all four tested N rates whereas disc tillage had no effect. However, the soil pH, C, N, Mehlich III extractable P, Ca, Mg, Cu, Mn, and Zn declined markedly in top soils after 75 years of cultivation compared to nearby undisturbed perennial grass pasture (GP). Nitrogen application improved the soil CN ratio and increased the P accumulation in wheat grain. Simultaneously, it decreased the soil pH also. Thus, N application with minimal soil disturbance tillage (in this study disc/sweep tillage) and greater surface cover after tillage would be best management practices under this cropping system.

In Chapter 6 and Chapter 7, I evaluated the effect of timing and intensity of tillage systems on plant essential nutrients in soil and wheat after 52 years of cropping under winter wheat-dry pea rotation cropping system. This study compared the impacts of the most common tillage regimes (Fall and Spring moldboard tillage) and the less common tillage regimes (Maximum and No tillage) of the inland PNW. Maximum (Chisel plow) and no tillage were the conservation tillage regime of the study. No differences on nutrient dynamics were observed between timing of tillage (Spring vs Fall tillage). However, we found markedly greater C, S, P, K, and Mn in upper 10 cm soil under no tillage compared to fall, spring and maximum tillage. Furthermore, the extractable Mn under no tillage was comparable to GP in 2015 which suggest that the impact of no tillage is manifesting gradually in 2015 as it was implemented only since 1995. The long-term impact of no tillage seems promising for the sustainability of agriculture in this region under winter wheat-dry pea rotation cropping system which is yet to be seen.

In a nutshell of this study, the agricultural practices that include the balance of FYM and inorganic N, greater surface cover after tillage, and less volume of soil structure disruption or inversion are the best agricultural practices that can be nutrient sustainable of the wheat and the soil of the drylands of PNW and similar ecoregion.

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