12-2020

Soil Health, Phosphorus and Carbon Dynamics in Response to a One-Time Compost Application and Cover Crops in Organic Dryland Winter Wheat

Idowu Ademola Atoloye
Utah State University

SOIL HEALTH, PHOSPHORUS AND CARBON DYNAMICS IN RESPONSE TO A ONE-TIME COMPOST APPLICATION AND COVER CROPS IN ORGANIC DRYLAND WINTER WHEAT

by

Idowu Ademola Atoloye

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Soil Science

Approved:

Jennifer Reeve, Ph.D. Major Professor	Astrid Jacobson, Ph.D. Major Professor
Jeanette Norton, Ph.D. Committee Member	Scott Jones, Ph.D. Committee Member
Urszula Norton, Ph.D. Committee Member	D. Richard Cutler, Ph.D. Interim Vice Provost for Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2020

ABSTRACT

Soil Health, Phosphorus and Carbon Dynamics in Response to a One-Time Compost Application and Cover Crops in Organic Dryland Winter Wheat

by

Idowu Ademola Atoloye, Doctor of Philosophy

Utah State University, 2020

Major Professors: Drs. Jennifer R. Reeve and Astrid R. Jacobson
Department: Plants, Soils, and Climate

As the demand for organic grain is on the rise in recent years, organic dryland winter wheat (*Triticum aestivum*) farmers in the intermountain west are searching for soil management practices that will improve soil health, sustain or increase crop yield while economically and environmentally sustainable. Understanding the sole and synergistic effects of soil management options may contribute to sustainable management in organic dryland agriculture.

The objective was to understand the effects of different rates of manure compost and the inclusion of cover crops on soil health in two organic dryland soils of varying characteristics, one at Snowville and the other at Blue Creek. Six rates of compost: 0, 12.5, 25 50 Mg DW ha^{-1} composted feedlot manure, 2 Mg chicken composted manure and 25 Mg DW ha^{-1} composted feedlot manure plus 45 kg N ha^{-1} of chicken feather meal were applied before a cover crop mix of Austrian winter pea (*Pisum sativum*) and hairy vetch (*Vicia villosa*) were planted on one half of all amended plots in the fallow phase.

Responses of physical, biological and chemical soil health indices were assessed. Changes in soil organic matter (SOM) and phosphorus pools were also examined.

The one-time application of the highest rate of composted feedlot manure had greater effects on all the soil health indices measured compared with the inclusion of cover crops versus fallow. Some impact of cover crops on soil health was observed with increased dehydrogenase enzyme activity and readily mineralizable carbon only at Snowville, suggesting that cover crops had minimal effects on the overall soil health. The more fertile soil (Mollisols) enhanced compost P mineralization while immobilization and sorption of compost P increased in the less fertile soil (Inceptisols). Both short- and long-term effects of compost on organic carbon were observed in the particulate organic matter and mineral-associated organic matter pools suggesting that organic carbon dynamics in the two pools are relevant to understanding compost effects in dryland soils. These findings suggest that applications of compost (25-50 Mg DW ha^{-1}) may be a more sustainable option for organic dryland farmers in the intermountain west than including cover crops.

(242 pages)

PUBLIC ABSTRACT

Soil Health, Phosphorus and Carbon Dynamics in Response to a One-Time Compost Application and Cover Crops in Organic Dryland Winter Wheat

Idowu Ademola Atoloye

Organic dryland winter wheat (*Triticum aestivum*) growers in the U.S. are faced with high interannual variability in yields. This is related to the low annual precipitation and low soil fertility on the cultivated soils. Improving soil health is the key to increasing and maintaining crop yields. In this study, we compared the effects of different rates (0, 12.5, 25 and 50 Mg DW ha^{-1} compost and 2 Mg ha $manure^{-1}$) of large quantities of steer manure compost and the inclusion of cover crops versus fallow on soil health and on carbon and phosphorus dynamics in two organic dryland systems with varying soil characteristics and microclimatic conditions. The two sites are located in Snowville and Blue Creek, Utah. At Snowille, the soil fertility is extremely low, pH is 8.5, and average total annual precipitation is 290 mm. At Blue Creek, the soil is more fertile, pH is 7.2 and average total annual precipitation is 485 mm. The results showed that the compost effect on measured physical, biological and chemical soil health indices (soil moisture, dehydrogenase and phosphatases enzyme activities, soil organic carbon, Olsen P) were greater than the effects of cover crops at both sites. Differences were also found in phosphorus cycling between the two sites, with potential long-term impacts in soils with extreme low fertility due to lower rate of nutrient mineralization. By applying large quantities of compost (25-50 Mg DW $ha\text{-}^{1}$) once, organic dryland winter wheat farmers

can improve soil health, enhance SOM associated water retention and availability, and provide an environment for continuous sustainable wheat yield.

Dedicated to the memory of my late father,

Timothy Atoloye

ACKNOWLEDGMENTS

First of all, I am grateful to God for giving me the strength, wisdom, and good health to complete this journey.

I like to thank my co-major professors Drs. Jennifer Reeve and Astrid Jacobson for their dedication, patience, encouragement, financial and technical support as I continue to learn and grow. I would also like to express my gratitude to everyone on my committee, Drs. Jeanette Norton, Scott Jones, and Urszula Norton for their mentorship, service and guidance. Thanks to David Powelson for his guidance on the use of C- and N-analyzer and other laboratory tasks. Many thanks to the United States Department of Agriculture Organic Research Initiative and Utah State University Presidential Research Program for funding this study.

Special thanks to my parents and parent in-laws for all that they have done to support me through this process. And to my children (Tomiloluwa and Tiwajopelo) for going along and providing me with fun distractions while I work through this long process. I would especially like to thank my wonderful spouse, Abiodun. Her love, sacrifices, and dedication have served as inspiration to me as we take this journey together. A special thanks goes to my colleagues and friends for their encouragement, patience and moral support during the entire process.

Idowu Ademola Atoloye

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER III

CHAPTER IV

CHAPTER I

1 | INTRODUCTION

Organic dryland winter wheat (*Triticum aestivum* L) is one of the main crops grown across the western intermountain region of northern Utah, western Montana and southeastern Idaho and in the inland Pacific Northwest (Schillinger et al., 2006). In Utah, approximately, 17,000 ha of organic wheat was grown in a dryland winter wheat-fallow rotation in 2015 (NASS, 2019), making it the second highest producer of organic wheat in the western U.S. However, yield in organic dryland systems is low and variable due to low soil fertility and health, and lack of rainfall. With the increase in the demand for organic wheat-based products in the U.S., farmers are interested in the adoption of sustainable soil management practices that can mitigate the low yield.

As a result of the low precipitation and subsequently limited soil moisture in this region, farmers have traditionally grown organic winter wheat with a fallow rotation. The fallow period is included to increase soil moisture storage for subsequent wheat crops and could last between 13-14 months (Schillinger & Papendick, 2008). The use of fallow, however, reduces the addition of soil organic carbon (SOC) due to the presence of small amounts of plant biomass during the fallow rotation. Furthermore, the loss of SOC is increased through continuous tillage and the minimal use of soil fertility inputs. Mitigating the limited soil moisture and low SOC will require the inclusion of soil fertility inputs, but farmers are faced with limited options (Reeve et al., 2012).

The use of leguminous cover crops (hereinafter known as ‘cover crops’) and manure compost (hereinafter known as ‘compost’) are two potential options available to farmers, but both have restrictions. The inclusion of cover crops during the fallow rotation could potentially increase SOC and nitrogen through the additional biomass inputs. However, cover crops could also reduce soil moisture and negatively impact subsequent crop yield (Nielsen et al., 2016). On the other hand, compost, an alternative to improving soil fertility, quality, and moisture, is rarely used due to costs associated with the haulage and application. The combined use of cover crops and compost could also be a possible potential to mitigate low SOC and soil fertility in organic dryland WW-F.

A prior study has reported the long-term beneficial effects of a one-time high rate of compost on soil health and yield in organic dryland WW-F systems (Reeve et al., 2012). The study reported the beneficial effects of compost on SOC, microbial biomass, dehydrogenase and phosphatase enzyme activity, and plant-available P in the top 5 cm and wheat yield 16 years later. after application. Thus, a detailed understanding of compost effect on soil fertility and quality following a single addition in organic dryland WW-F systems becomes important in order to assist the farmers in making economically viable and environmentally sustainable decisions.

2 | LITERATURE REVIEW

2.1 | Characteristics of organic dryland soils

Soils in semi-arid areas vary widely in characteristics and microclimatic conditions but, overall, soils are neutral to basic in pH, low in SOM, nitrogen (N) and phosphorus (P) supply capacity and total annual precipitation (usually less than 600 mm)

(Aase & Pikul, 2000). The soil types can vary from Inceptisols (relatively young and little weathering), to Aridisols (xeric moisture regime and high accumulation of salts), to Entisols (poorly developed), to Mollisols (dark soil color and a higher rate of weathering) and Alfisols (Neary et al., 2002). Semi-arid soils are mostly calcareous due to the high percentage of calcium carbonate ($CaCO_3$) within the soil profile. The high $CaCO_3$ is usually present because the parent materials are rich in shells, limestones, or calcareous glacial tills (Taalab et al. 2019). Also, low precipitation and high evaporation rate in arid and semiarid soils prevent the leaching of $CaCO_3$ and cause salts to move by capillary action to the upper horizons where they are deposited. The percent equivalence of $CaCO_3$ typically varies between 0 to 95 % with the pH of the soils usually above 7 and could be as high as 8.5-9. In some soils, the $CaCO_3$ can form a caliche layer, a layer formed by the secondary accumulation of carbonates (Ca or Mg) in soils with 15 % or more $CaCO_3$ equivalency, which is hard and typically impermeable to plant roots and water. Based on the total annual precipitation, drylands can be classified into 3 groups namely, (i) low, $<$ 300 mm, (ii) intermediate, 300-450 mm, and (iii) high, $>$ 450 mm (Schillinger et al., 2006).

2.2 | Soil health in organic dryland agriculture

Soil health, also known as soil quality, can be defined as the sustained capacity of a soil to function as an essential living system within land-use and ecosystem boundaries to support biological productivity, enhance or maintain environmental quality and promote plant, animal and human health (Doran & Zeiss 2000; Kuzyakov et al., 2020). Dryland organic soils need to be judiciously managed for the long-term sustainability of

soil health and economically viable yields. Dryland farmers have typically adopted fallowing to stabilize yield. The land is left idle every other year to store water to increase the chances of producing crops the subsequent year with adequate yield. Fallow, however, has been widely criticized as inefficient because the soil is left bare and this increases the susceptibility of the soil to both water and wind erosion (Schillinger et al., 2006). Also, fallow decreases organic carbon (OC) addition and increases the rate of loss of SOM through biological oxidation (Machado et al., 2006). Likewise, tillage is used to control weeds during the fallow year, and this contributes to the loss of soil moisture and SOM. To address the problem of poor soil health and increase crop yield in dryland agriculture, several options have been proposed such as the use of no-till (Stibbe & Ariel, 1970), cover crops (Aase & Pikul, 2000; Lyon et al., 2007; Moyer et al., 2000) and compost (Reeve et al., 2012; Stukenholtz et al., 2002).

2.3 | Inclusion of cover crops and compost in dryland agriculture

The use of cover crops has been touted to be beneficial for dryland agriculture because of the numerous impacts of cover crops on soil health which includes, increased SOM due to increasing residual biomass return, decreased water and wind erosion and weed pressure, (Schillinger, 2017). Whether cover crops will improve soil health and become a beneficial and sustainable practice depends on whether the farm is organic or conventional, or if irrigation is used or not, and the total annual precipitation and evaporative demand. The successful use of cover crops to control for weed was shown when combined with no-till by Moyer et al. (2000). In the Moyer et al. (2000) experiment, fall-planted rye subsequently terminated with glyphosate suppressed weed

compared to fallow, but the yield was not increased compared with the yield in plots left in bare fallow. Elsewhere, Büchi et al. (2018) reported that growing pea cover crops with the use of inorganic nitrogen fertilizer and herbicides to control for weeds increased yield compared with a no cover crop control. Contrarily, in an experiment examining the effects of cover mixtures on subsequent wheat yield in Akron, CO, and Sidney, NE, in 2012–2013 and 2013–2014, the use of cover crops was shown to reduce winter wheat yield and was not justifiable, especially under drier conditions (Nielsen et al., 2016).

Although the use of cover crops in non-organic dryland agriculture had varying outcomes, the inclusion of cover crops in organic dryland agriculture may potentially lead to negative effects. In long-term organic dryland winter wheat in northern Montana, researchers reported that winter planted pea increased soil nitrate and used an average of 27 mm less water and increased wheat yield by 13-39 % compared with spring-planted pea (Miller et al., 2011). The researchers also showed that the use of annual green manures could not be relied upon by farmers to increase soil nitrate as the grain protein concentrations were still lower than industry standards required by organic mills (Miller et al., 2011). The decrease in yield (40-70 %) and net returns (50-100 %) have also been reported when cover crops were grown in place of fallow in a winter wheat-fallowing rotation in central great plains (Holman et al., 2018). Holman et al. (2018) showed that for every 125 kg ha^{-1} of cover crop biomass produced, plant available water and yield decreased by 1 mm and 5.5 kg ha^{-1}, respectively. Trying to trade-off cover crops biomass for water use may not be beneficial in organic dryland winter wheat agriculture.

An alternative option may be the use of compost to lead to appreciable increases in SOM. Incorporating organic inputs such as manure compost in organic dryland farming can improve soil fertility, health and decrease weed pressure (Demelash et al., 2014; Wang et al., 2016). Cotton gin compost was reported to increase soil microbial activities and structural stability in a dryland cultivated wheat (Tejada and Gonzalez, 2003). In another study by Stukenholtz et al. (2002) the application of compost at 50 Mg ha^{-1} DW was reported to double the yield. However, Stukenholtz et al. (2002) concluded that due to the inability to recoup hauling and application costs in the short-term, compost application in dryland systems was not viable. Another study was carried out by Reeve et al. in 2012 at the same location as the Stukenholtz et al. (2002), showed the long-term effects of the single application of compost 50 Mg ha^{-1} DW on SOM, soil available phosphorus, and wheat yield in the organic dryland WW-F system 16 years later. Reeve et al. (2012) suggested that organic dryland WW-F farmers could benefit from the long-term benefits of a one-time application and potentially recoup costs over 16 years. The use of compost in organic dryland WW-F has also been restrictive due to the high cost of purchase and transportation and the inability to recoup the cost as a result of high variability in yield from year to year. There is therefore, the need to determine an economically viable rate that will be beneficial to farmers. In addition, it remains to be determined if the effects of cover crops mixtures combined with lower rates of compost will bring about long-term enhanced soil health and yield in organic dryland agriculture. In addition, because of the spatial variation in soil properties, there is the need to

determine the mechanism behind the long-term legacy effects of compost in dryland soils.

2.4 | Phosphorus limitation

Phosphorus (P) is the second most important element in crop production required by plants in large quantities (Yan et al., 2016). The two foremost challenges in P management in agroecosystems are oversupply and depletion (von Wandruszka, 2006). The oversupply arises when organic amendments are applied to meet the nitrogen requirements of crops, thereby leading to excess P supply. Excess P is transported in surface or drainage runoff after irrigation, rainfall or snowmelt, thus threatening eutrophication of nearby water bodies. Depletion is primarily a problem in zero-input agricultural systems under continuous cultivation (von Wandruszka, 2006). The problem of depletion of plant-available P is widespread across dryland soils under organic crop production, particularly in calcareous soils where P is made unavailable through complex formation mostly with calcium ions (Schillinger et al., 2003). Braschi et al. (2003), von Wandruszka (2006) and Yan et al. (2016) have documented the benefits of organic amendments such as manure and manure-derived compost on P availability in calcareous soils. Composted manure can enhance the availability of P by blocking sorption sites and preventing it from being complexed by calcium, iron, or aluminum (von Wandruska, 2006). According to Braschi et al. (2003), P solubility increased when organic matter was added to calcareous soils. In a 150-day experiment on semi-arid calcareous soils, Halajnia et al. (2007) reported that 37 % of the added manure P was available compared with 17 % of added inorganic P. Thus, organic amendments such as green manures,

animal manures, composts and crop residue can significantly improve the supply of P in dryland agroecosystems.

2.5 | Forms of P

Phosphorus exists both in organic (P_o) and inorganic (P_i) forms in soils, and is only slightly soluble and often low in availability to plants (Braschi et al., 2003; Sharma et al., 2013). Both forms of P interface widely with soil components. The removal of P_i from soil solution is primarily due to adsorption and precipitation (Braschi et al., 2003; von Wandruszka, 2006). P_i in soils can be complexed by iron (Fe), aluminum (Al), or calcium (Ca) ions, thus making it unavailable for crop utilization. In acidic soils, the soil P_i ions are complexed by either Fe or Al ions to form Fe- or Al-phosphatase; whereas in calcareous soils, P_i ions are complexed and precipitated by Ca ions as dicalcium and thereafter, octacalcium phosphate (Gerke, 2015). Likewise, P_o can be immobilized through fixation to soil minerals (Gerke, 2015), or stabilized in organic compounds (Turner et al., 2005; Shen et al., 2011).

The role of P_o in soils has been reviewed by several authors who report that its form significantly alters its bioavailability in soils (Martinez, 1967; Turner et al., 2002; Turner & Haygarth, 2005; Shen et al., 2011; Singh & Satyanarayana, 2011; Menezes-Blackburn et al., 2013). Phosphate diesters, organic polyphosphates, and phosphate monoesters (D-glucose-6-phosphate, mononucleotides, phosphoproteins) are labile and play an essential role in P bioavailability most especially in low-input agricultural systems (Turner & Haygarth, 2005). For instance, Hansen et al. (2004) reported that orthophosphate diesters are likely to rapidly undergo mineralization than orthophosphate

monoesters. Although soil P_o makes up a great proportion (40-80 %) of soil total P, plants cannot use it directly (Menezes-Blackburn et al., 2013; Wei et al., 2015). Differences in the amount of available soil water, pH, and $CaCO_3$ content affect the availability of different forms of P in soils (Sharma et al., 1963). In turn, differences in the forms and amounts of P can influence crop responses. Understanding how management practices affect the chemical composition and transformation of soil P is vital in zero- and low-input agriculture (Turner et al., 2003).

2.6 | Soil organic carbon

The continuous cultivation of dryland soils has led to considerable loss of soil organic carbon (SOC) (Ghimire et al., 2015, 2018). Results from the oldest long-term experiment in dryland in western U.S.A shows that cropping practices have varying effects on changes in SOC (Rasmussen & Parton, 1994). Long fallow periods, repeated tillage, and cover crops have resulted in a continuous loss of SOC while manure application has maintained SOC at a new lower steady-state than native grasslands (Ghimire et al., 2015). An estimated 45 Mg C ha^{-1} has been lost in the first 70 years of the Pendleton experiment (Ghimire et al., 2015). This has led to a generally low, below 1 %, organic carbon content (OC) in most cultivated semiarid systems. The low SOC in cultivated organic dryland soils negatively affects crop yield by reducing the soil-water holding capacity, aggregate stability, nutrient supply capacity, and microbial activities (Reeves, 1997). To maintain the sustainability of drylands for crop production, there is a need for the adoption of soil management practices that will increase and sustain SOC. Results from the oldest long-term dryland experiment in Pendleton showed that different

cropping practices had varying effects on SOC (Ghimire et al., 2015). While continuous cover crop decreased SOC, the annual application of manure maintained it (Ghimire et al., 2015). Also, depending on the soil characteristics, organic amendments could have varying effects on SOC concentration and composition in surface and subsoils (Wright & Hons, 2005; Zinati et al., 2001).

Quantifying the effects of soil management practices on SOC is usually thought to take decades to detect (Rasmussen & Parton, 1994). However, because SOC is made of different pools, the effects of management practices may be detected earlier in some pools. For instance, the particulate organic matter (POM) is a labile SOC pool composed of incompletely decomposed macro-organic matter and is known to rapidly respond to changes in soil management practices (Cambardella & Elliott, 1992; Janzen et al., 1992). Even though SOM fractions have varying decomposition rates, physical protection from microorganisms and enzymes enhance SOM persistence in the environment compared to chemical protection. Effects of SOM addition on variations in moisture and temperature regimes can also lead to differences in the effects of soil management practices on the quantity and quality of residue return as well as decomposition rate on SOC (Biederbeck et al., 1994).

Also, subsoil carbon has received increased attention because recent studies have documented that soil management practices affect subsoil SOM fractions (Wang et al., 2019). The addition of organic inputs can alter carbon storage in subsoils because priming effects due to additions of organic carbon to subsoils are lower than in topsoil (Struecker et al., 2016). While climatic variables such as rainfall control carbon storage in

surface soils, bulk density, soil type, and pedological processes greatly influenced carbon storage in subsurface soils (Hobley & Wilson, 2016; Rumpel & Kögel-Knabner, 2011). However, the effects of soil management practices on the dynamics of subsoil OC fractions are not yet fully understood.

3 | OBJECTIVES AND HYPOTHESIS

The main objective of this study was to examine how a one-time application of large quantities of compost and inclusion of cover crops in fallow will affect soil health, SOC and phosphorus dynamics in organic dryland WWF and to determine if variations in soil properties can be used to predict areas where the use of large quantities of compost will be economically viable. Chapter II describes the effects of a one-time compost application and inclusion of cover crops during fallow rotation on soil health in two organic dryland WWF soils. Chapter III describes the effects of a one-time compost application on P cycling in two organic dryland WWF soils. Chapter IV, describes short- and long-term changes in SOM pools in surface and subsoils. Chapter V provides a summary of the findings and implications for organic dryland WWF farmers seeking to adopt sustainable soil management practices. An appendix is included for data not presented in chapters II-IV.

Objective I: Assess how a one-time compost application affects soil health in different organic dryland wheat soils.

Hypothesis 1: Soil health benefits liked to the application of larger quantities of compost will last longer compared with smaller application rates, where gains will be lost much faster.

Objective II: Determine whether the inclusion of cover crops with compost will enhance the benefits gained from compost only.

Hypothesis II: The inclusion of cover crops with either 25 or 50 Mg DW ha^{-1} manure compost will not significantly increase the observed changes in soil health because cover crops add lower organic matter to soils compared with organic amendments.

Objective III: Understand how a one-time compost application affects changes in the biological transformation of P.

Hypothesis III: Compost application will have a greater effect on potential phosphatase activities in more marginal soils with pH greater than 7.

Objective IV: To understand how a one-time compost application affects the dynamics and relationships of soil P fractions (pools).

Hypothesis IV: Compost P mineralization will be greater in soils with higher soil fertility and moisture.

Objective V: Assess changes in total SOC and SOC fractions following a one-time compost application 1-, 3- and 24-years later in surface- and sub-soils in organic dryland WW-F systems in the Intermountain West.

Hypothesis V: We hypothesized that in WW-F dryland soils with low SOC, where the effects of soil management practices on total SOC are subtle, the effects of compost application on SOC will be higher in specific SOC fractions compared to total SOC, especially in the subsoils (30-90 cm).

References

Aase, J. K., & Pikul, J. L. (2000). Water use in a modified summer fallow system on semiarid northern Great Plains. *Agricultural Water Management*, *43*(3), 345–357. https://doi.org/10.1016/S0378-3774(99)00062-1

Biederbeck, V. O., Janzen, H. H., Campbell, C. A., & Zentner, R. P. (1994). Labile soil organic matter as influenced by cropping practices in an arid environment. *Soil Biology and Biochemistry*, *26*(12), 1647–1656. https://doi.org/10.1016/0038-0717(94)90317-4

Braschi, I., Ciavatta, C., Giovannini, C., & Gessa, C. (2003). Combined effect of water and organic matter on phosphorus availability in calcareous soils. *Nutrient Cycling in Agroecosystems*, *67*(1), 67–74. https://doi.org/10.1023/A:1025143809825

Büchi, L., Wendling, M., Amossé, C., Necpalova, M., & Charles, R. (2018). Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system. *Agriculture, Ecosystems & Environment*, *256*, 92–104. https://doi.org/10.1016/j.agee.2018.01.005

Cambardella, C. A., & Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, *56*(3), 777–783. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Gerke, J. (2015). Phytate (Inositol Hexakisphosphate) in Soil and Phosphate Acquisition from Inositol Phosphates by Higher Plants. A Review. *Plants*, *4*(2), 253–266. https://doi.org/10.3390/plants4020253

Ghimire, R., Machado, S., & Rhinhart, K. (2015). Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat–fallow systems. *Agronomy Journal*, *107*(6), 2230–2240. https://doi.org/10.2134/agronj14.0601

Ghimire, R., Norton, J. B., & Norton, U. (2018). Soil organic matter dynamics under irrigated perennial forage–annual crop rotations. *Grass and Forage Science*, *73*(4), 907–917. https://doi.org/10.1111/gfs.12378

Hansen, J. C., Cade-Menun, B. J., & Strawn, D. G. (2004). Phosphorus speciation in manure-amended alkaline soils. *Journal of Environment Quality*, *33*(4), 1521. https://doi.org/10.2134/jeq2004.1521

Hobley, E. U., & Wilson, B. (2016). The depth distribution of organic carbon in the soils of eastern Australia. *Ecosphere*, *7*(1), e01214. https://doi.org/10.1002/ecs2.1214

Holman, J. D., Arnet, K., Dille, J., Maxwell, S., Obour, A., Roberts, T., Roozeboom, K., & Schlegel, A. (2018). Can cover or forage crops replace fallow in the semiarid

central great plains? *Crop Science*, *58*(2), 932–944. https://doi.org/10.2135/cropsci2017.05.0324

Janzen, H. H., Campbell, C. A., Brandt, S. A., Lafond, G. P., & Townley-Smith, L. (1992). Light-fraction organic matter in soils from long-term crop rotations. *Soil Science Society of America Journal*, *56*(6), 1799–1806. https://doi.org/10.2136/sssaj1992.03615995005600060025x

Lyon, D. J., Nielsen, D. C., Felter, D. G., & Burgener, P. A. (2007). Choice of summer fallow replacement crops impacts subsequent winter wheat. *Agronomy Journal*, *99*(2), 578–584. https://doi.org/10.2134/agronj2006.0287

Machado, S., Rhinhart, K., & Petrie, S. (2006). Long-term cropping system effects on carbon sequestration in eastern Oregon. *Journal of Environmental Quality*, *35*(4), 1548–1553. https://doi.org/10.2134/jeq2005.0201

Menezes-Blackburn, D., Jorquera, M. A., Greiner, R., Gianfreda, L., & de la Luz Mora, M. (2013). Phytases and phytase-labile organic phosphorus in manures and soils. *Critical Reviews in Environmental Science and Technology*, *43*(9), 916–954. https://doi.org/10.1080/10643389.2011.627019

Miller, P. R., Lighthiser, E. J., Jones, C. A., Holmes, J. A., Rick, T. L., & Wraith, J. M. (2011). Pea green manure management affects organic winter wheat yield and quality in semiarid Montana. *Canadian Journal of Plant Science*, *91*(3), 497–508. https://doi.org/10.4141/cjps10109

Moyer, J. R., Blackshaw, R. E., Smith, E. G., & McGinn, S. M. (2000). Cereal cover crops for weed suppression in a summer fallow-wheat cropping sequence. *Canadian Journal of Plant Science*, *80*(2), 441–449. https://doi.org/10.4141/P99-099

Nielsen, D. C., Lyon, D. J., Higgins, R. K., Hergert, G. W., Holman, J. D., & Vigil, M. F. (2016). Cover crop effect on subsequent wheat yield in the central great plains. *Agronomy Journal*, *108*(1), 243–256. https://doi.org/10.2134/agronj2015.0372

Rasmussen, P. E., & Parton, W. J. (1994). Long-term effects of residue management in wheat-fallow: I. inputs, yield, and soil organic matter. *Soil Science Society of America Journal*, *58*(2), 523–530. https://doi.org/10.2136/sssaj1994.03615995005800020039x

Reeve, J. R., Endelman, J. B., Miller, B. E., & Hole, D. J. (2012). Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. *Soil Science Society of America Journal*, *76*(1), 278–285. https://doi.org/10.2136/sssaj2011.0123

Reeves, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research*, *43*(1–2), 131–167. https://doi.org/10.1016/S0167-1987(97)00038-X

Rumpel, C., & Kögel-Knabner, I. (2011). Deep soil organic matter—A key but poorly understood component of terrestrial C cycle. *Plant and Soil*, *338*(1–2), 143–158. https://doi.org/10.1007/s11104-010-0391-5

Schillinger, W. F. (2017). Winter pea: Promising new crop for Washington's dryland wheat-fallow region. *Frontiers in Ecology and Evolution*, *5*(43), 1–7. https://doi.org/10.3389/fevo.2017.00043

Schillinger, W. F., & Papendick, R. I. (2008). Then and now: 125 years of dryland wheat farming in the inland pacific northwest. *Agronomy Journal*, *100*(3), 166–182. https://doi.org/10.2134/agronj2007.0027c

Schillinger, W. F., Papendick, R. I., Guy, S. O., Rasmussen, P. E., & Van Kessel, C. (2003). Conservation tillage systems and equipment. In *Pacific Northwest Conservation Tillage Handbook* (pp. 1–23). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://doi.org/10.2134/agronmonogr23.2ed.c11

Schillinger, W. F., Papendick, R. I., Guy, S. O., Rasmussen, P. E., & van Kessel, C. (2006). Dryland cropping in the western United States. In *Dryland Agriculture* (pp. 365–393). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. https://dl.sciencesocieties.org/publications/books/abstracts/agronomymonogra/drylandagricult/365?access=0&view=pdf

Sharma, D. L., Mathur, C. M., & Mehta, K. M. (1963). Forms of phosphorus in soils of Rajasthan. *Soil Science and Plant Nutrition*, *9*(6), 6–9. https://doi.org/10.1080/00380768.1963.10431055

Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *Springer Plus*, *2*(1), 587. https://doi.org/10.1186/2193-1801-2-587

Singh, B., & Satyanarayana, T. (2011). Microbial phytases in phosphorus acquisition and plant growth promotion. *Physiology and Molecular Biology of Plants*, *17*(2), 93–103. https://doi.org/10.1007/s12298-011-0062-x

Stibbe, E., & Ariel, D. (1970). No-tillage as compared to tillage practices in dry-land farming of a semi-arid climate. *NJAS Wageningen Journal of Life Sciences*, *18*(4), 293–307.

Struecker, J., Kaiser, M., Dyckmans, J., & Joergensen, R. G. (2016). Maize root decomposition in subsoil horizons of two silt foams differing in soil organic C accumulation due to colluvial processes. *Geoderma*, *283*, 101–109. https://doi.org/10.1016/j.geoderma.2016.07.026

Stukenholtz, P. D., Koenig, R. T., Hole, D. J., & Miller, B. E. (2002). Partitioning the nutrient and nonnutrient contributions of compost to dryland-organic wheat. *Compost Science & Utilization*, *10*(3), 238–243. https://doi.org/10.1080/1065657X.2002.10702085

Turner, B. L., Cade-Menun, B. J., & Westermann, D. T. (2003). Organic phosphorus composition and potential bioavailability in semi-arid arable soils of the western United States. *Soil Science Society of America Journal*, *67*(4), 1168. https://doi.org/10.2136/sssaj2003.1168

von Wandruszka, R. (2006). Phosphorus retention in calcareous soils and the effect of organic matter on its mobility. *Geochemical Transactions*, *7*, 6. https://doi.org/10.1186/1467-4866-7-6

Wang, B., Gao, L., Yu, W., Wei, X., Li, J., Li, S., Song, X., Liang, G., Cai, D., & Wu, X. (2019). Distribution of soil aggregates and organic carbon in deep soil under long-term conservation tillage with residual retention in dryland. *Journal of Arid Land*, *11*(2), 241–254. https://doi.org/10.1007/s40333-019-0094-6

Wright, A. L., & Hons, F. M. (2005). Soil carbon and nitrogen storage in aggregates from different tillage and crop regimes. *Soil Science Society of America Journal*, *69*, 141–147.

Yan, Z., Chen, S., Li, J., Alva, A., & Chen, Q. (2016). Manure and nitrogen application enhances soil phosphorus mobility in calcareous soil in greenhouses. *Journal of Environmental Management*, *181*, 26–35. https://doi.org/10.1016/j.jenvman.2016.05.081

Zinati, G. M., Li, Y. C., & Bryan, H. H. (2001). Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous soil. *Compost Science & Utilization*, *9*(2), 156–162. https://doi.org/10.1080/1065657X.2001.10702030

CHAPTER II

EFFECTS OF COVER CROPS AND A ONE-TIME COMPOST APPLICATION ON SOIL HEALTH IN ORGANIC DRYLAND WINTER WHEAT-FALLOW SYSTEMS

ABSTRACT

The concurrent use of cover crops and manure compost may improve soil health in water-limited, low soil fertility organic dryland winter wheat-annual fallow systems in the semiarid Intermountain West. The objective of this study was to determine the synergy between cover crops and the single application of different rates of manure compost on soil health. The study was conducted at Snowville and Blue Creek, UT during the 2015-2019 growing seasons. At each location, manure compost (0, 12.5, 25 and 50 Mg DW ha^{-1}), and cover crops (winter pea *plus* hairy vetch) were included as treatments in a split-plot randomized complete block design. Soil health indices were measured at two depths (0-10 and 0-30 cm) and soil water, dissolved organic carbon and nitrogen, nitrate, and ammonia were measured at three depths in 30 cm increments (0-90 cm). Manure compost maintained greater residual effects compared to cover crops on measured soil health indices at both sites. Overall, combining cover crops with manure compost did not show any additive effect on soil health indices except for an increase in labile carbon under fallow and chicken manure. Unlike manure compost that showed immediate beneficial effects on soil health, cover crops had minimal immediate effects on soil health and may require several years before seeing benefits in organic dryland winter wheat-fallow systems. Organic dryland winter wheat growers may need to apply a

minimum of 25 Mg ha^{-1} DW manure compost to gain long-term benefits for soil health.

Keywords: compost, cover crops, winter wheat-fallow, organic farming, dryland, semiarid

1 | INTRODUCTION

The acreage of land devoted to organic dryland winter wheat (*Triticum aestivum*)-fallow (WW-F) cultivation in the Intermountain West has increased by approximately 13 % between 2008 and 2015 (NASS, 2019). However, low soil fertility coupled with high variability in rainfall continues to contribute to low and unpredictable crop yield in organic dryland WW-F systems (Lyon & Hergert, 2014; Roche et al., 2017). The fallow system is widely used in organic dryland WW production despite concerns about its negative effects on soil health and crop productivity (Lyon & Hergert, 2014). The fallow period between cropping cycles, which usually lasts between 13-14 months, is used to increase soil water storage due to the low annual precipitation, 250 and 550 mm (Bowden, 1979). More so, continuous WW-F rotations, which also use tillage for weed control, enhance the loss of soil organic matter (SOM) over time and promote soil loss and degradation (Ghimire et al., 2018). Thus, sustainable crop production becomes difficult to maintain on the degraded soils due to poor soil fertility and health. Despite this challenge, organic dryland WWF farmers find it difficult to justify the use of external inputs due to the risks and cost associated with the use of organic amendments such as leguminous cover crops (hereinafter known as cover crops) and manure compost (hereinafter known as compost).

The use of cover crops could be an alternative to reduce erosion and increase SOM and nitrogen for increased subsequent wheat yield in organic dryland WW-F, but it could lead to variable outcomes (Unger & Vigil, 1998). Through increased biomass return, continuous cropping with cover crops in a WW-F reduced bulk density, increased porosity and organic C content while yield was unchanged (Peterson & Westfall, 2004; Zentner et al., 1996). However, the inclusion of cover crops in dryland agriculture systems with total annual precipitation less than 550 mm, can lead to reduced soil moisture subsequently affecting wheat yield (Lyon & Hergert, 2014; Nielsen et al., 2016; Peterson et al., 1998; Tanaka et al., 1997). Studies have shown that short-term gains of nitrogen and biomass from cover crops did not compensate for the decrease in soil water and ensuing crop yield decreases in dryland WW-F (Nielsen & Vigil, 2005; Schlegel & Havlin, 1997; Tanaka et al., 1997; Unger & Vigil, 1998). For example, in a study conducted by Nielsen et al. (2016), spring planted cover crops reduced succeeding wheat yield in the semiarid central Great Plains by about 12.39 kg ha^{-1} for every 1 mm of water use, with greater reduction experienced under drier conditions. Similarly, in an organic dryland WW-F system in Montana, the inclusion of winter pea did not significantly increase the yield compared to fallow (Miller et al., 2011). If efficiently managed, however, cover crops may represent a usable option for farmers in this region (Unger & Vigil, 1998; Zentner et al., 1996). The combination of cover crops with lower rates of compost offers great promise to increase crop yield in organic dryland WW-F, but the benefits associated with this combination on soil health are still not well understood.

Recent studies have documented the long-term benefits of a single compost application on soil health in organic dryland WW-F soils. After 11.5 years of application, the residual effects of composted cattle manure were still detectable in a surface (0-15 cm) calcareous soil seeded annually to spring wheat with minimum tillage (Larney et al., 2011). Similarly, in a long-term organic dryland WW-F rotation experiment in Utah, Reeve et al (2012) showed that the residual effects of a single 50 Mg ha^{-1} DW application of manure compost were detectable 16 years later (0-10 cm) and correlated with the increased crop yield. The long-term residual effects of compost can be linked, in part, to improved soil physical condition, increased return of straw residue, and greater amounts of root biomass triggered from the outset. The residual effects of compost has also been documented to be greater as soil degradation increases (Larney et al., 2009). The high cost associated with the purchase and transportation, and uncertainty in cost recovery due to unpredictable yield, however, still makes it difficult for the farmers to adopt this approach. Considering the low-quality status of organic dryland WW-F soils, it remains to be determined if compost at a lower rate will have similar long-term effects as those earlier reported.

The concurrent use of leguminous cover crops and lower rates of compost could be an alternative to mitigate the problem of low soil health in organic dryland winter wheat-fallow (WW-F) in the Intermountain West (IW). Since the inclusion of cover crops can increase nitrogen fixation, and is less costly than compost, combining cover crops with lower rates of compost might compensate for water use by cover crops, increase cover crops biomass return and nitrogen fixation, and enhance soil health (Figure 1).

Thus, making both combinations may have potential for a positive impact on subsequent crop yield while lowering the cost of inputs. The objectives of the study were to determine in the short-term (3-7 years) (i) if lower rates of compost have commensurate effects on soil health as earlier reported with higher rates (50 Mg ha^{-1} DW); and (ii) if there is a synergistic relationship between cover crops and compost on soil health. We hypothesized that i) soil health in nutrient depleted organic WW-F systems could be improved by using lower rates of compost (i.e. < 50 Mg ha^{-1} DW); ii) the use of cover crops with compost applications could lead to greater soil health benefits.

2 | MATERIALS AND METHODS

2.1 | Study sites and treatments

Two long-term organic dryland WWF research projects focused on the inclusion of cover crops during fallow and the use of different rates of a single application of compost were established. The first experiment, which began in 2011, is situated at the Utah State Agricultural Experimental Station in Blue Creek, Utah (41°56’ N, 112°25’ W), while the second experiment, which was established in 2015, is located on a commercial dryland organic wheat farm in Snowville, Utah (41°53’ N, 112°46’ W). The initial soil properties of the sites and the characteristics of the manure compost and chicken manure used are described in Tables 1 and 2, respectively.

The Snowville experimental research site has been certified organic since the early 1990s and consisted of two experiments started in either 2015 or 2016. The soil is a calcareous Thiokol silt loam (fine-silty, mixed, active, mesic Sodic Calcixerepts) and belongs to the soil order Inceptisol based on USDA soil classification. The Snowville

experiment (henceforth referred to as “Snowville”) was established as a randomized complete block split-plot design with four replicates in two sites (South and North sides of the road) in 2015/2016. The whole plot factor was cover crops (Austrian winter pea plus hairy vetch (CC)) or no cover crop (fallow (F)), and the split-plot factor was compost rate [0, 12.5, 25 and 50 Mg DW ha^{-1}, chicken manure (CHM, 2 Mg ha^{-1}), and positive control (PC, 25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1})] making a total of 96 plots (Figure 2A). Chicken manure was included because growers were interested in the long-term effects of a more concentrated organic fertilizer applied at lower rates, while feather meal was applied together with compost to create a balanced nutrient source of organic fertilizers to act as a positive control treatment. Compost was applied once in August in 2015 and 2016 to the South and North sites respectively, while cover crops were planted in the spring immediately after snowmelt during the fallow phase of the rotation. Cover crops were terminated in early June before flowering to avoid seed production. Steer manure compost was purchased locally from Miller Companies LC (Hyrum, UT), while the organic chicken manure was sourced from Oakdell Egg Farms Inc (Lewiston, UT). The subplot measured 7.6 x 24.3 m. A local winter wheat cultivar, Juniper, adapted to low-rainfall, was planted at the rate of 67 kg ha^{-1} with a spacing of 30 cm and depth of 3.8 cm using a deep-furrow drill in August of the cropping year and harvested in July of the following year. During the fallow year, the sites were tilled thrice Flexicoil chisel plow with 45.72 cm sweeps. The first tillage pass was a depth of 10 cm in mid-March, the second tillage pass to a depth of 7.62 cm in late May, and the third pass to a depth of 5 cm in early July.

The Blue Creek experimental research site, previously used for commercial fertilizer trials, was transitioned to organic management in 2011 and certified organic in 2017. The soil is classified as a Parleys silt loam (fine-silty, mixed, superactive, mesic Calcic Argixerolls) based on USDA soil classification. The study design was a randomized complete block split-plot design with four replicates, with steer manure compost rate (0, 12.5, 25, and 50 Mg DW ha^{-1}) obtained locally (Miller Companies LC, Hyrum, UT) as the whole plot and cover crop (winter pea/hairy vetch and fallow control) as the split-plot. Conventional nitrogen fertilizer (56 kg N ha^{-1} as anhydrous ammonia) was applied to the positive control (PC) treatment yearly before planting according to soil test recommendations, making a total of 64 plots (Figure 2B). Buffer plots were included on either side of the PC so as not to compromise the integrity of the organic plots. Compost was first applied in 2011and 2012 and later in 2016 to previously unamended plots as compost was applied only once to any given plot throughout the experiment. Cover crops, Austrian winter pea *plus* hairy vetch were planted during the 2015-2016 and 2017-18 fallow cycles in March immediately after snowmelt and terminated in early June before flowering. The subplot measured 7.3 x 24.3 m and a local winter wheat cultivar, Juniper, adapted to low-rainfall, was planted at the rate of 78 kg/ha with a spacing of 30 cm to a depth of 5 cm using a deep-furrow drill in November of the cropping year and harvested in September of the following year. The land was fallowed for the next 13-14 months before the planting of the next wheat crop. The wheat-fallow plots where tilled three times with a Flexicoil chisel plow with 40.64 cm sweeps with 10 shanks. The first tillage pass was a depth of 25 cm in mid-May, the second tillage pass to a depth of 25 cm

in mid-June. The plots were disked in early August to a depth of 15 cm before the third chisel plow with sweeps to a depth of 7 cm in mid-October.

2.2 | Soil sampling and laboratory analysis

Soil samples were collected during the wheat cropping phase in either late April or early May, depending on weather conditions. Soil samples at 0-10 cm depth were collected using a soil probe (i.d. 1.8 cm) while samples at 0-90 cm depth were collected using a Giddings hydraulic soil probe with an internal diameter of 4.3 cm (Model SMGSRH, Giddings Machine Company Inc Windsor, CO). Six soil cores were collected at 0-10 cm depth, while three soil cores were collected for 0-90 cm depth. The samples were bulked, thoroughly mixed, and a subsample was placed in polyethylene bags and transported on ice to the laboratory. A portion of the soil was used for gravimetric moisture content determination by oven-drying soil at 110˚C for 24 h, while the other portion was sieved through a 2 mm sieve and either stored at 4˚C or air-dried and stored at room temperature. Soil samples, 0-10 cm, stored at 4˚C were used for the determination of biological assays within 2 weeks of sample collection. Also, duplicate soil cores were collected for bulk density at 0-10 cm using a slide hammer.

2.3 | Soil Biological Properties

Soil respiration and microbial biomass were measured using 5 g of field moist soils adjusted to 22% moisture as described by (Anderson & Domsch, 1978). The soils were weighed into 40 ml glass vials, capped with a screw cap septum, and incubated for 10 days at 25˚C in the dark. On day 11, readily mineralizable carbon (C_{min}, µg CO_2-C g^{-1} soil) was quantified by measuring the CO_2 evolved using an infrared CO_2 analyzer

(Model LI-6251, LICOR Biosciences, Lincoln, Nebraska). Thereafter, the vials were uncapped for 2 hours, flushed with moisture saturated air, sealed using parafilm, incubated overnight at 25˚C, recapped for exactly 2 hours after which soil basal respiration (BR, µg CO_2-C g^{-1} soil hr^{-1}) was measured. On day 13, microbial biomass carbon (C_{mic}) was quantified using the substrate-induced respiration method by adding 250 µL 0.33 M D-glucose to each sample, capped for 2 hours and measured for CO_2. The C_{mic} was calculated according to the equation proposed by Anderson and Domsch (1978),

$$C_{mic} = 40.4Y + 0.37$$

where y = µl CO_2 g $soil^{-1}$ hr^{-1}, C_{mic} = µg microbial biomass C g^{-1} soil.

Dehydrogenase activity (DHA) was quantified using 2.5 g of field moist soil in triplicate by estimating the rate of reduction of triphenyl tetrazolium chloride (TTC) to triphenyl formazan (TPF) (Tabatabai, 1994). Briefly, the moisture content of the soils was adjusted to 22% by weight with distilled deionized water and incubated overnight at 25 ˚C. On the following day, 0.5 mL of 3% TTC and 1.0 mL of 2% $CaCO_3$ were added to each tube, vortexed, and incubated for 24 hours at 37˚C. Thereafter, TPF, (product of TTC reduction), was extracted using 10 mL methanol and measured colorimetrically with a microplate reader at a wavelength of 490 nm (SpectraMax M2, Molecular Devices, Sunnyvale, California). A standard curve was used to determine the µg TPF g^{-1} dry weight (dwt) soil. Acid and alkaline phosphatases activities were determined as described by Tabatabai and Bremner (1969). Soil samples equivalent to 1 g dwt were placed in 15 mL centrifuge tubes, mixed with 4.0 mL modified universal buffer (MUB) (pH 6.5 for acid and pH 11 for alkaline phosphatase), 1.0 mL disodium *p*-nitrophenyl hexahydrate

solution (excluding controls), vortexed and incubated at 37˚C for 24 hours. After incubation, the reaction was stopped using 1.0 mL of 0.5 M $CaCl_2$ and 4.0 mL 0.5 M NaOH to both samples and controls. Thereafter, disodium *p*-nitrophenyl phosphate solution was added to the controls only. Samples were vortexed and centrifuged for 5 mins at 4000 rpm. The concentration of the *p*-nitrophenol released was determined by absorbance at 405 nm with a microplate reader (SpectraMax M2, Molecular Devices, Sunnyvale, California). Control readings were deducted from each sample and the µg *p*-nitrophenol g^{-1} soil was quantified using a standard curve.

2.4 | Soil Chemical Analyses

Soil samples from 0-30 cm were used to measure the pH, electrical conductivity (EC), available phosphorus (P), while 0-10 and 0-30 cm soil samples were used for total soil nitrogen (TN), and total carbon (TC) and inorganic carbon (IC). Soil pH and EC were measured in a 1:2 soil water suspension using an electrode pH meter Symphony B10P (VWR International, LLC, West Chester, PA) (Thomas, 1996). Available P was quantified as Olsen P by extracting 1 g of soil with 20 mL 0.5 mol L^{-1} sodium bicarbonate and determined colorimetrically using ammonium molybdate-ascorbic acid method at a wavelength of 882 nm with a microplate reader (SpectraMax M2, Molecular Devices, Sunnyvale, CA). The TN, TC, and IC were determined using finely grounded (0.15 mm) soils using Primacs SNC total C and N analyzers (Skalar Inc., Buford, GA). Total organic C (TOC) was quantified as the difference between TC and IC. Air-dried soil samples (0-30 cm) were used for in measuring DTPA–extractable elements Fe, Zn, Cu, Mn (Method S6.10) as described by (Gavlak et al., 2005)

Ammonium-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) were measured using 0-30, 30-60 and 60-90 cm depth increments using field-moist soils (Jones & Willett, 2006). Soil NH_4^+-N and NO_3^--N were extracted using 1 M KCl (1:5 w/v) (Gavlak et al., 2005) and measured with a Lachat QuickChem 8500 Flow Injection Analyzer (Hach Company, Loveland, Colorado). The DOC and DON were quantified using 10 g of field-moist soil shaken with 45 mL of deionized distilled water. The soil suspension was placed on a horizontal end-to-end shaker for 16 h and later filtered through 0.45 µm glass fiber filters (Sterilitech Corporation, Kent, Washington), and froze at -4 ˚C when samples were not measured immediately. Incomplete reconstitution occurs during the thawing of frozen samples resulting in lower recovery of DOC and DON (Jones & Willett, 2006). Total carbon (TC) and inorganic carbon (IC) concentrations were measured using the TOCN-liquid analyzer (Shimadzu, Kyoto Prefecture, Japan). Total organic carbon was determined as the difference between TC and IC. The DON was measured as TN on the TOCN-liquid analyzer.

2.5 | Statistical analysis

Data were checked for normality and homogeneity of variance, and log or square root transformed were necessary. Data analysis for each site was done separately. Data from Snowville was analyzed as a randomized complete block split-plot design. The fixed factor effects in the model are year of establishment (2015 or 2016), cover crop, compost, and year after application. The random effects are block, plot, and subplot. Cover crop was specified as the whole plot factor, compost, the split-plot factor, and

years after compost application as repeated measure. The effects of all fixed factors and interactions were evaluated except for year of establishment. Data from Blue Creek was analyzed as a randomized complete block split-plot design with compost as the whole plot factor, cover crop as the split-plot factor and year after compost application as repeated measure. Plots that received compost in 2011 and 2012 were classified as 2012 as there were no differences in treatment effects between the two years. Simple effect comparison was used (LSMEANS) to compare means among significant interactions in each year of data collection (2017 and 2019) to evaluate the year after compost application effect. Data from each depth were analyzed separately. Statistical analysis was done using PROC GLIMMIX in SAS Studio University Edition (version 9.4, SAS Institute, Cary, NC, USA). Graphical presentations were made using Origin Pro 8.5 software (OriginLab, Northampton, MA, USA).

3 | RESULTS

3.1 | Snowville

3.1.1 | Bulk density and soil moisture

The bulk density at 50 Mg ha^{-1} compost rate (1.13 g cm^{-3}) was lower ($p=0.0315$) compared to the control (1.23 g cm^{-3}) three years after application (Figure 3A), while it was not different ($p>0.05$) across control and other compost treatments. Three years after, bulk density in fallow and cover crop treatments did not differ ($p=0.8141$) (Figure 3B). This implies that greater quantities of organic amendments are required to improve soil physical characteristics in organic dryland soils. Similarly, when averaged over the two years, compost significantly increased ($p<0.001$) soil moisture in the top 10 cm soil

(Figure 4A). Regardless of the year after compost application or presence or absence of cover crops, gravimetric moisture content was highest at 50 Mg ha^{-1}. There were no significant differences among control, CHM, and 12.5 Mg ha^{-1} compost rate. On the other hand, cover crop increased soil moisture three years after compost application (0.16 vs 0.15 g g^{-1} soil, p=0.0006) but not one year after (p=0.8592) at 0-10 cm depth (Figure 3B). At the 0-30 cm depth, 50 Mg ha^{-1} compost treatment had the lowest (p<0.0001) moisture one year after compost application while three years after 50 Mg ha^{-1} compost treatment this treatment had the highest (p=0.0052) soil moisture (Figure 5A) and cover crops did not change the soil moisture across both years (p=0.8873) (Figure 5B). The lower soil moisture in year one at 50 Mg ha^{-1} compost is indicative of higher water uptake, which may be linked to increased plant biomass and roots while the increased soil moisture at 50 Mg ha^{-1} compost after year three suggests compost increased water storage after snowmelt. In 30-60 and 60-90 cm depths, the main effects of compost (p=0.2057, p=0.6692, respectively) and cover crop (p=0.4507, p= 0.7382, respectively) were not significant (Table 4). However, moisture in 30-60 and 60-90 cm were lower in year 1 compared to year 3 (p=<0.0001), which likely reflects differences in precipitation amount as higher precipitation was recorded around the sampling time in year 3 than year 1 (101 versus 53 mm).

3.1.2 | Soil biological properties

In general, compost application increased soil microbial activity compared to cover crops. Averaged over the two years, soil potential dehydrogenase (p<0.0001), acid phosphatase (p<0.0001), and alkaline phosphates (p<0.001) enzyme activities increased

linearly with compost application. Dehydrogenase activity at 50 Mg DW ha^{-1} was higher than other treatments (Figure 6A). The addition of feather meal to 25 Mg ha^{-1} did not increase DHA and this was not different from the 12.5 Mg ha^{-1} compost rate. The DHA in the control, CHM, and 25 Mg ha^{-1} compost were not significantly different. Cover crop increased DHA three years after ($p<0.0001$) but not one year after ($p=0.2326$) the application of compost (Figure 6B), indicating potential cumulative benefits of cover crop on soil health in organic dryland soils. Potential acid phosphatase activity was highest ($p<0.0001$) at 50 Mg DW ha^{-1} while PC, other compost rates were intermediate, and control and CHM were lowest (Figure 7A). Similarly, potential alkaline phosphatase activity was highest ($p<0.0001$) at 50 Mg DW ha^{-1} while the control, CHM, and 12.5 Mg ha^{-1} rates were not different from one another (Figure 8A). Potential acid and alkaline phosphatases did not differ between cover crop and fallow ($p=0.8124$ and $p=0.1352$) but both phosphatases were higher in year one compared to year three (acid phosphatase $p=0.0003$, alkaline phosphatase $p<0.0001$) (Figures 7B-C and 8B-C). The inclusion of cover crops increased readily mineralizable carbon (C_{min}) in control ($p=0.0061$) and chicken manure ($p=0.0033$) treatments but not in PC ($p=0.5163$), 12.5 ($p=0.9637$), 25 ($p=0.9833$) and 50 Mg ha^{-1} compost ($p=0.9193$) (Figure 9A). The mean value of C_{min} was higher ($p<0.0001$) in year three, a wetter year, compared to year one (Figure 9B). There were significant differences in the mean microbial biomass C (C_{mic}) ($p<.0001$) following the application of compost while there were no significant changes in basal respiration (BR) ($p=0.4981$) following compost application (Table 4).Unlike Cmin, cover crops did not enhance BR or MB ($p=0.9103$ and $p=0.5813$) (Table 5) while BR was higher

(P<0.0001) in year 1 compared to year 3 and MB was higher in year 3 than 1 (P<0.0001) (Table 4).

3.1.3 | Soil chemical properties

Compost increased TOC at 0-10 (p<0.0001) and 0-30 cm (p=0.0001) depth. The TOC was highest at 50 Mg ha^{-1} compost while control and CHM did not differ at 0-10 cm (Figure 10A). Likewise, at 0-30 cm, TOC was highest at 50 Mg ha^{-1} and not different from PC and 25 Mg ha^{-1}, while TOC in the control and CHM treatments did not differ (Figure 11A). In contrast, TOC in cover crops and fallow treatments did not differ (0-10 cm p=0.9975, 0-30 cm p=0.7227) (Figure 10B-C). However, at 0-10 cm TOC was greater (p<0.0001) in year one than three, while at 0-30 cm there was no difference (p=0.0609) in TOC between the years (Figures 10B-C and 11B-C). Similarly, compost addition increased TN concentration at 0-10 cm depth. Compost at 50 and 25 Mg ha^{-1} DW increased TN (p<.0001) with the greatest effect seen at the higher rate (Figure 12A). However, compost effect on TN in 0-30 cm depth was not different (p=0.2616) (Figure 13A). In addition, cover crop did not affect TN(0-10 cm p=0.6486, 0-30 cm p=0.3871) (Figures 12B and 13B). At 0-10 cm depth, TN between years was not different (p=0.2083) but at 0-30 cm, TN was greater (p<0.0001) in year one than in year three (Figures 12C and 13C).

The main effect of compost on Olsen P was significant (p<0.0001). Averaged across cover crops treatments and year, Olsen P was greatest at 50 Mg ha^{-1} compost and least in the control (Figure 14A). The Olsen P concentration increased with increasing

compost rate ($p<0.001$) but there were no significant differences in Olsen P with chicken manure and 12.5 Mg ha^{-1} compost treatment. The use of feather meal with compost increased P availability. There were no significant differences ($p=0.1194$) in the Olsen P concentration between fallow and cover crops, while Olsen P was higher in year 3 than year 1 (Figure 14 B-C). The main effects of compost and cover crops on pH (compost $p=0.233$, cover crops $p=0.0716$) and EC (compost $p=0.0589$, cover crops $p=0.3007$) were not significant while pH in year three was higher ($p<0.0001$) than in year one and EC in year one was higher ($p<0.0001$) than in year three (Table 6).

The DTPA extractable nutrients were affected by compost and year but not by cover crops (Table 7). For Zn, the main effect of compost was significant ($p<0.0001$) but the main effect of year after application was not indicating a strong carryover effect. The 50 Mg DW ha^{-1} compost had the highest (0.896 mg kg^{-1}) Zn concentration and the control the lowest (0.292 mg kg^{-1}). Likewise, the main effects of compost and year on Fe were significant ($p<0.0001$). The Fe concentration increased linearly with increasing compost addition and was higher in year three than year one. Furthermore, the main effects of compost and year were significant ($p=0.0001$ and <0.0001, respectively) on Mn. Similar to the compost effect on Fe, Mn concentration increased with increasing compost addition with the highest value recorded at 50 Mg ha^{-1} and was higher in year three than one. In contrast, the main effects of compost, year, and cover crops on Cu were not significant ($p=0.3363$, 0.2126, and 0.66334, respectively).

The compost effect on dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) varied with depth (Table 8). The concentration of DOC and DON was

significantly different between control and 50 Mg ha^{-1} at 0-30 cm depth (DOC p=0.0004, DON p=0.0023) but there were no differences among treatments in DOC at 30-60 cm depth (p=0.4585), while DON was highest in 50 Mg ha^{-1} (p=0.024) at that depth. At the 60-90 cm depth, there were no differences in DOC and DON among the treatments. The main effect of cover crops on DOC and DON was not significant. Both DOC and DON were higher in year 3 than in year 1 across all depths. Soil ammonium and nitrate concentrations did not differ between compost and cover crop treatments across the different depths (Table 8). Soil ammonium was higher in year 3 than in year 1 across all depths, while soil nitrate was higher in year 3 than in year 1 at 0-30 cm depth only.

3.2 | Blue Creek

3.2.1 | Bulk density and soil moisture

Similar to the Snowville site, the bulk density was lowest in 50 Mg ha^{-1} compost in years 1 and 5, while compost effect was not significant in years 3 and 7 (Figure 15A). There was no significant difference in the effects of 25 and 50 Mg ha^{-1} compost on bulk density in years 1 and 5. The inclusion of cover crops did not have a significant effect on bulk density (Figure 15B). At the 0-10 cm depth, soil moisture was highest at 50 Mg ha^{-1} compost and least in anhydrous ammonium plot in year 1 and 5 (Figure 16A). Soil moisture at 50 Mg ha^{-1} compost was different from control only in year 1. There was no significant compost effect on soil moisture in years 3 and 7 at 0-10 cm depth. Similarly, at 0-30 cm, soil moisture was lowest in PC in years 1 and 5 and highest in 25 Mg ha^{-1} compost in year 1 and 50 Mg ha^{-1} compost in year 3 (Figure 17 A). There was no significant ($p>0.05$) compost effect on soil moisture in years 3 and 7. At 0-10 cm depth

cover crop did not have a significant effect on soil moisture (Figure 16B), while at 0-30 cm, soil moisture was not significantly different in year 1 but in year 3, cover crop led to a decline in soil moisture compared to fallow plots (Figure 17B). There was some evidence of compost treatment effects on subsoil moisture as moisture at 30-60 cm depth in year 1 was lowest ($p<0.05$) in the 50 Mg ha^{-1} compost treatment, lowest in the control treatment in year 3 and highest at the highest compost rate in year 5. There were no significant compost treatment effects in year 7 (Table 9). Similarly, moisture at 60-90 cm was lowest in the anhydrous ammonia plot in years 1 and 5 and highest in 25 Mg ha^{-1} compost in year 3 with no significant compost treatment effect in years 3 and 7 (Table 9).

3.2.2 | Soil biological properties

Overall, compost had a significant effect on soil microbial activities, but the effect of cover crops was not significant ($p>0.05$). Potential dehydrogenase activity (DHA) was highest at the 50 Mg ha^{-1} compost rate seven years after application, while anhydrous ammonia lowered DHA, although this was not different from the control (Figure 18A.). The differences in compost rate on DHA were more prominent in years 5 and 7 where 50 Mg ha^{-1} was greatest compared with other compost rates. There were no significant differences in DHA between fallow and cover crop treatments (Figure 18B). There were few effects of treatment on acid phosphatase. The 50 Mg ha^{-1} compost had the greatest effect in year 1 and anhydrous ammonia did not affect acid phosphatase compared to the control (Figure 19A). In year 5, there was no significant effect of 50 Mg ha^{-1} compost, anhydrous ammonia, and control on acid phosphatase, while the lower rates of compost showed a significant effect. On the other hand, the effect of compost on alkaline

phosphatase was significant in all years. Alkaline phosphatase activity was highest at 50 Mg ha^{-1} compost and least in control and anhydrous ammonia treatments (Figure 20A). Cover crops did not have a significant effect on either acid or alkaline phosphatase (Figures 19B and 20B). The effect of compost on phosphomonoesterases was more distinct in potential alkaline phosphatase activity compared to potential acid phosphatase activity.

The C_{min}, BR, and C_{mic} reflected the effect of compost but not cover crop (Figures 21 – 23). The effect of 50 Mg ha^{-1} compost on C_{min} compared to control was significant only in year 1 but not in years 3, 5, and 7 (Figure 21A). The anhydrous ammonia treatment had the lowest C_{min} in years 3 and 7. Averaged over the years, 50 Mg ha^{-1} compost led to significant ($p<0.05$) elevation of BR and C_{mic} compare with control and anhydrous ammonia treatments (Figures 22B and 23B). The higher compost rates had similar effects on BR and C_{mic} except in year 5 where the effect of 50 Mg ha^{-1} compost was higher ($p<0.05$) than the 25 Mg ha^{-1} compost rate.

3.2.3 | Soil chemical properties

Averaged across the years, 50 Mg ha^{-1} compost had the greatest effect on TOC at the 0-10 cm depth (Figure 24A). The TOC was lowest in control and anhydrous ammonia treatments and there were no significant differences in TOC between 12.5 and 25 Mg ha^{-1} compost. Similarly, at 0-30 cm depth, 50 Mg ha^{-1} compost had the greatest TOC and the control and anhydrous ammonia treatments had the least (Figure 25A). There was no significant difference between the two higher compost rates on TOC. On the other hand,

the cover crops did not significantly affect TOC at either depth, suggesting OC from cover crops had little or no effect on soil organic carbon, at least in the short-term.

Like TOC, compost had a significant effect on TN at 0-10 cm with 50 Mg ha^{-1} compost having the greatest effect and different from control and anhydrous ammonia in year 1 (Figure 26A). Averaged over the other years, TN was least in control and not different from the 12.5 Mg ha^{-1} compost rate. The 25 and 50 Mg ha^{-1} compost effects on TN were not significantly different. At 0-30 cm depth, there were no significant differences in treatments except in year 3 were 50 Mg ha^{-1} compost was significantly greater than the control only (Figure 27A). As was the case with TOC, the inclusion of cover crops did not significantly ($p<0.05$) affect TN at 0-10 and 0-30 cm depths (Figures 26B and 27B), suggesting biomass was insufficient to significantly affect N or rapid loss.

The Olsen P measured was highest at 50 Mg ha^{-1} compost and least in control and anhydrous ammonia treatments (Figure 28A) although all treatments were within the sufficiency range for P. The effects of the two higher compost rates on Olsen P were different from 12.5 Mg ha^{-1} compost except for years 5 and 7 where there were no significant differences ($p>0.05$) among the compost rates. There was no significant effect of cover crops on Olsen P (Figure 28B).

Soil pH and EC were affected by compost treatments. Averaged over all years, pH was lowest ($p<0.05$) in anhydrous ammonia and highest at the 25 and 50 Mg ha^{-1} compost rates (Table 10). Similarly, EC was significantly affected by the different compost rates with 50 Mg ha^{-1} compost having the highest EC value (0.078 dS m^{-1}) and

control having the lowest (0.048 dSm^{-1}) (Table 10). Cover crops did not significantly affect ($p>0.05$) pH or EC.

Overall, compost had a varied ($p<0.05$) effect on DTPA extractable nutrients while cover crops had no significant effect (Table 10). The Zn concentration was highest at 50 Mg ha^{-1} compost and least in control and anhydrous ammonia. The Zn concertation between the higher compost rates was not different in other years except in year 1 with 50 Mg ha^{-1} compost higher than 25 Mg ha^{-1} compost. On the other hand, in years 1 and 3, Fe concentration increased ($p<0.05$) with compost application while in years 5 and 7, Fe concentration was lowest in compost treated plots. Besides, except in year 1 where 50 Mg ha^{-1} compost had the highest ($p<0.05$) concentration of Mn, Mn was lowest at this rate and highest in control plots. The Cu concentration was also affected by compost treatments, except in years 3 and 7. In year 1, Cu concentration was highest in 50 Mg ha^{-1} compost and lowest in control, while in year 5, Cu concentration was highest in anhydrous ammonia and lowest in control. There were no significant differences in the Mn concentrations among the compost rates.

The DOC concentration was highest at 0-30 cm and decreased with depth (Table 11). The DOC at 0-30 cm depth was highest at 50 Mg ha^{-1} compost and lowest in the control except in years 5 and 7 were treatment effect on DOC was not significant ($p>0.05$). Although not significantly different from the control, DOC in 30-60 and 60-90 cm depths was higher in compost treated plots, especially in years 5 (30-60), 3, and 7 (60-90 cm). Likewise, the DON was significantly affected by compost at 0-30 and 60-90 cm depths in different years. In years 3 and 5, DON increased with compost addition at

60-90 cm depth indicating the loss of compost N through leaching. The main effects of cover crops on DOC and DON were not significant ($p>0.05$) at all depths studied.

Soil ammonium and nitrate concentrations were also different between compost and cover crop treatments across the different depths (Table 12). Soil ammonium at 0-30 cm depth was highest at the highest compost rate in years 1 and 5. Likewise, at 60-90 cm depth, the soil ammonium concentration was highest at the highest compost rate. There was no significant effect of cover crops on soil ammonium concentration. Soil nitrate levels were highest at the highest compost rate 1 year after application across all three depths. However, anhydrous ammonia increased the soil nitrate levels at depths in other years except at the 0-30 cm depth in year 5, where the highest rate of compost application had the highest soil nitrate level.

4 | DISCUSSION

Improved and sustained soil health is critical to achieving long-term economically sustainable yields in non-irrigated organic dryland grain systems, where soil fertility inputs are not typically used. The reduced bulk density, attributable to compost application at both sites, could contribute to an increase in water infiltration and storage and a decrease in mechanical resistance to root elongation and increase root access to soil nutrients (Celik et al., 2010). Reduced mechanical resistance to root elongation suggests less energy sources will be directed to root development and more to shoot development thus potentially contributing to faster plant growth, most especially immediately after snowmelt in April and May. The effects of applying higher rates of compost on bulk density were greater at Blue Creek compared to Snowville and the variation in compost

effect on bulk density could be linked to higher calcium carbonate at Snowville. Both organic matter from compost, and calcium carbonate are known to affect the binding of soil particles (Blanco-Canqui et al., 2013; Fernández-Ugalde et al., 2011). Compost effects on soil moisture were greatest at 50 Mg DW ha^{-1} as was demonstrated by the higher values when plots where sampled in late April (Snowville Year 3) and lower values when sampled in mid-May/early June (Blue Creek). The impact of compost on soil moisture immediately after snowmelt can be attributed to a lower evaporation rate, while the decrease at later times is likely indicative of increased water uptake. Cover crops on the other hand either increased soil moisture (Snowville) or decreased soil moisture (Blue Creek).

Our study also shows compost and cover crops affected soil microbial activities. The field experiment showed that potential dehydrogenase enzyme activity (DHA) was higher at 50 Mg ha^{-1} at Snowville (mean 7.5 µg TPF g^{-1} soil h^{-1}) compared to Blue Creek (mean 4.8 µg TPF g^{-1} soil h^{-1}). The increase in potential DHA in year 3 in cover crops plots at Snowville also suggests the potential of cover crops in enhancing soil health in organic dryland systems. Dehydrogenase enzyme is a major enzyme that belongs to the oxidoreductase enzymes class, which is known to be sensitive to management practices and plays a significant role in soil organic matter biological oxidation (Wolińska & Stępniewska, 2012). Similar effects were observed for compost and cover crops on RMC BR and C_{mic} at both sites except for RMC, which responded to cover crops in control and manure treated plots at Snowville, the drier site. This suggests that cover crops effects on

SOM are short-lived compared to compost in organic dryland grain systems (Blanco-Canqui et al., 2013).

This study also showed site variability in compost effect on soil acid and alkaline phosphatase enzymes, which play a key role in organic phosphorus mineralization. The effect of compost was more prominent on acid phosphatase at Snowville with an average pH of 8.5, while compost effect was greater on alkaline phosphatase at Blue Creek with an average pH of 7.2. Thus, showing that compost had a greater effect on the less prominent form of phosphomonoesterase at both sites. Studies have shown that acid phosphatase is dominant in acid to neutral soils while alkaline phosphatase is dominant in alkaline soils. More so, acid phosphatase mineralizes more organic P compared to alkaline phosphatase and may be a useful index in predicting long-term compost effects (Dick & Tabatabai, 1978). The production of acid and alkaline phosphatase is known to be controlled by different genes, suggesting variability in compost effect on soil microbial communities at the two sites (Fraser et al., 2015; Ragot et al., 2015). Three years after compost application, changes in Olsen P were similar at both sites, although the initial level of Olsen P at Blue Creek (30 mg kg^{-1}) was higher than at Snowville (5 mg kg^{-1}). The effects of compost 25 and 50 Mg DW ha^{-1} compost on Olsen P was significantly different at Snowville but not at Blue Creek, which could be related to the higher soil fertility at Blue Creek. The initial Olsen P at Blue Creek was high (> 30 mg kg^{-1}) and low at Snowville (< 8 mg kg^{-1}) (Cardon et al., 2008). Contrarily, cover crops did not have a significant effect on soil available P. Similarly, Rick et al. (2011) found that the use of cover crops did not increase P availability of phosphate rock in a dryland

organic winter wheat system in the northern Great Plains. Although some greenhouse studies have shown the potential of cover crops to increase P availability following incorporation in dryland organic cropping systems (Cavigelli & Thien, 2003; Rick, 2009), our field study did not show any evidence of cover crops benefit on soil available P.

Compost and not cover crops had a clear effect on C and N at both sites. The greater effects of compost compared to cover crops agrees with other studies that have shown smaller cover crops effect on SOC and N. For example over 8 years the change in SOC stocks in an organic vegetable system was two folds that of leguminous cover crops, with compost having a greater impact on SOC and cover crops affecting permanganate oxidizable labile C (White et al., 2020). Organic C and N derived from green manure are known to mineralize faster compared to compost derived C and N, which has been linked to the increased proportion of aromatic portions of SOC and lignin that are known to be resistant to microbial attack (Leifeld et al., 2002). Thus, compost effects can persist relative to cover crops, as compost is gradually decomposed. The smaller influence of compost on total N compared to SOC at both sites can be linked to the lower amounts of compost added N compared to C. Nitrogen is also prone to quicker loss via multiple pathways, especially in dry hot semi-arid climates (Shelton et al., 2017; Yang et al., 2013). After 7 years, the compost effect on C at 0-10 and 0-30 cm was still significant while its effect on N was limited to the 0-10 cm depth. Furthermore, the compost effect at 50 Mg DW ha^{-1} on C was greater than 25 Mg DW ha^{-1} at both sites, but not for N. Between site variability of compost on DOC, DON, NH_4^+-N, and NO_3^--N was also

observed with greater effects at Blue Creek compared to Snowville. This could be as a result of the higher annual precipitation at Blue Creek compared to Snowville, as higher soil moisture is known to increase the concentration of dissolved C in soil solutions. Indeed, variability in subsoil accumulations of C and N reflects between site variation in surface loss of compost added nutrients and deep storage of SOC (van Kessel et al., 2009).

Measurements of pH and EC were unaffected at Snowville compared to Blue Creek where significant compost effect was observed. The highest EC at 50 Mg DW ha^{-1} compost at Blue Creek, 0.091 dS m^{-1} was lower than the EC in control plots (0.187 dS m^{-1}) at Snowville, which is classified as low according to Cardon et al. (2008). The contribution of compost to pH at Blue Creek increased slightly by 0.4 units relative to the control and PC plots. The average pH at 0-30 cm from 25 and 50 Mg DW ha^{-1} compost was 7.2. Similarly, Mendoza et al. (2006) reported that the application of organic amendments increased pH in soils with lower pH. Contrarily, another study showed that the application of organic amendments such as farmyard manure and municipal solid waste compost at 120 t ha^{-1} was reported to lower the pH from 8.3 to 8.05 (Achiba et al., 2009). The addition of basic cations such as K^+, Ca^{2+}, and Mg^{2+} and the presence of OH^- ions through ligand exchange following compost mineralization could explain the observed increase in pH and EC at Blue Creek (Mkhabela & Warman, 2005).

DTPA extractable nutrients, such as Zn, Fe, Mn, and Cu, are known to be limiting in organic dryland soils (Reeve et al., 2012). Compost affected the DTPA extractable nutrients but cover crops did not. Compost application had identical effects at Snowville

and Blue Creek, although Blue Creek had higher DTPA nutrient concentrations and higher average change in nutrient concentrations. According to Cardon et al. (2008), in control plots at Snowville, Olsen P (5.2 mg kg^{-1})is very low, K (595 mg kg^{-1}) is very high, Zn (0.29 mg kg^{-1}) is very low, Fe (3.82 mg kg^{-1}) is low, and Mn (4.91 mg kg^{-1}) and Cu (1.61 mg kg^{-1}) are adequate while at Blue Creek Olsen P (38 mg kg-1) is high, K (545 mg kg^{-1}) is very high, Zn (0.56 mg kg^{-1}) is low, while Fe (15 mg kg^{-1}), Mn (28 mg kg^{-1}) and Cu (0.96 mg kg^{-1}) are adequate. Considering the initial levels of DTPA extractable nutrients at both sites, the relative effect of compost on soil health may be higher in soils with initial lower concentrations even though compost effect on the magnitude of change is comparable. Furthermore, increasing soil Zn concentration is known to decrease cadmium (Cd) uptake by plants (Choudhary et al., 1994). The addition of 25-50 Mg DW ha^{-1} compost increased soil Zn up to 2.5 – 3.5 kg ha^{-1}. This can be important for organic producers as earlier studies have shown that increasing Zn concentration up to 2.5-5.0 kg ha^{-1} in marginal soils decreased concentration of Cd in wheat grains (Oliver et al., 1994).

Overall, differences in cover crops and compost effects on soil health showed that compost had greater benefits on soil health. We had hypothesized that there will be a synergistic effect between cover crops and compost and that lower rates of compost may have equivalent effects as higher rates when used in combination with cover crops. Our results showed that there was no synergy between cover crops and manure compost and that lower rates of compost had less benefits on soil health. The lack of synergy could be linked to the rapid loss of cover crops derived nutrients after termination (Miller et al., 2011). Considering the observed short-term cover crops effects on soil health at the drier

site, it might take several years to observe similar short-term compost effects. Pikul et al. (1997) reported minimal effects of cover crops compared to fallow on soil chemical properties in a conventional fallow-spring wheat rotation. In another organic dryland field study conducted in the northern Great Plains of Nebraska, Lyon and Hergert (2014) did not observe the impact of repeated application of composted cattle manure at 11.2 or 22.5 Mg ha^{-1} on soil nitrate and crop yield in an organic dryland wheat study with a green fallow during the first 3 years. To attain a yield of 7 Mg ha^{-1}, about 134 kg N ha^{-1} is needed (Cardon et al., 2008). However, with a compost of 34 % moisture content, 17.7 g N kg^{-1} and 20 % mineralization during the growing cycle, 25 and 50 Mg ha^{-1} compost will supply approximately 58 kg N ha^{-1} and 54.4 kg P ha^{-1}, and 110 kg N ha^{-1} and 109 kg P ha^{-1}, respectively. Whereas early terminated winter peas cover crop was able to supply about 20 kg N ha^{-1} (Miller et al., 2011). This could explain why cover crops, which provide low soil health benefits and decrease available water lowers the yield of subsequent wheat. Whereas compost can meet, in part, the N and P requirements, and increases crop yield. Our study also suggests that organic dryland WW growers in semiarid Intermountain West are not likely to see benefits of composted manure on soil health at rates lower than 25 Mg ha^{-1} DW. Although, this is also dependent on the quality and nutrient concentrations of the compost. In addition, our findings provide some evidence of variations in site responsiveness to compost and cover crops in the short-term, although this requires data from more sites.

5 | CONCLUSION

In summary, this study showed that the application of 25 Mg ha^{-1} DW compost had a comparable effect on soil health as 50 Mg ha^{-1} DW. The application of 12.5 Mg ha^{-1} DW compost plus cover crops did not have the same effects on soil health as higher rates of compost only suggesting that there was no synergy between cover crops and composts on soil health. Furthermore, the inclusion of cover crops within fallow slightly improved soil health, indicating that it might require several years to observe beneficial cover crops effects on soil health in non-irrigated organic dryland WWF systems. Between the organic amendments, a one-time compost application had greater benefits on soil health. Moreover, long-term ramifications of compost on soil health can be masked by the initial soil properties, as benefits may be higher in areas with lower soil health and lower annual precipitation (pH 8.5, 300 mm). Thus, there is a need for further assessment of the effects of a single compost application on soil health across a larger number of organic dryland WWF sites. This will assist farmers in making informed decisions on whether or not to use compost.

REFERENCES

Achiba, W. B., Gabteni, N., Lakhdar, A., Laing, G. D., Verloo, M., Jedidi, N., & Gallali, T. (2009). Effects of 5-year application of municipal solid waste compost on the distribution and mobility of heavy metals in a Tunisian calcareous soil. *Agriculture, Ecosystems & Environment*, *130*(3), 156–163. https://doi.org/10.1016/j.agee.2009.01.001

Anderson, J. P. E., & Domsch, K. H. (1978). A physiological method for the quantitative measurement of microbial biomass in soils. *Soil Biology and Biochemistry*, *10*(3), 215–221. https://doi.org/10.1016/0038-0717(78)90099-8

Blanco-Canqui, H., Holman, J. D., Schlegel, A. J., Tatarko, J., & Shaver, T. M. (2013). Replacing fallow with cover crops in a semiarid soil: Effects on soil properties.

Soil Science Society of America Journal, *77*(3), 1026–1034. https://doi.org/10.2136/sssaj2013.01.0006

Bowden, L. (1979). Development of present dryland farming systems. In A. E. Hall, G. H. Cannell, & H. W. Lawton (Eds.), *Agriculture in Semi-Arid Environments* (pp. 45–72). Springer. https://doi.org/10.1007/978-3-642-67328-3_2

Cardon, E., Kotuby-Amacher, J., Hole, P. & Koenig, R. (2008). Understanding your soil test report. Available at http://extension.usu.edu/files/_publications/publication/AG_Soils_2008-01pr.pdf (accessed 20 February_2020). Utah State Univ., Logan

Cavigelli, M. A., & Thien, S. J. (2003). Phosphorus bioavailability following Incorporation of green manure crops. *Soil Science Society of America Journal*, *67*(4), 1186–1194. https://doi.org/10.2136/sssaj2003.1186

Celik, I., Gunal, H., Budak, M., & Akpinar, C. (2010). Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. *Geoderma*, *160*(2), 236–243. https://doi.org/10.1016/j.geoderma.2010.09.028

Dick, W. A., & Tabatabai, M. A. (1978). Hydrolysis of organic and inorganic phosphorus compounds added to soils. *Geoderma*, *21*(3), 175–182. https://doi.org/10.1016/0016-7061(78)90025-3

Fernández-Ugalde, O., Virto, I., Barré, P., Gartzia-Bengoetxea, N., Enrique, A., Imaz, M. J., & Bescansa, P. (2011). Effect of carbonates on the hierarchical model of aggregation in calcareous semi-arid Mediterranean soils. *Geoderma*, *164*(3–4), 203–214. https://doi.org/10.1016/j.geoderma.2011.06.008

Fraser, T. D., Lynch, D. H., Bent, E., Entz, M. H., & Dunfield, K. E. (2015). Soil bacterial phoD gene abundance and expression in response to applied phosphorus and long-term management. *Soil Biology and Biochemistry*, *88*, 137–147. https://doi.org/10.1016/j.soilbio.2015.04.014

Gavlak, R., Horneck, D. A., & Miller, R. O. (2005). Soil, plant and water reference methods for the western region. Corvallis, OR. Western Rural Development Center.

Ghimire, R., Machado, S., & Bista, P. (2018). Decline in soil organic carbon and nitrogen limits yield in wheat-fallow systems. *Plant and Soil*, *422*(1), 423–435. https://doi.org/10.1007/s11104-017-3470-z

Jones, D. L., & Willett, V. B. (2006). Experimental evaluation of methods to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil.

Soil Biology and Biochemistry, *38*(5), 991–999. https://doi.org/10.1016/j.soilbio.2005.08.012

Larney, F. J., Henry Janzen, H., & Olson, A. F. (2011). Residual effects of one-time manure, crop residue and fertilizer amendments on a desurfaced soil. *Canadian Journal of Soil Science*, *91*(6), 1029–1043. https://doi.org/10.4141/cjss10065

Larney, F. J., Janzen, H. H., Olson, B. M., & Olson, A. F. (2009). Erosion–productivity–soil amendment relationships for wheat over 16 years. *Soil and Tillage Research*, *103*(1), 73–83. https://doi.org/10.1016/j.still.2008.09.008

Leifeld, J., Siebert, S., & Kögel-Knabner, I. (2002). Changes in the chemical composition of soil organic matter after application of compost. *European Journal of Soil Science*, *53*(2), 299–309. https://doi.org/10.1046/j.1351-0754.2002.00453.x

Lyon, D. J., & Hergert, G. W. (2014). Nitrogen fertility in semiarid dryland wheat production is challenging for beginning organic farmers. *Renewable Agriculture and Food Systems*, *29*(1), 42–47. https://doi.org/10.1017/S1742170512000324

Mendoza, J., Garrido, T., Castillo, G., & Martin, N. S. (2006). Metal availability and uptake by sorghum plants grown in soils amended with sludge from different treatments. *Chemosphere*, *65*(11), 2304–2312. https://doi.org/10.1016/j.chemosphere.2006.05.012

Miller, P. R., Lighthiser, E. J., Jones, C. A., Holmes, J. A., Rick, T. L., & Wraith, J. M. (2011). Pea green manure management affects organic winter wheat yield and quality in semiarid Montana. *Canadian Journal of Plant Science*, *91*(3), 497–508. https://doi.org/10.4141/cjps10109

Mkhabela, M. S., & Warman, P. R. (2005). The influence of municipal solid waste compost on yield, soil phosphorus availability and uptake by two vegetable crops grown in a Pugwash sandy loam soil in Nova Scotia. *Agriculture, Ecosystems & Environment*, *106*(1), 57–67. https://doi.org/10.1016/j.agee.2004.07.014

Nielsen, D. C., Lyon, D. J., Higgins, R. K., Hergert, G. W., Holman, J. D., & Vigil, M. F. (2016). Cover crop effect on subsequent wheat yield in the central great plains. *Agronomy Journal*, *108*(1), 243–256. https://doi.org/10.2134/agronj2015.0372

Nielsen, D. C., & Vigil, M. F. (2005). Legume green fallow effect on soil water content at wheat planting and wheat yield. *Agronomy Journal*, *97*(3), 684–689. https://doi.org/10.2134/agronj2004.0071

Peterson, G. A., Halvorson, A. D., Havlin, J. L., Jones, O. R., Lyon, D. J., & Tanaka, D. L. (1998). Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. *Soil and Tillage Research*, *47*(3), 207–218. https://doi.org/10.1016/S0167-1987(98)00107-X

Peterson, Gary A., & Westfall, D. G. (2004). Managing precipitation use in sustainable dryland agroecosystems. *Annals of Applied Biology*, *144*(2), 127–138. https://doi.org/10.1111/j.1744-7348.2004.tb00326.x

Pikul, J. L., Aase, J. K., & Cochran, V. L. (1997). Lentil green manure as fallow replacement in the semiarid northern great plains. *Agronomy Journal*, *89*(6), 867–874. https://doi.org/10.2134/agronj1997.00021962008900060004x

Ragot, S. A., Kertesz, M. A., & Bünemann, E. K. (2015). PhoD alkaline phosphatase gene diversity in soil. *Applied and Environmental Microbiology*, *81*(20), 7281–7289. https://doi.org/10.1128/AEM.01823-15

Reeve, J. R., Endelman, J. B., Miller, B. E., & Hole, D. J. (2012). Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. *Soil Science Society of America Journal*, *76*(1), 278–285. https://doi.org/10.2136/sssaj2011.0123

Rick, T. L., Jones, C. A., Engel, R. E., & Miller, P. R. (2011). Green manure and phosphate rock effects on phosphorus availability in a northern Great Plains dryland organic cropping system. *Organic Agriculture*, *1*(2), 81–90. https://doi.org/10.1007/s13165-011-0007-2

Rick, T.L. (2009). Phosphorus fertility in northern great plains dryland organic cropping systems (Master's thesis). Retrieved from MSU Library https://scholarworks.montana.edu/xmlui/handle/1/2133

Roche, E. H., Mallory, E. B., & Darby, H. (2017). Evaluating split nitrogen applications and in-season tests for organic winter bread wheat. *Organic Farming*, *3*(1), 3–15. https://doi.org/10.12924/of2017.03010003

Schlegel, A. J., & Havlin, J. L. (1997). Green fallow for the central great plains. *Agronomy Journal*, *89*(5), 762–767. https://doi.org/10.2134/agronj1997.00021962008900050009x

Shelton, R. E., Jacobsen, K. L., & McCulley, R. L. (2017). Cover crops and fertilization alter nitrogen loss in organic and conventional conservation agriculture systems. *Frontiers in Plant Science*, *8*, 1–13. https://doi.org/10.3389/fpls.2017.02260

Tabatabai, M.A. 1994. Soil Enzymes. In R.W. Weaver et al. (Eds.), *Methods of soil analysis. Part 2. Microbiological and biochemical properties* (pp. 775-883). Madison, WI: SSSA.

Tabatabai, M. A., & Bremner, J. M. (1969). Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. *Soil Biology and Biochemistry*, *1*(4), 301–307. https://doi.org/10.1016/0038-0717(69)90012-1

Tanaka, D. L., Bauer, A., & Black, A. L. (1997). Annual legume cover crops in spring wheat-fallow systems. *Journal of Production Agriculture*, *10*(2), 251–255. https://doi.org/10.2134/jpa1997.0251

Thomas, G.W. (1996). Soil pH and Soil Acidity. In D.L. Sparks et al. (Eds.) *Methods of soil analysis. Part 3. Chemical Methods* (pp.475-490). Madison, WI: SSSA. doi: 10.2136/sssabookser5.3.c16.

Unger, P. W., & Vigil, M. F. (1998). Cover crop effects on soil water relationships. *Journal of Soil and Water Conservation*, *53*(3), 200–207.

van Kessel, C., Clough, T., Groenigen, V., & Willem, J. (2009). Dissolved organic nitrogen: An overlooked pathway of nitrogen loss from agricultural systems? *Journal of Environmental Quality*, *38*(2), 393–401. https://doi.org/10.2134/jeq2008.0277

White, K. E., Brennan, E. B., Cavigelli, M. A., & Smith, R. F. (2020). Winter cover crops increase readily decomposable soil carbon, but compost drives total soil carbon during eight years of intensive, organic vegetable production in California. *PLOS ONE*, *15*(2), e0228677. https://doi.org/10.1371/journal.pone.0228677

Wolińska, A., & Stępniewska, Z. (2012). Dehydrogenase activity in the soil environment. *Dehydrogenases*. https://doi.org/10.5772/48294

Yang, X., Reynolds, W. D., Drury, C. F., Fleming, R., Tan, C. S., Denholm, K., & Yang, J. (2013). Organic carbon and nitrogen stocks in a clay loam soil 10 years after a single compost application. *Canadian Journal of Soil Science*, *94*(3), 357–363. https://doi.org/10.4141/cjss2013-076

Zentner, R., Campbell, C., Biederbeck, V., & Selles, F. (1996). Indianhead black lentil: A green manure crop for the brown soil zone*?* 61–69. http://hdl.handle.net/10388/10330

TABLES

TABLE 1 Average physical and chemical properties at Snowville and Blue Creek at the initiation of the experiments.

	Snowville		Blue Creek	
	0-10	0-30	0-10	0-30
	cm			
Physical				
Soil series	Thiokol Silt Loam		Parleys Silt Loam	
Soil texture, g kg^{-1}				
Sand	140	290	160	130
Silt	660	530	600	610
Clay	200	180	240	250
Bulk density, g cm^{-3}	1.16	n.d.	1.14	n.d.
Chemical				
Total organic carbon, g kg^{-1}	10.7	11	12.4	9.6
Total nitrogen, g kg^{-1}	1.8	1.28	3.09	1.32
Phosphorus, mg kg^{-1}	n.d.	5.2	n.d.	38.1
Potassium, mg kg^{-1}	n.d.	595	n.d.	545
Zinc, mg kg^{-1}	n.d.	0.23	n.d.	1.17
Iron, mg kg^{-1}	n.d.	4.56	n.d.	20.3
Copper, mg kg^{-1}	n.d.	1.29	n.d.	2.18
Manganese, mg kg^{-1}	n.d.	2.96	n.d.	44.0

[a] n.d., not determined.

TABLE 2 Chemical properties of composted steer manure and chicken manure applied to the long-term plots.

	Compost	Chicken manure
Moisture, (%)	6.4	8.2
pH, 2:1	8.0	6.8
EC, dS m^{-1} (2:1)	9.16	9.56
Total organic carbon, g kg^{-1}	227	331
Total nitrogen, g kg^{-1}	17.7	59.5
Phosphorus, (%)	1.16	1.32
Potassium, (%)	1.95	1.32
Calcium, (%)	3.81	4.13
Magnesium, (%)	0.95	0.58
Zinc, mg kg^{-1}	205	280
Iron, mg kg^{-1}	18272	1175
Copper, mg kg^{-1}	39.7	30.1
Manganese, mg kg^{-1}	376	286

TABLE 3 Total annual precipitation and potential total annual evapotranspiration during the fallow and winter wheat phases at Snowville and Blue Creek from 2015 to 2019 (Utah Climate Center, 2019)

Year	Total annual precipitation (mm)	
	Snowville	Blue Creek
2015-2016	315	396
2016-2017	342	515
2017-2018	214	262
2018-2019	296	455
	Total potential annual evapotranspiration (mm)	
2015-2016	1091	1092
2016-2017	1107	1133
2017-2018	1109	1158
2018-2019	1071	1114

TABLE 4 The main effects of compost, cover crop and year on gravimetric soil moisture in 30-60 and 60-90 cm depths at Snowville in late April. Means with the different lower case indicate differences at $p<0.05$ (n=4).

Depth	**Compost**	Gravimetric soil moisture
cm	Mg DW ha^{-1}	g g^{-1}
30-60	Control	0.24a[a]
	Manure	0.24a
	PC	0.24a
	12.5	0.24a
	25	0.24a
	50	0.24a
60-90	Control	0.23a
	Manure	0.24a
	PC	0.25a
	12.5	0.24a
	25	0.24a
	50	0.24a
	Cover crop	
30-60	Fallow	0.24a
	P+HV	0.24a
60-90	Fallow	0.24a
	P+HV	0.24a
	Year	
30-60	1	0.23a
	3	0.25b
60-90	1	0.23a
	3	0.26b
		ANOVA
30-60	Compost	NS[†]
	Cover crop	NS
	Year	***
60-90	Compost	NS
	Cover crop	NS
	Year	***

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, † NS, nonsignificant

PC = 25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1})

TABLE 5 Main effects of compost, cover crop and year on microbial basal respiration and microbial biomass (n=8) in 0-10 cm depth at Snowville.

	Basal respiration $\mu g\ CO_2$- C g^{-1} soil hr^{-1}	Microbial Biomass $\mu g\ CO_2$-C g^{-1} soil
Compost (Mg DW ha^{-1})		
Control	4.58	748c[a]
Manure	4.85	806bc
PC	5.88	942a
12.5	5.35	864bc
25	5.84	848ab
50	6.15	983a
Cover crop		
Fallow	5.33	850a
Winter Pea +Hairy Vetch	5.56	881a
Year		
1	8.60a	630b
3	2.29b	1101a
	ANOVA	
Compost	NS†	***
Cover Crop	NS	NS
Year	***	***
Cover crop x Compost	NS	NS
Compost x Year	NS	NS
Cover crop x Year	NS	NS

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, † NS, nonsignificant.

PC = 25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1})

TABLE 6 Main effects of compost, cover crop and year on pH and electrical conductivity (n=8) in 0-10 cm at Snowville.

	pH	Electrical conductivity dS m^{-1}
Compost (Mg DW ha^{-1})		
Control	8.7	0.187
Manure	8.6	0.179
PC	8.6	0.182
12.5	8.6	0.189
25	8.6	0.184
50	8.6	0.199
Cover crop		
Fallow	8.6	0.185
Winter Pea +Hairy Vetch	8.7	0.189
	pH	Electrical conductivity dS m^{-1}
Year		
1	8.60b[a]	0.213a
3	8.66a	0.160b
	ANOVA	
Compost	NS†	NS
Cover Crop	NS	NS
Year	***	***
	pH	Electrical conductivity dS m^{-1}
	ANOVA	
Cover crop*Compost	NS	NS
Compost*Year	NS	NS
Cover crop*Year	NS	NS

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, † NS, nonsignificant.

PC = 25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1})

TABLE 7 Compost application had a significant impact on zinc (Zn), iron (Fe) and manganese (Mn) but not copper (Cu) in 0-30 cm depth at Snowville. The inclusion of cover crops did not have a significant effect on the micronutrients (n=8).

	Zn	Fe	Mn	Cu
	(mg kg^{-1} soil)			
Compost (Mg DW ha^{-1})				
Control	0.292c[a]	3.82d	4.91c	1.61
Manure	0.315c	3.88d	4.87c	1.5
PC	0.696a	5.80b	5.48b	1.47
12.5	0.487b	4.75c	5.49b	1.55
25	0.705a	5.52b	5.34bc	1.65
50	0.896a	7.10a	6.24a	1.69
Cover crop				
Fallow	0.575	5.33	5.46	1.56
Winter Pea+Hairy Vetch	0.551	4.97	5.32	1.6
Year				
1	0.552	4.49b	4.77b	1.63
3	0.589	5.81a	6.00a	1.53
ANOVA				
Compost	***	***	***	NS
Cover crop	NS[†]	NS	NS	NS
Year	NS	***	***	NS
Compost x Cover crop	NS	NS	NS	NS
Compost x Year	**	NS	NS	NS
Cover crop x Year	NS	NS	NS	NS

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, [†] NS, nonsignificant.

PC = 25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1})

TABLE 8 Main effects of compost, cover crops and year on dissolved organic carbon (DOC), dissolved organic nitrogen (DON), ammonium (NH4+-N) and nitrate (NO3—N) across the depths at Snowville (n=4).

Depth cm	Compost Mg DW ha^{-1}	DOC	DON	NH_4^+-N	NO_3^--N
		mg kg^{-1}			
0-30	Control	48.6b[a]	9.30b	0.97a	3.11a
	Manure	48.9ab	10.3ab	1.09a	2.97a
	PC	58.0ab	10.2ab	1.16a	1.84a
	12.5	53.4ab	9.34ab	1.38a	2.42a
	25	59.1ab	10.9ab	1.07a	1.67a
	50	70.2a	11.58a	1.14a	2.62a
30-60	Control	77.7a	15.7ab	0.89a	8.75a
	Manure	69.0a	15.6ab	0.83a	7.31a
	PC	66.3a	17.7ab	1.16a	6.96a
	12.5	74.3a	15.1b	1.16a	6.30a
	25	77.6a	16.9ab	1.03a	7.30a
	50	67.1a	19.2a	1.02a	8.59a
60-90	Control	54.8a	16.0a	1.13a	8.62a
	Manure	46.1a	18.4a	1.09a	5.51a
	PC	58.0a	20.8a	1.25a	8.30a
	12.5	53.1a	14.6a	1.13a	8.18a
	25	52.6a	15.9a	1.16a	7.43a
	50	49.7a	19.4a	1.19a	6.95a
	Cover crop				
0-30	Fallow	54.1a	11.2a	1.21a	2.62a
	Winter Pea +Hairy Vetch	58.7a	9.33a	1.06a	2.26a
30-60	Fallow	68.9a	18.8a	1.17aa	8.13a
	Winter Pea +Hairy Vetch	75.1a	14.6a	0.86	6.95a
60-90	Fallow	45.7a	17.3a	1.46a	8.05a
	Winter Pea +Hairy Vetch	59.6a	17.5a	0.85a	6.83a
	Year				
0-30	1	39.9b	5.26b	1.37a	2.34b
	3	72.9a	15.3a	0.65a	2.64a

Depth cm	Compost Mg DW ha^{-1}	DOC	DON	NH_4^+-N	NO_3^--N
		mg kg^{-1}			
30-60	1	48.5b	10.5b	1.21a	8.10a
	3	95.5a	22.8a	0.63b	6.43a
60-90	1	41.9b	11.9b	1.39a	8.09a
	3	63.5a	25.2a	0.41b	5.02a
	Effects	ANOVA			
		DOC	DON	NH_4^+-N	NO_3^--N
0-30	Compost	***	**	NS	NS
	Cover crop	NS[†]	NS	NS	NS
	Year	***	***	***	**
30-60	Compost	NS	**	NS	NS
	Cover crop	NS	NS	NS	NS
	Year	***	***	***	NS
60-90	Compost	NS	NS	NS	NS
	Cover crop	NS	NS	NS	NS
	Year	**	***	***	NS

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, [†] NS, nonsignificant.

PC = 25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1})

TABLE 9 The main effects of compost across the different years and cover crop on gravimetric soil moisture in 30-60 and 60-90 cm depths at Blue Creek in June (years 1 and 5) and May (years 3 and 7) (n=4).

Year	**Compost**	30-60	60-90
	Mg DW ha^{-1}	Gravimetric soil moisture (g g^{-1})	
1	Control	0.156a[a]	0.165a
	12.5	0.145ab	0.158ab
	25	0.153a	0.161ab
	50	0.138b	0.152ab
	PC	0.142ab	0.146b
3	Control	0.182b	0.191a
	12.5	0.192ab	0.187a
	25	0.20a	0.190a
	50	0.189ab	0.191a
	PC	0.19ab	0.184a
5	Control	0.156ab	0.165ab
	12.5	0.149b	0.158ab
	25	0.148b	0.173a
	50	0.165a	0.171a
	PC	0.142b	0.146b
7	Control	0.182a	0.191a
	12.5	0.186a	0.183a
	25	0.191a	0.191a
	50	0.192a	0.189a
	PC	0.19a	0.184a
	Cover Crop		
	Fallow	0.171a	0.176a
	Winter Pea +Hairy Vetch	0.169a	0.173a

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05). PC = anhydrous ammonia.

TABLE 10 Compost application had a significant impact on zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) in 0-30 cm depth in 0-30 cm depth at Blue Creek (n=4).

Year	**Compost**	pH	EC	Zn	Fe	Mn	Cu
	Mg DW ha^{-1}		dS m^{-1}	mg kg^{-1}			
1	Control	6.9b[a]	0.051c	0.471c	13.15b	24.4b	0.86b
	12.5	7.0b	0.063b	0.6b	13.63b	24.0b	0.94ab
	25	7.3a	0.08a	0.902a	16.67a	24.9b	0.98ab
	50	7.0b	0.091a	0.961a	18.52a	29.3a	1.06a
	PC	6.7c	0.049c	0.577bc	16.62a	33.3a	1.03a
3	Control	7.1b	0.044c	0.637c	17.3b	32.5ab	1.03a
	12.5	7.3a	0.056bc	0.854b	16.64b	29.0bc	1.12a
	25	7.3a	0.063ab	0.999b	18.68ab	27.9c	1.0ba
	50	7.4a	0.073a	1.37a	21.16a	27.3c	1.04a
	PC	6.8c	0.07a	0.689bc	19.21ab	35.9a	1.07a
5	Control	6.9b	0.051c	0.471c	13.15b	24.4b	0.86b
	12.5	7.1a	0.056bc	0.686b	12.73b	24.5b	0.88ab
	25	7.0ab	0.06b	0.739b	12.54b	21.7bc	0.91ab
	50	7.2a	0.075a	0.993a	10.78b	19.0c	0.88ab
	PC	6.7c	0.049c	0.577bc	16.62a	33.3a	1.03a
7	Control	7.1c	0.044c	0.637c	17.3ab	32.5ab	1.03a
	12.5	7.2bc	0.059ab	0.889b	16.47b	28.8bc	1.1a
	25	7.3b	0.056b	1.00b	15.5bc	27.9c	1.1a
	50	7.5a	0.07a	1.349a	13.12c	23.1d	1.11a
	PC	6.8d	0.07a	0.689c	19.21a	35.9a	1.07a

Cover Crop	pH	EC	Zn	Fe	Mn	Cu
		dS m^{-1}	———	mg kg^{-1}	———	
Fallow	7.1a	0.065a	0.857a	16.0a	27.3a	1.0a
Winter Pea +Hairy Vetch	7.1a	0.062a	0.858a	15.6a	26.9a	1.02a

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

PC = anhydrous ammonia.

TABLE 11 The main effects of compost across the different years and cover crop on dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) in 0-90 cm depth at Blue Creek (n=4).

		DOC			DON		
		mg kg^{-1}					
Year	**Compost**	0-30	30-60	60-90	0-30	30-60	60-90
	Mg DW ha^{-1}						
1	Control	50.6b[a]	26.0a	9.5.0a	7.90b	3.90a	5.50ab
	12.5	67.9b	19.0a	10.7a	9.30b	4.90a	6.20ab
	25	116a	19.9a	11.9a	15.5a	3.50a	6.10ab
	50	124a	23.1a	9.80a	16.7a	4.50a	8.60a
	PC	56.0b	19.1a	10.0a	9.20b	3.70a	5.10b
3	Control	129ab	118a	63.0b	21.4a	37.6a	14.3bc
	12.5	121b	121a	53.5b	20.5a	26.6a	13.3c
	25	155a	151a	79.4a	21.3a	41.9a	16.7bc
	50	156a	140a	65.7b	23.0a	38.5a	32.8a
	PC	114b	144a	66.2b	22.6a	37.3a	17.5abc
5	Control	50.6a	26ab	9.50a	7.90a	3.90a	5.50b
	12.5	67.2a	38.1a	12.4a	8.80a	5.70a	5.60b
	25	77.7a	17.1b	11.3a	10.2a	6.50a	9.50a
	50	71.8a	29.3ab	10.4a	10.4a	4.90a	4.90b
	PC	56.0a	19.1ab	10.0a	9.20a	3.70a	5.10b
7	Control	129a	118a	63.0ab	21.4a	37.6a	14.3a
	12.5	123a	134a	52.1b	15.9a	45.8a	14.3a
	25	123a	136a	58.8b	23.7a	35.2a	13.6a
	50	113a	130a	70.1a	36.5a	32.2a	14.9a
	PC	114a	144a	66.2ab	22.6a	37.3a	17.5a
	Cover Crop						
	Fallow	104a	78.7a	36.7a	17.2a	21.6a	11.3a
	Winter Pea +Hairy Vetch	100a	80.3a	37.2a	16.9a	20.0a	12.3a

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

PC = anhydrous ammonia.

TABLE 12 The main effects of compost across the different years and cover crop on ammonium (NH_4^+-N) and nitrate (NO_3^--N) in 0-90 cm depth at Blue Creek (n=4).

		NH_4^+			NO_3^-		
		mg kg^{-1}					
Year	**Compost Mg DW ha^{-1}**	0-30	30-60	60-90	0-30	30-60	60-90
1	Control	0.21b[a]	0.21a	0.29a	0.41b	0.51c	0.88b
	12.5	0.37a	0.22a	0.41a	0.58ab	0.42c	0.71b
	25	0.41a	0.43a	0.34a	0.58ab	0.96ab	2.81a
	50	0.38a	0.25a	0.39a	0.76a	1.05a	3.50a
	PC	0.18b	0.30a	0.46	0.73a	0.63bc	0.84b
3	Control	0.74a	0.96a	0.63a	1.65b	1.39ab	1.81ab
	12.5	0.79a	0.83a	0.50a	1.74b	1.11ab	1.46b
	25	0.98a	0.90a	0.78a	1.61b	1.08b	1.34b
	50	0.91a	0.88a	0.74a	1.61b	1.14a	2.09ab
	PC	0.81a	0.91a	0.59a	5.47a	1.63a	2.59a
5	Control	0.21ab	0.21a	0.29b	0.41c	0.51a	0.88a
	12.5	0.25ab	0.26a	0.40ab	0.42c	0.50a	0.64a
	25	0.23ab	0.47a	0.32ab	0.48bc	0.58a	0.61a
	50	0.30a	0.27a	0.58a	0.82a	0.46a	0.81a
	PC	0.18b	0.30a	0.46ab	0.73ab	0.63a	0.84a
7	Control	0.74a	0.96a	0.63a	1.65b	1.39a	1.81ab
	12.5	0.83a	0.84a	0.84a	1.44b	1.26a	1.53b
	25	0.74a	0.98a	0.59a	1.42b	1.14a	1.21b
	50	0.83a	1.00a	0.66a	1.88b	1.16a	1.46b
	PC	0.81a	0.91a	0.59a	5.47a	1.63a	2.59a
	Cover Crop						
	Fallow	0.56a	0.61a	0.52a	1.35a	0.97a	1.38b
	Winter Pea +Hairy Vetch	0.55a	0.60a	0.45a	1.16b	0.91a	1.62a

[a] Means within the same column with the same lower-case letter are not significantly different according to Tukey (.05).

PC = anhydrous ammonia.

FIGURES

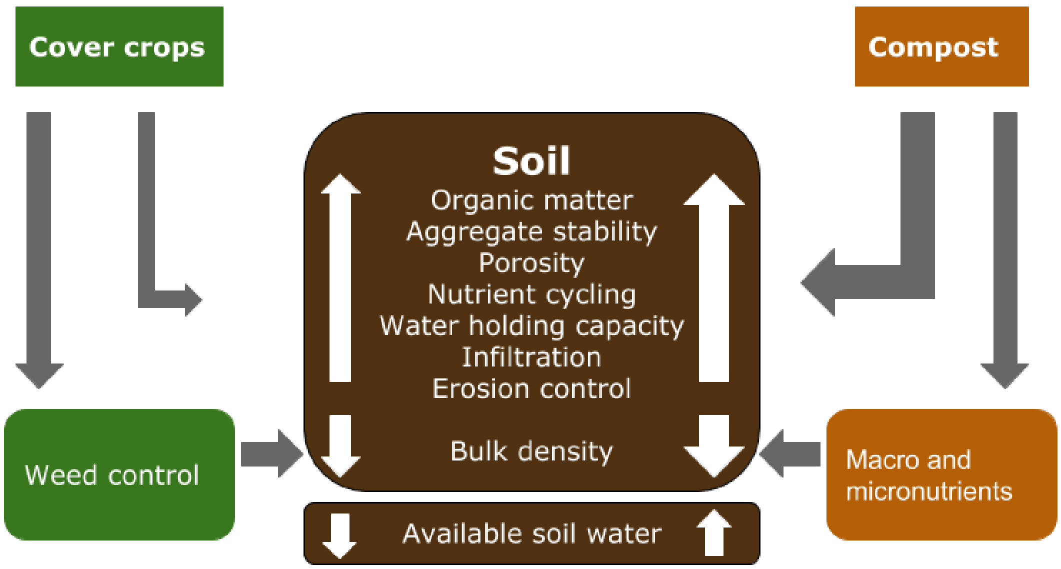


FIGURE 1 Potential synergistic effect between cover crops and compost on soil properties in non-irrigated dryland WW-AF systems.

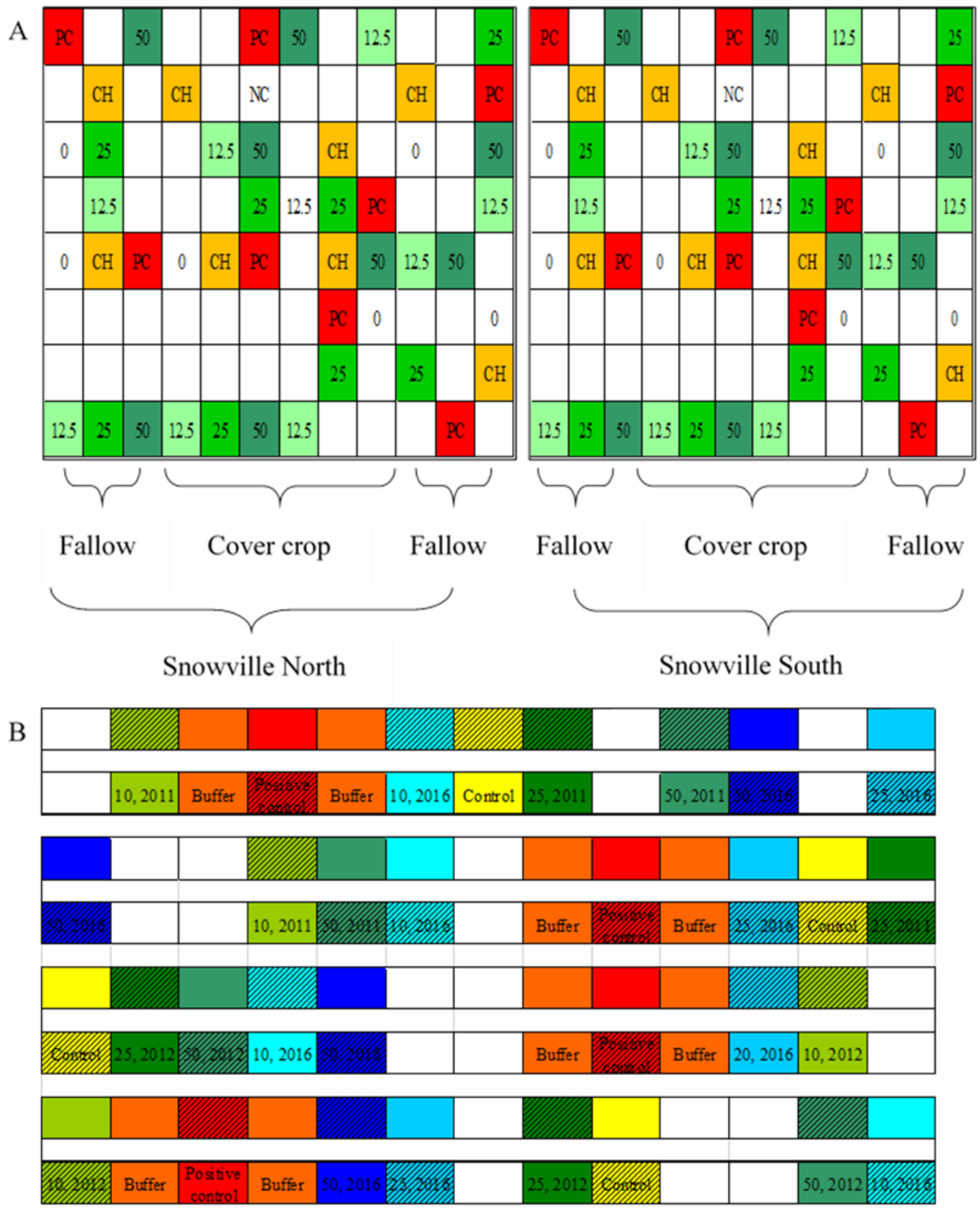


FIGURE 2 The plot layouts for field experiments at Snowville, Utah (A) and at Blue Creek, Utah (B). The experiment is a randomized complete block split-plot design with four blocks. In panel B, hatching represents cover crop while the plain color represents fallow. Chicken manure = CH and Positive control = PC (PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}) at Snowville and anhydrous ammonia at Blue Creek).

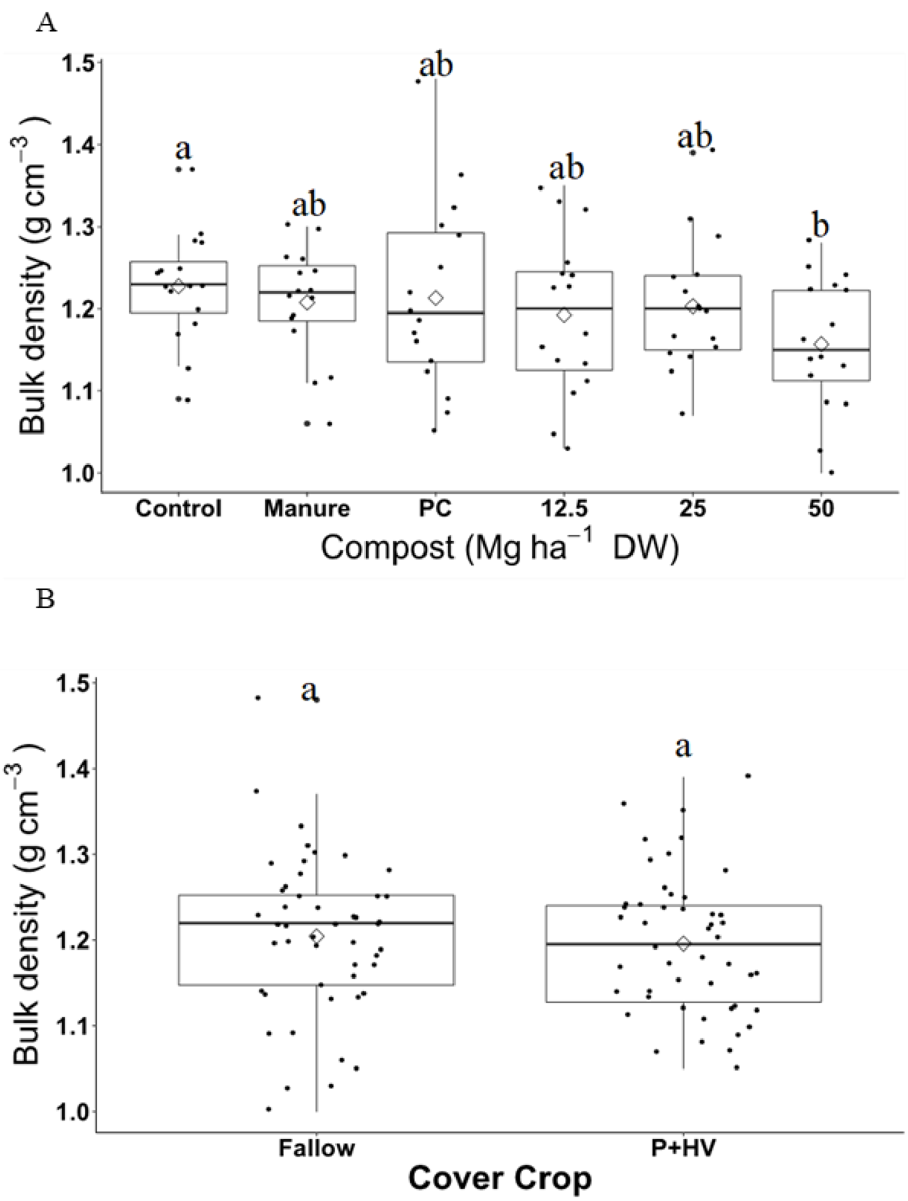


FIGURE 3 Compost (A), and cover crop (B) effects on bulk density three years after in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

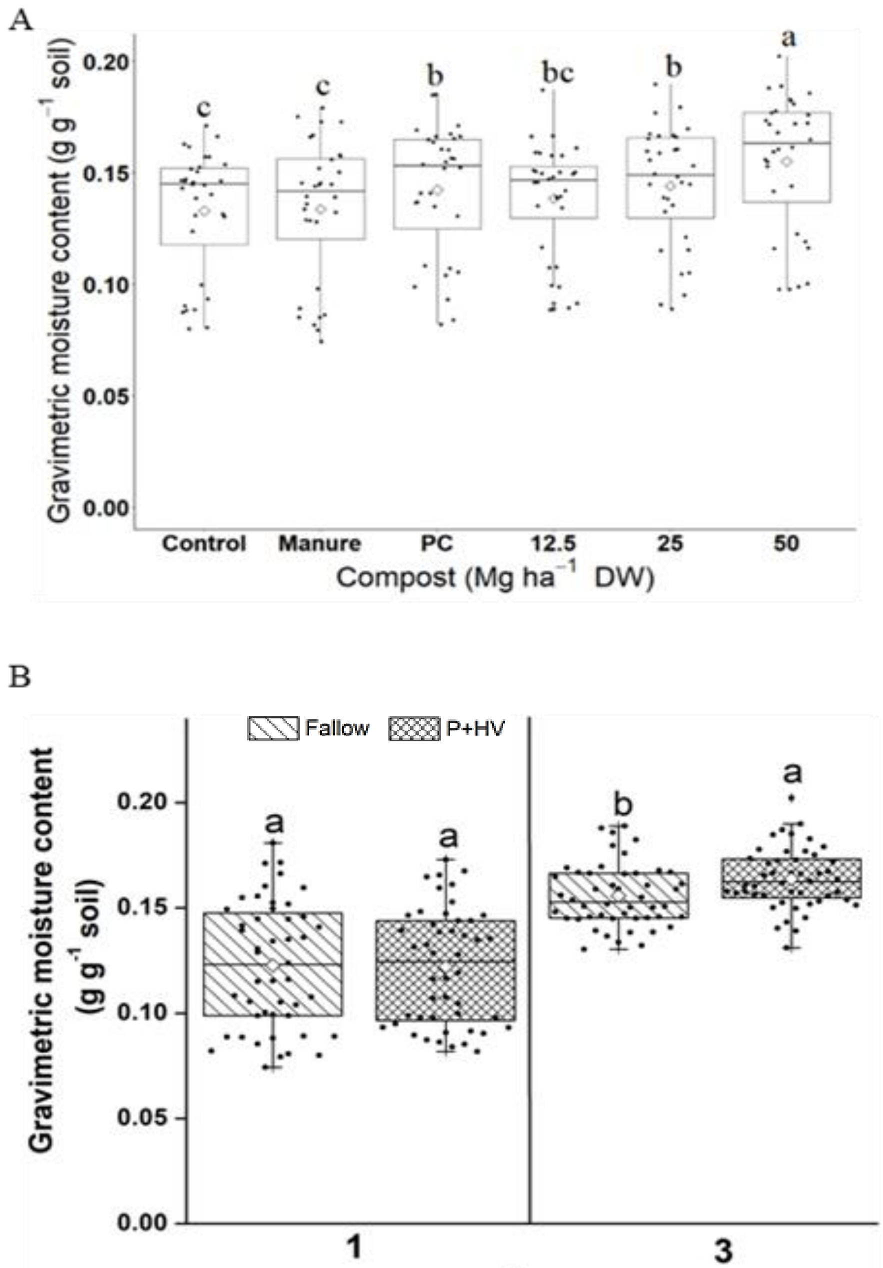


FIGURE 4 Significant compost effect (A) and cover crop by year after interaction (B) on gravimetric soil moisture in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}), P+HV = Austrian winter pea plus hairy vetch.

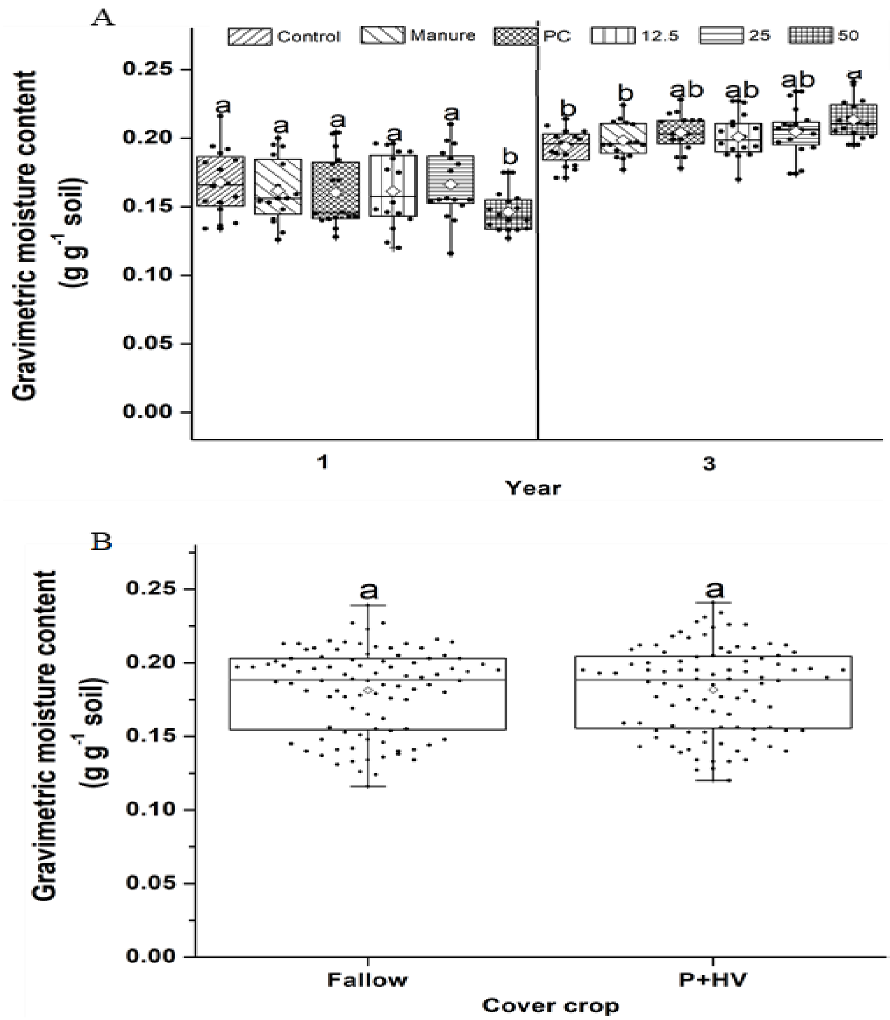


FIGURE 5 Significant compost by year interaction (A) and cover crop (B) on gravimetric soil moisture in 0-30 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}) and PV = Austrian winter pea plus hairy vetch.

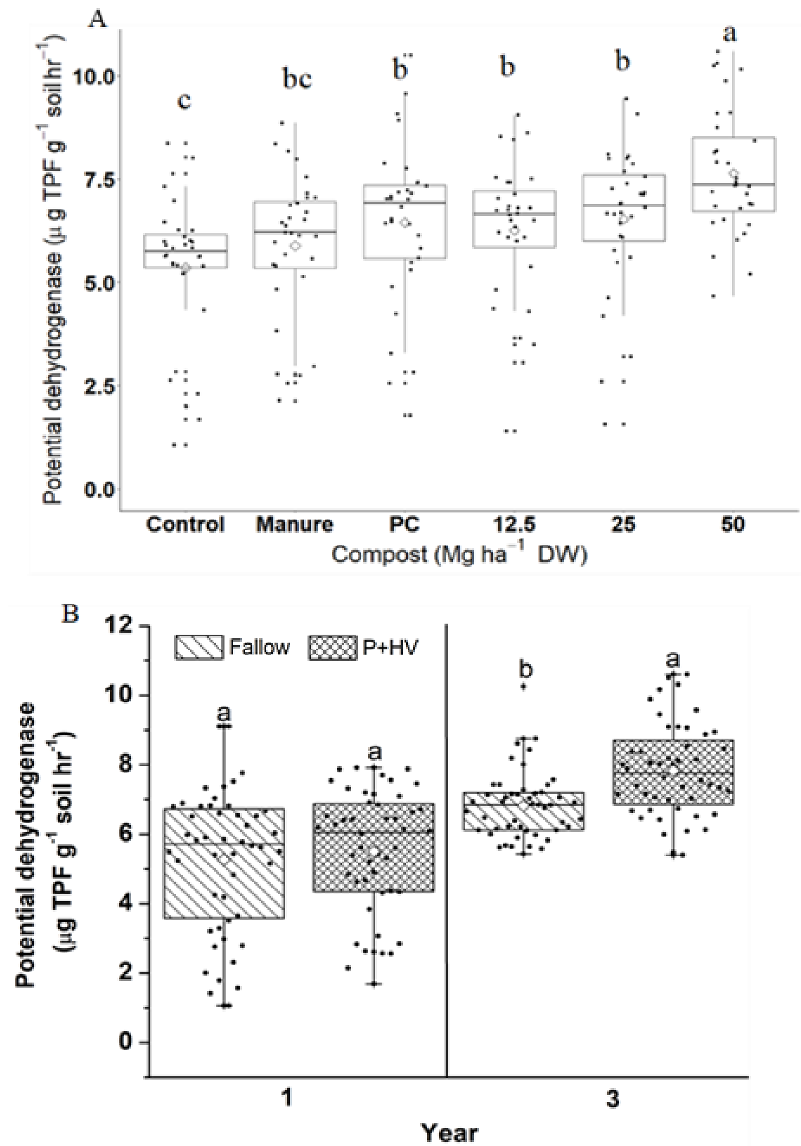


FIGURE 6 Potential dehydrogenase increased with compost ($p<0.0001$) addition (A) while cover crop (B) increased ($p=0.0299$) the enzyme activity three years after compost application in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

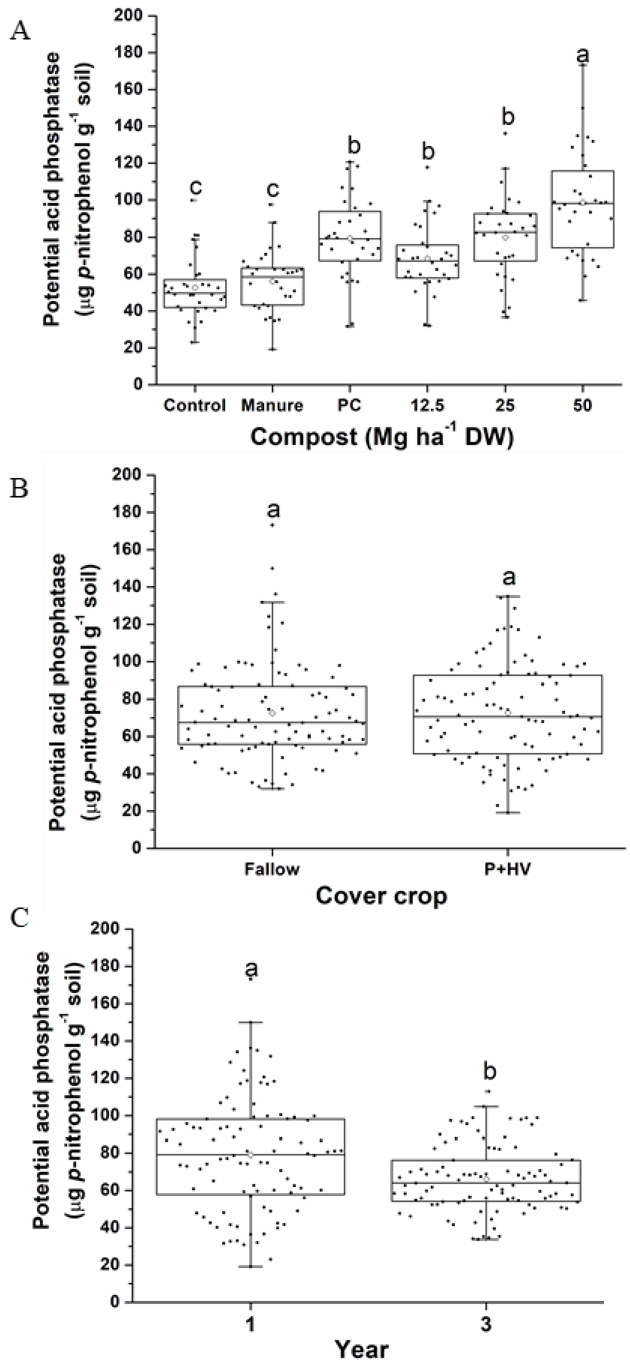


FIGURE 7 Main effects of compost (A), cover crop (B) and year (C) on acid phosphatases in 0-10 cm depth at Snowville. Treatments with the same lower-case letters

are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

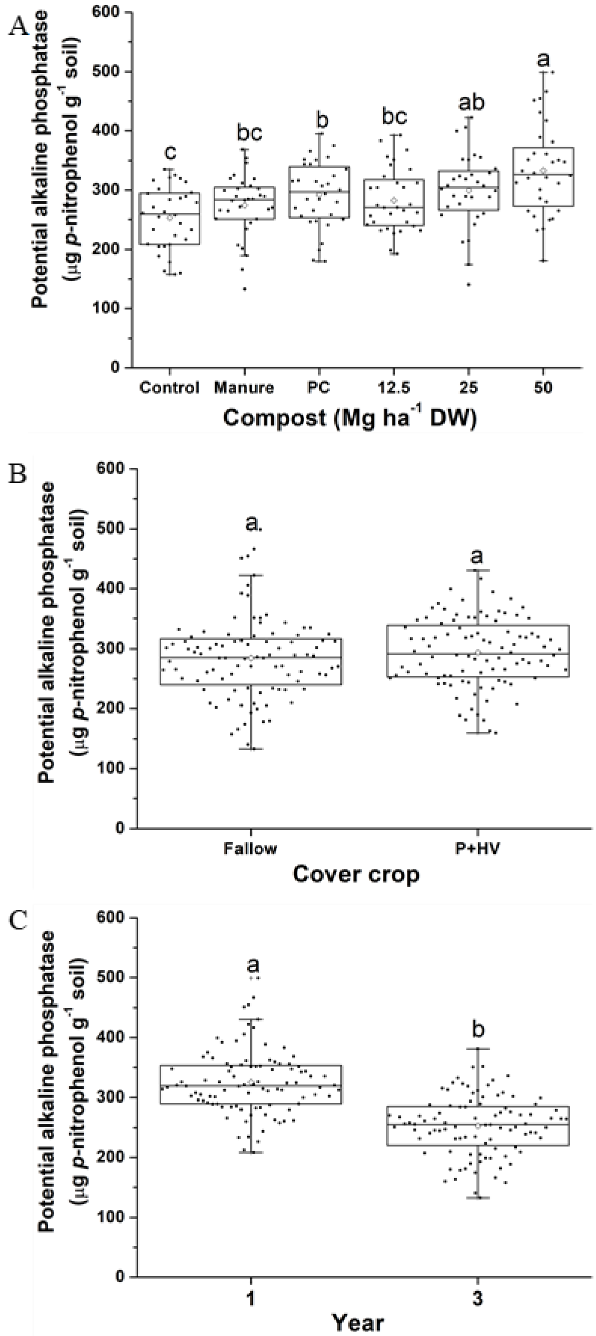


FIGURE 8 Main effects of compost (A), cover crop (B) and year (C) on alkaline phosphatases in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

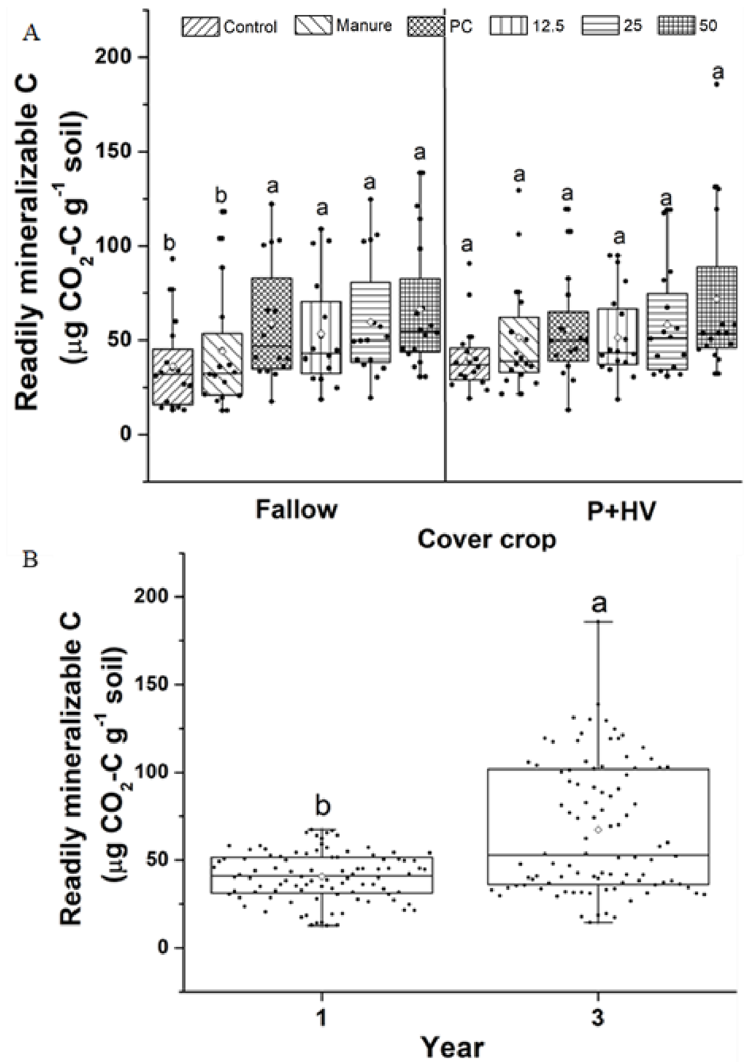


FIGURE 9 Readily mineralizable carbon (RMC) increased with the inclusion of cover crop under control and chicken manure treatments (A) while RMC was higher during year 3 than year 1 (B) in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

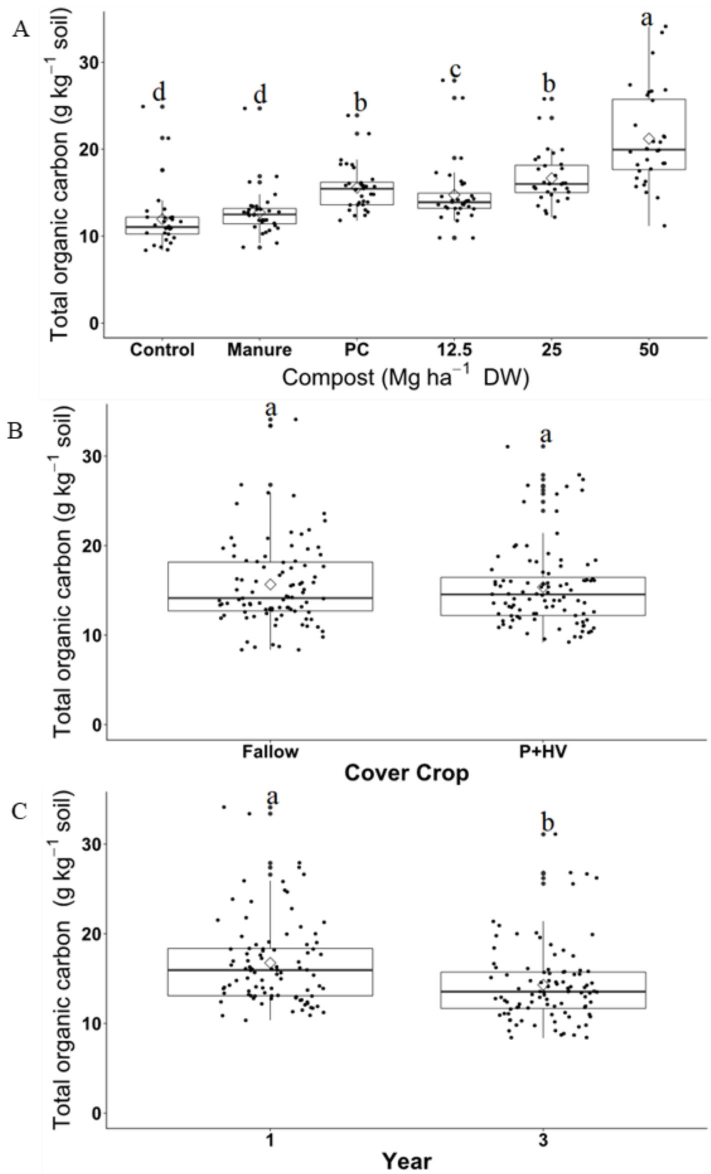


FIGURE 10 Main effects of compost (A), cover crop (B) and year (C) on total organic carbon in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

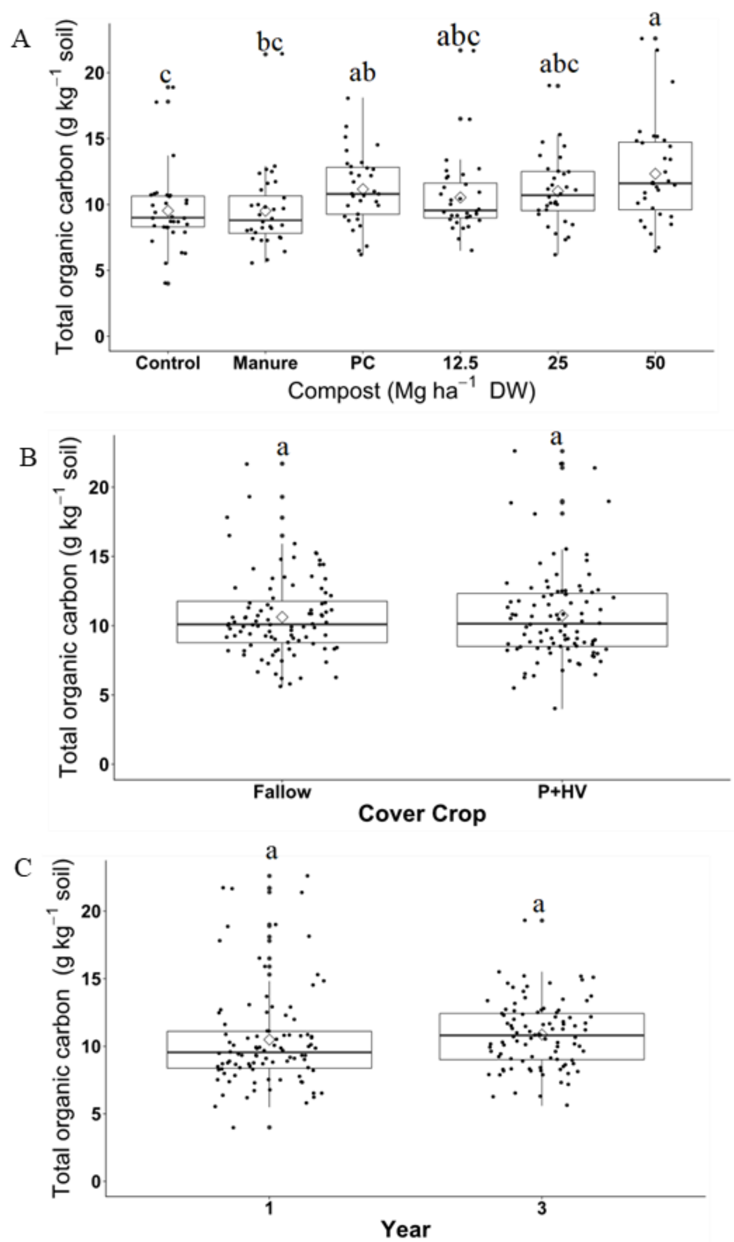


FIGURE 11 Main effects of compost (A), cover crop (B) and year (C) on total organic carbon in 0-30 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

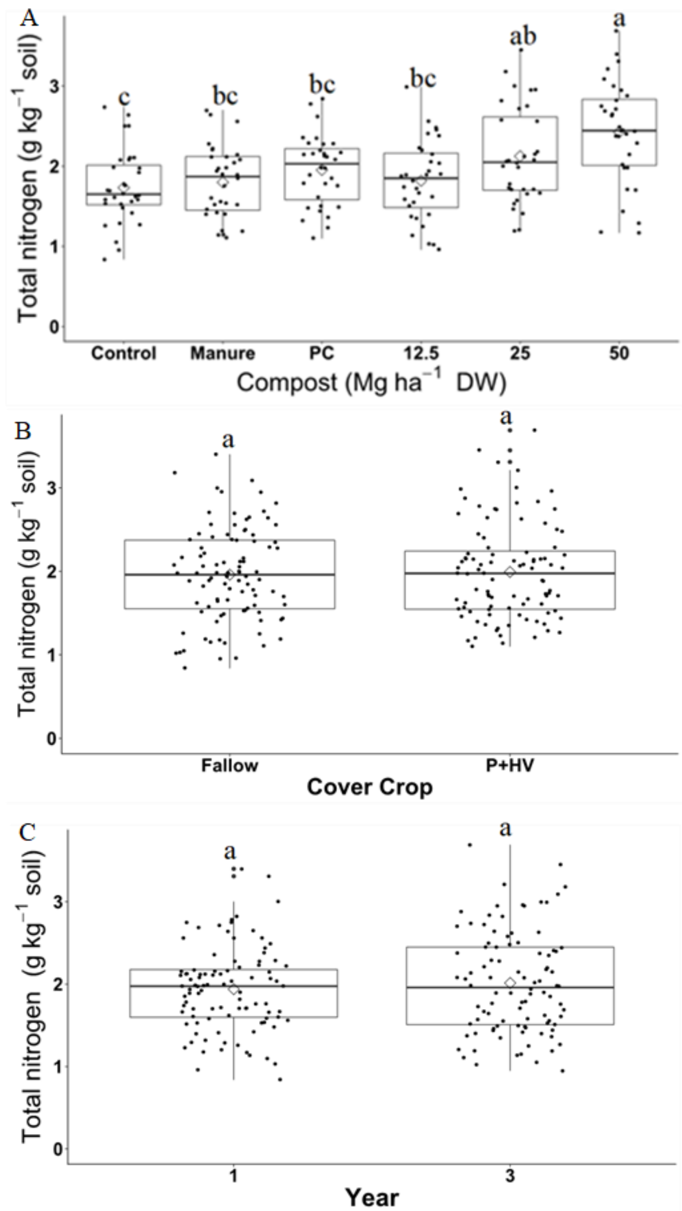


FIGURE 12 Main effects of compost (A), cover crop (B) and year (C) on total nitrogen in 0-10 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

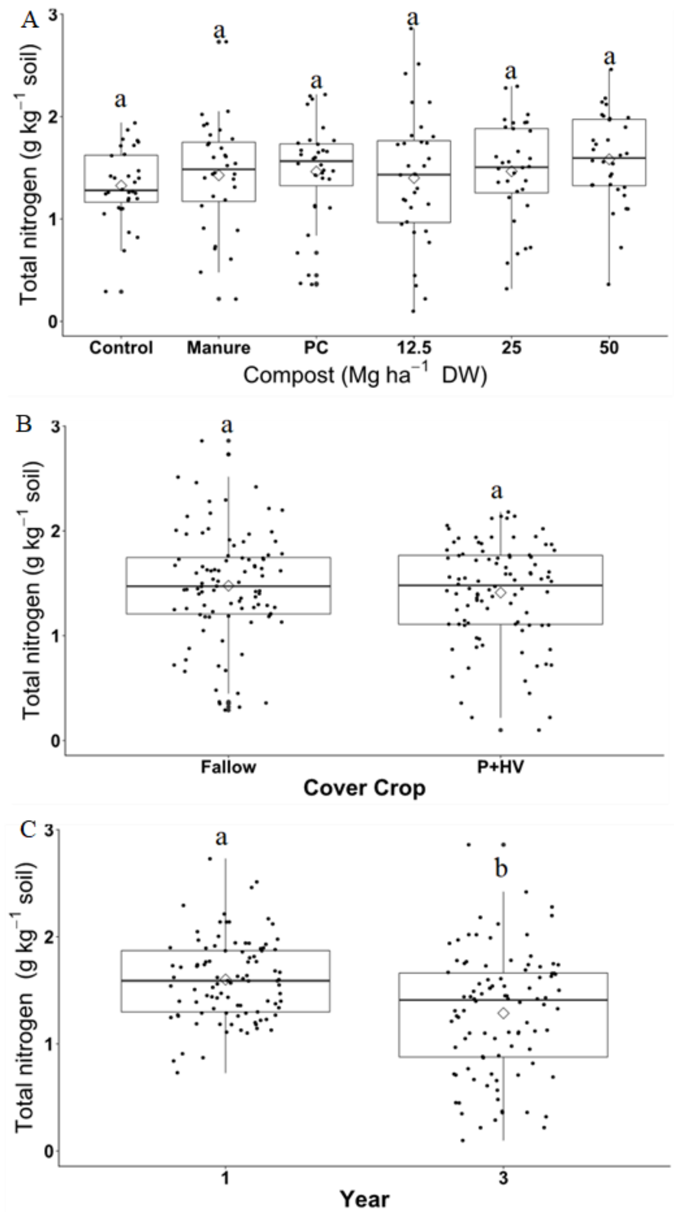


FIGURE 13 Main effects of compost (A), cover crop (B) and year (C) on total nitrogen in 0-30 cm depth at Snowville. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

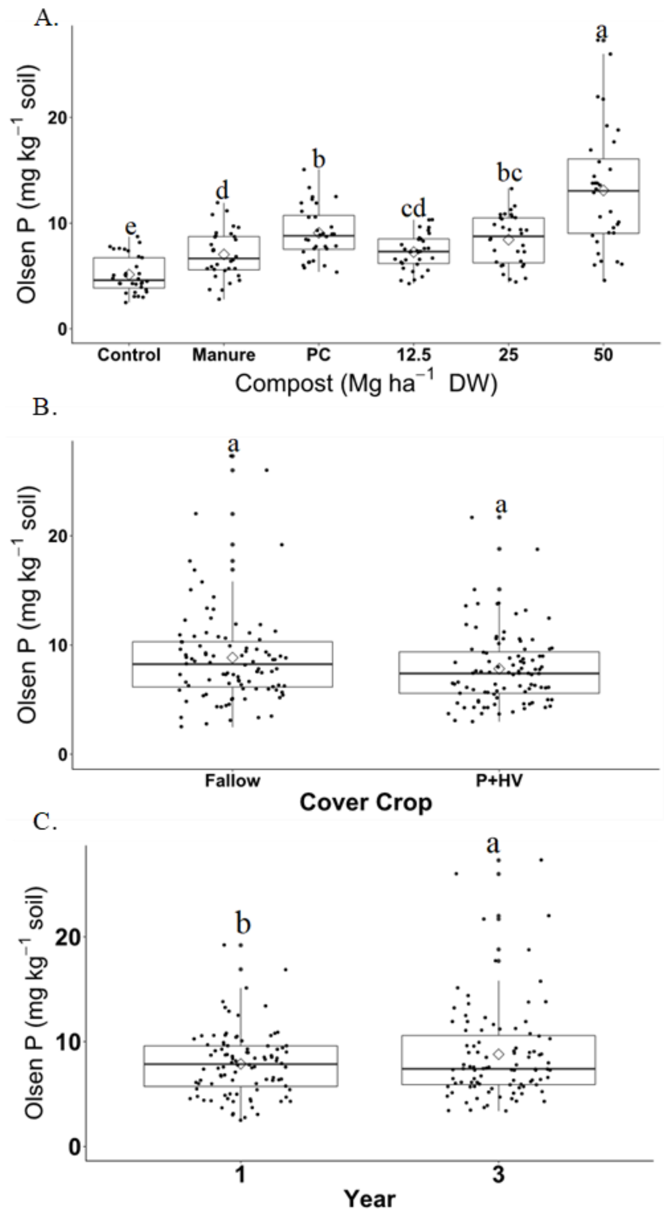


FIGURE 14 Main effects of compost (A, p<0.0001), cover crop (B, p=0.0637) and year (C, p=0.0154) on Olsen P in 0-30 cm depth at Snowville. PC=25 Mg compost DW ha^{-1} + feather meal (45 kg N ha^{-1}).

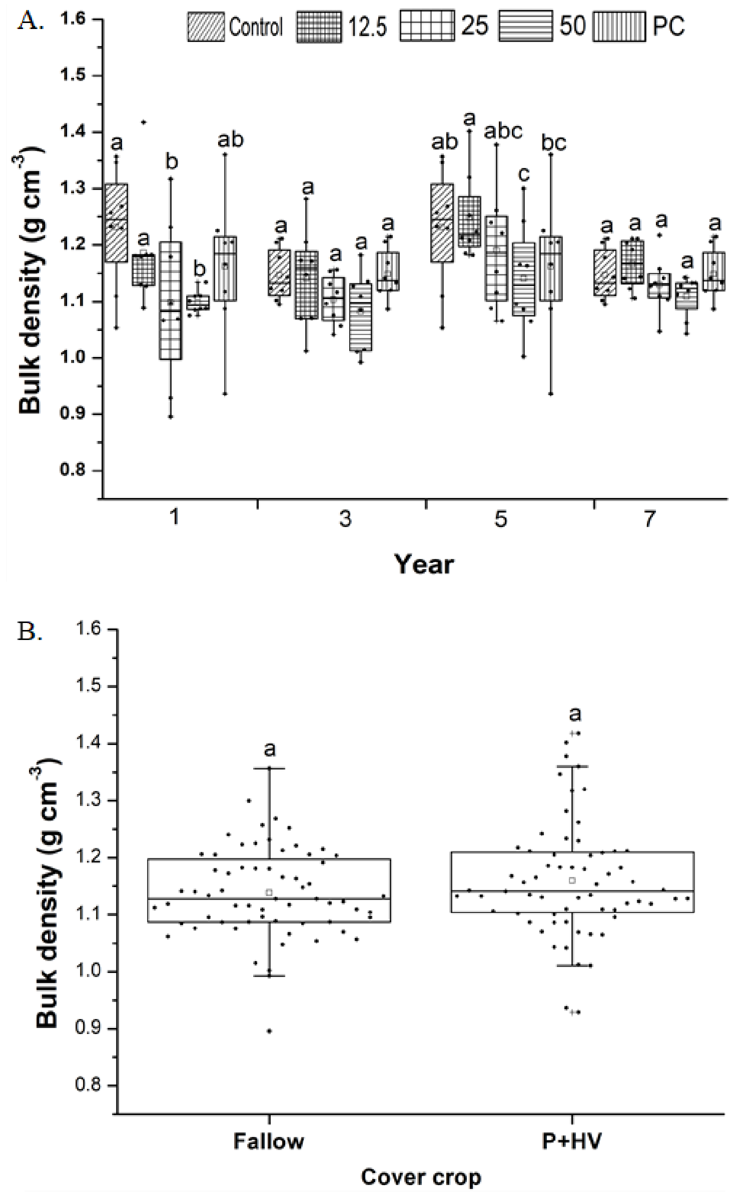


FIGURE 15 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on bulk density (panels A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

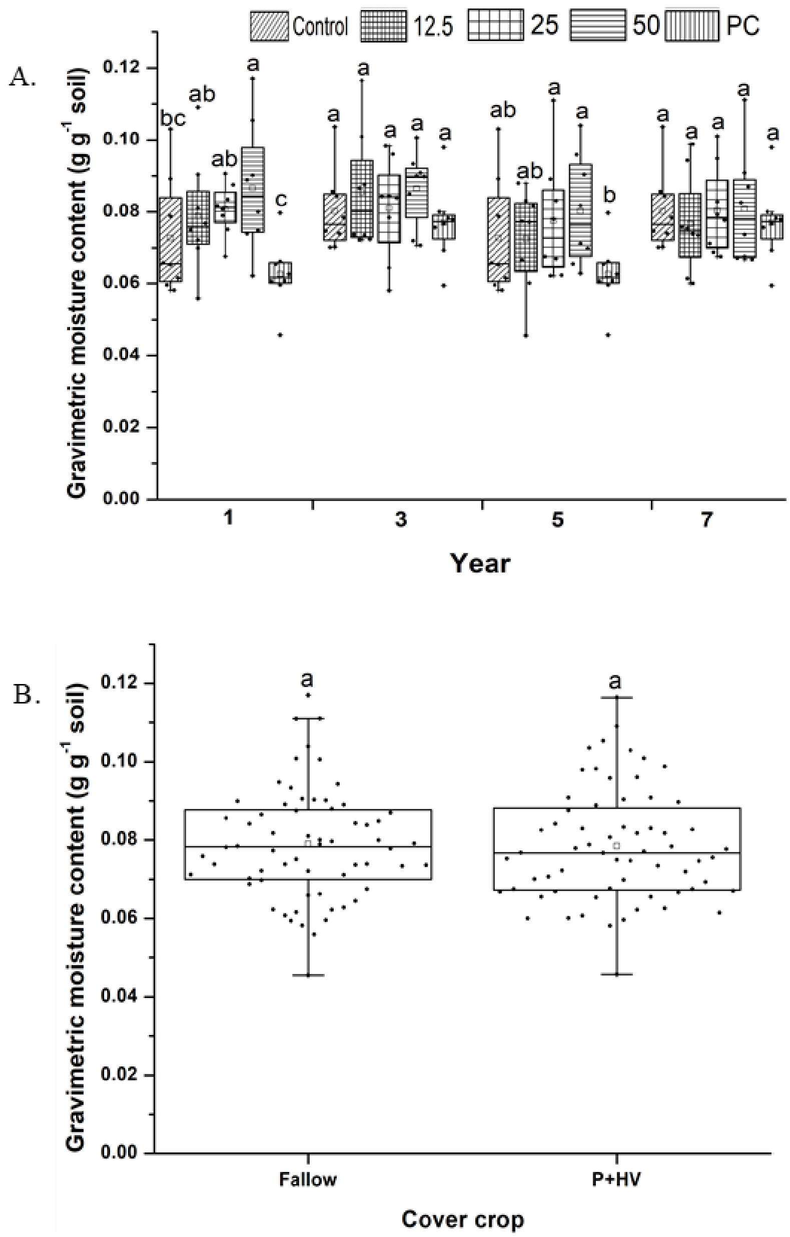


FIGURE 16 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on gravimetric moisture content (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different

according to Tukey (0.05). PC = anhydrous ammonia. Data for years 1 and 5 were collected in June and for years 3 and 7 in May.

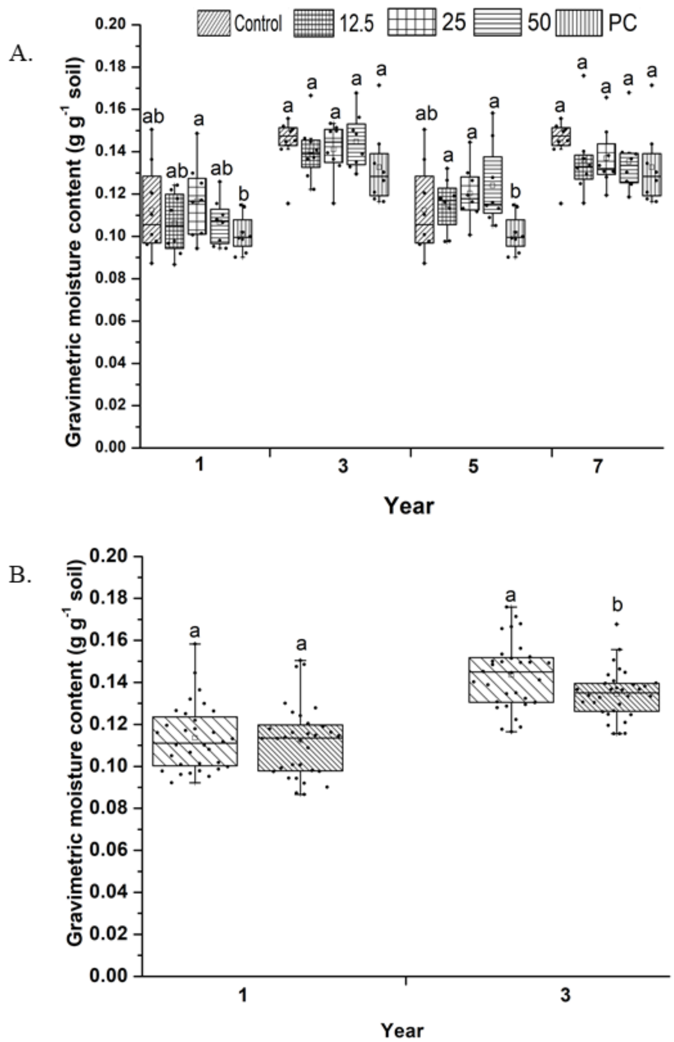


FIGURE 17 Main effects of compost (1, 3, 5, and 7 years) and cover crop by year interaction (1 and 3 years) effects on gravimetric moisture content (A and B, respectively) in 0-30 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia, P+HV =

Austrian pea plus hairy vetch. Data for years 1 and 5 were collected in June and for years 3 and 7 in May.

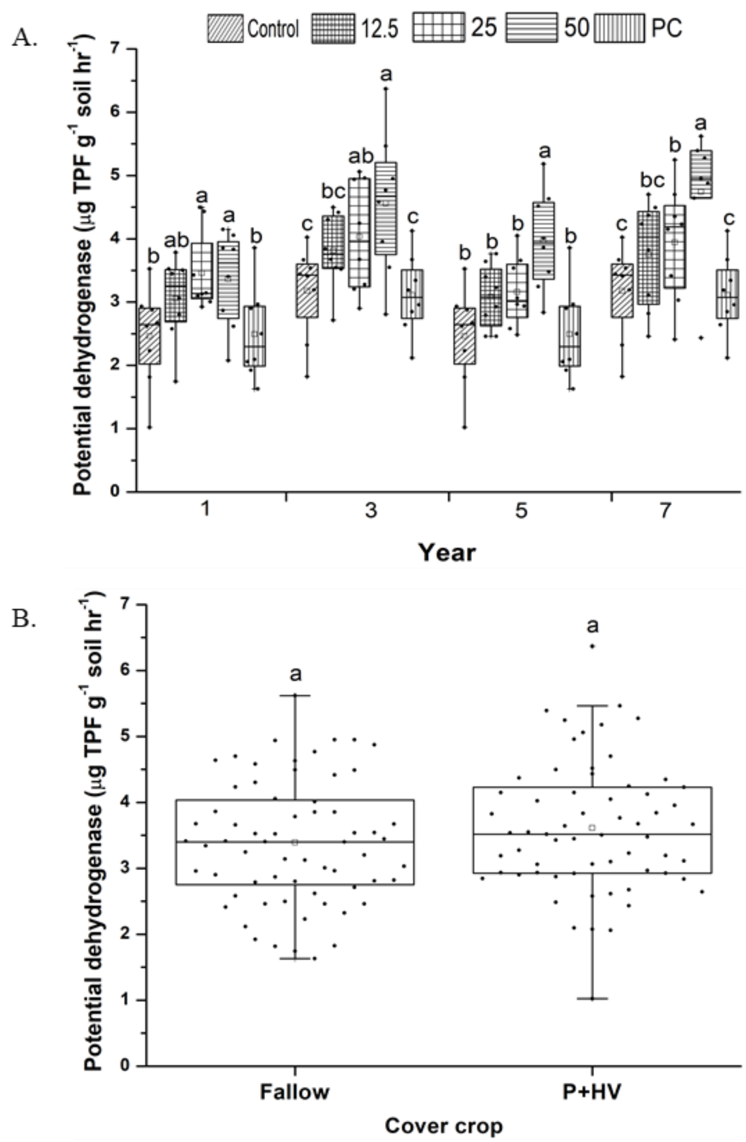


FIGURE 18 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on potential dehydrogenase activity (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

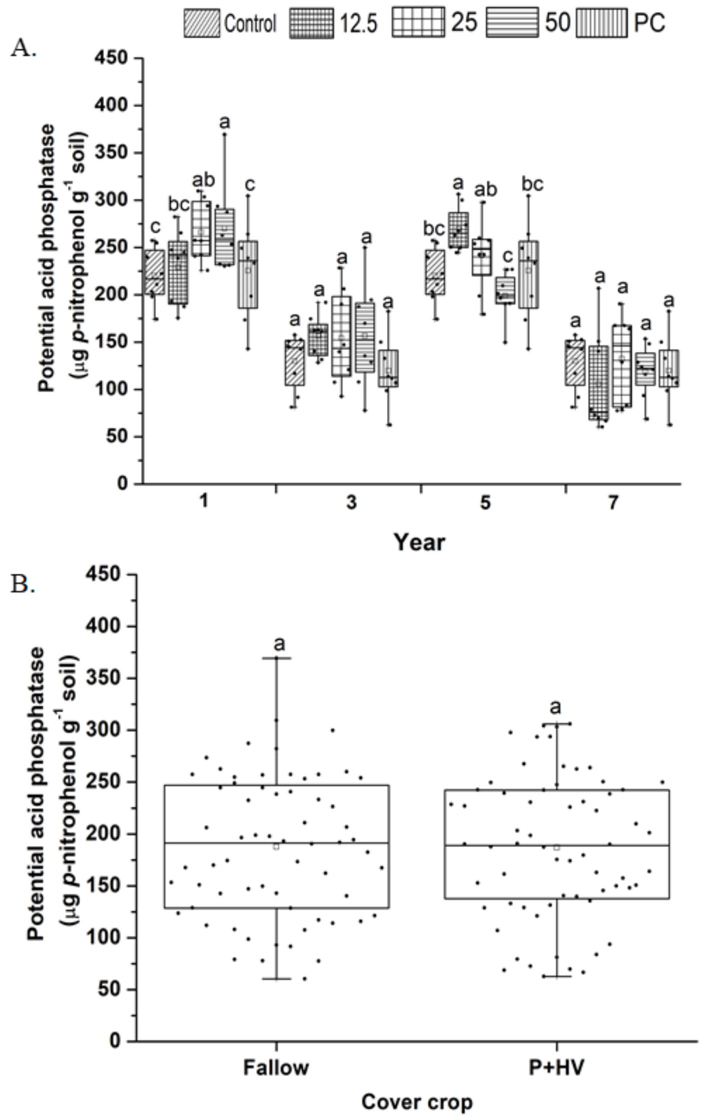


FIGURE 19 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on potential acid phosphatase activity (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

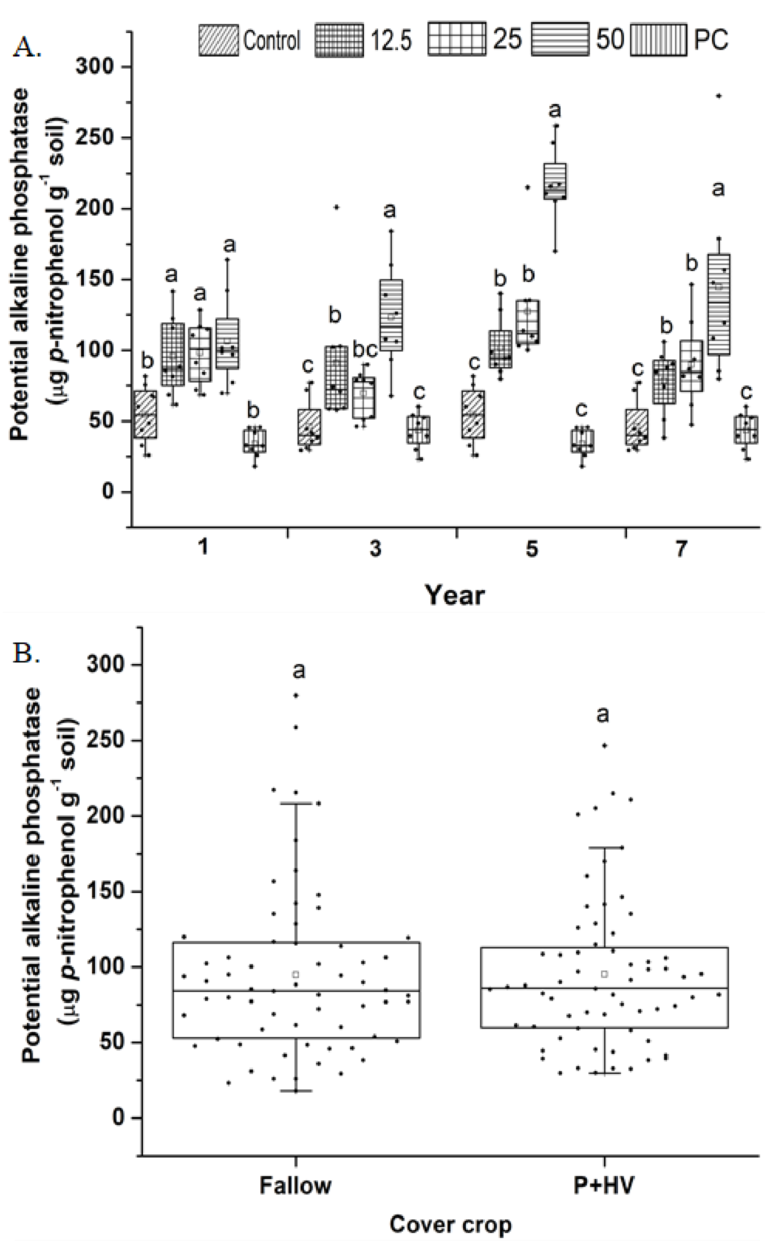


FIGURE 20 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on potential alkaline phosphatase activity (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

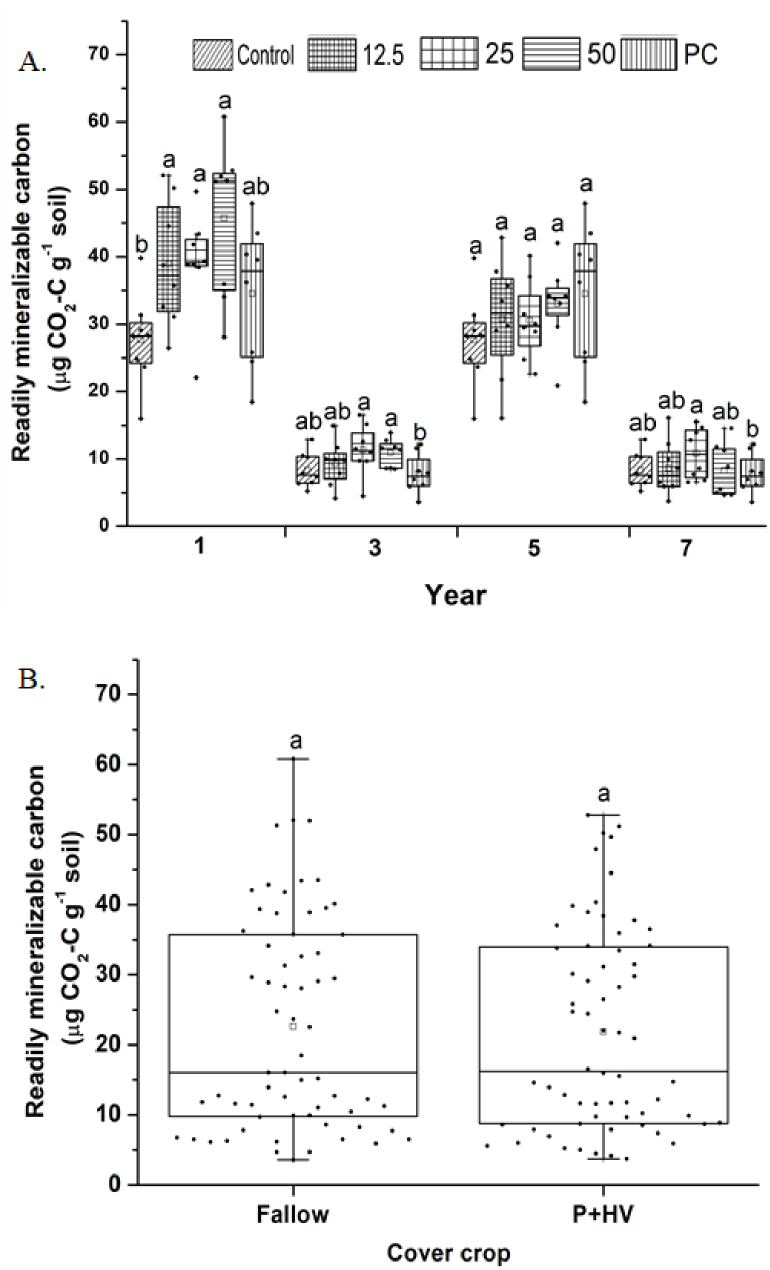


FIGURE 21 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on readily mineralizable carbon (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

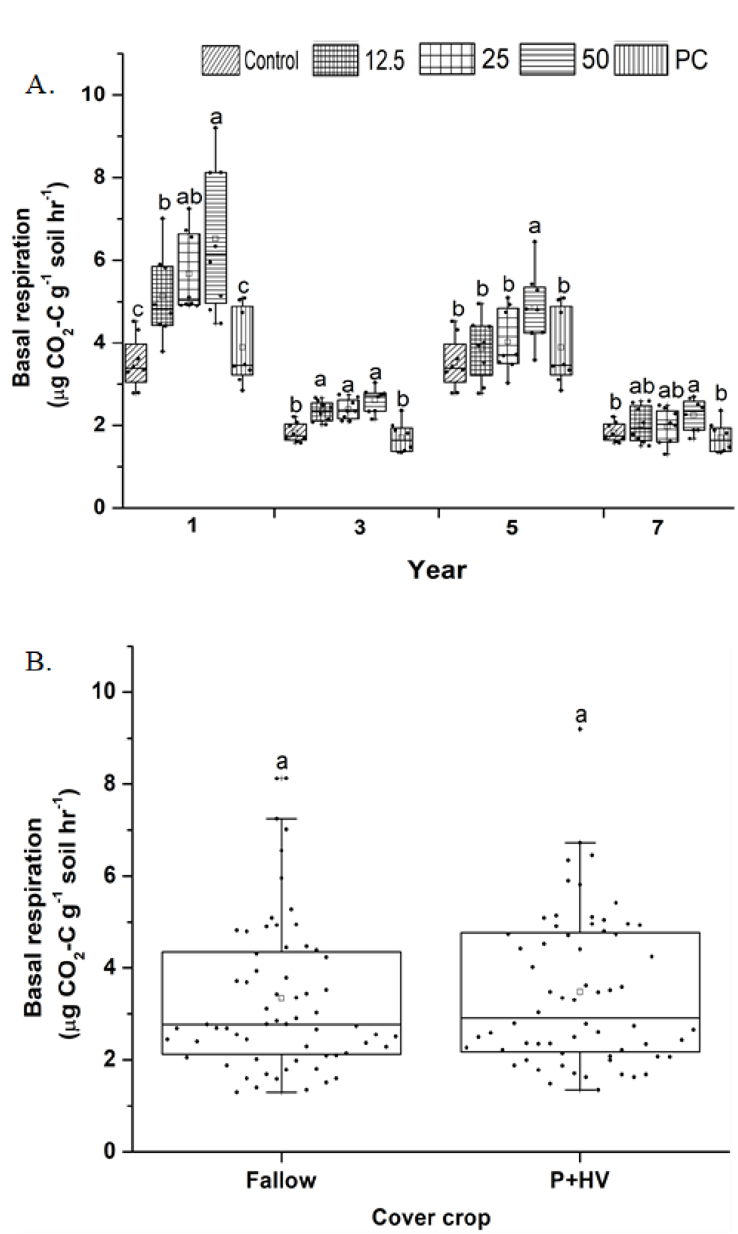


FIGURE 22 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on basal respiration (panels A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

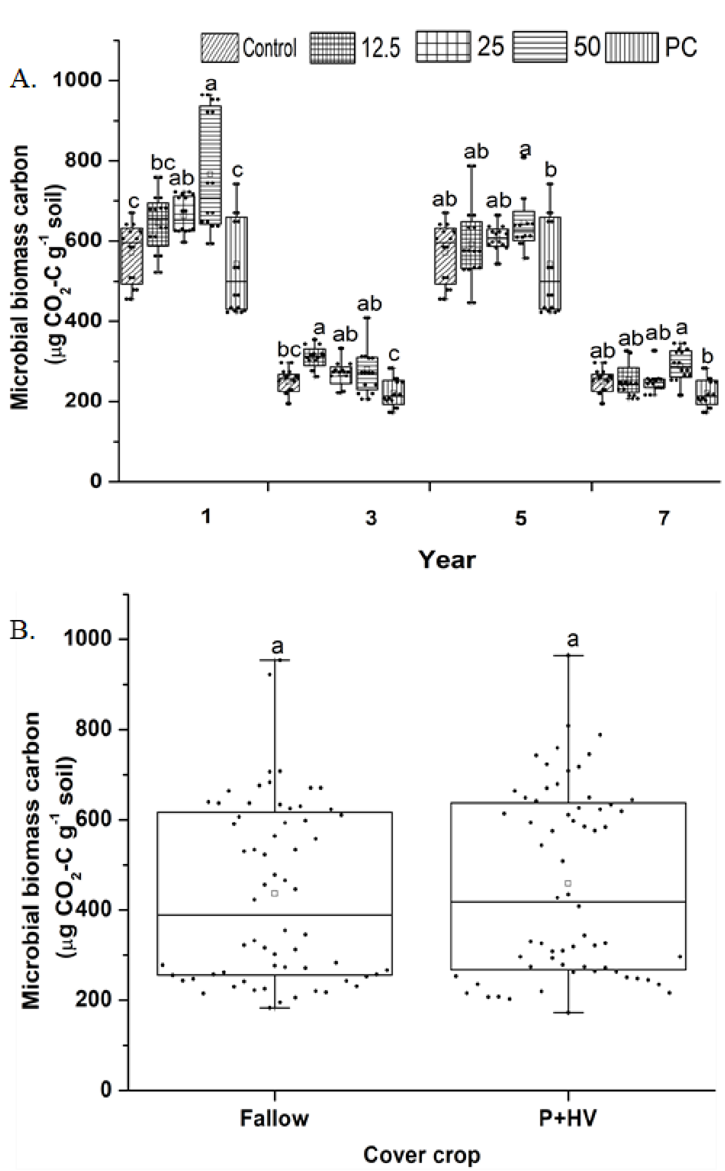
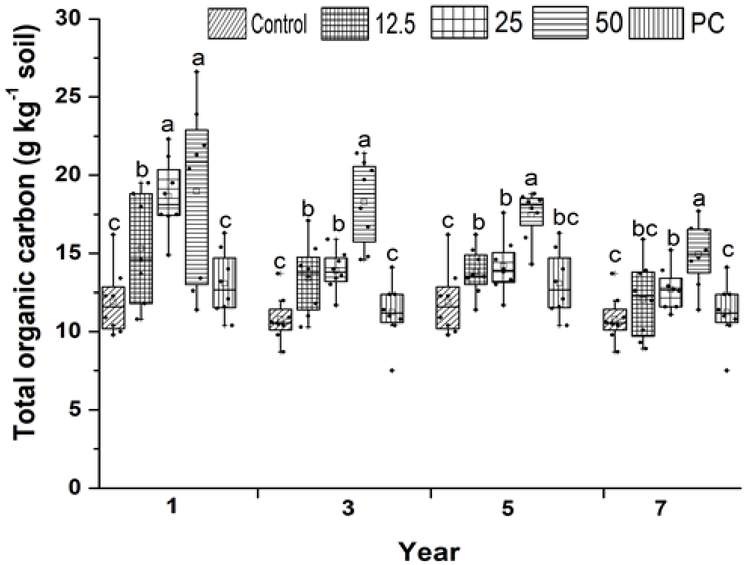


FIGURE 23 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on microbial biomass carbon (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

A.



B.

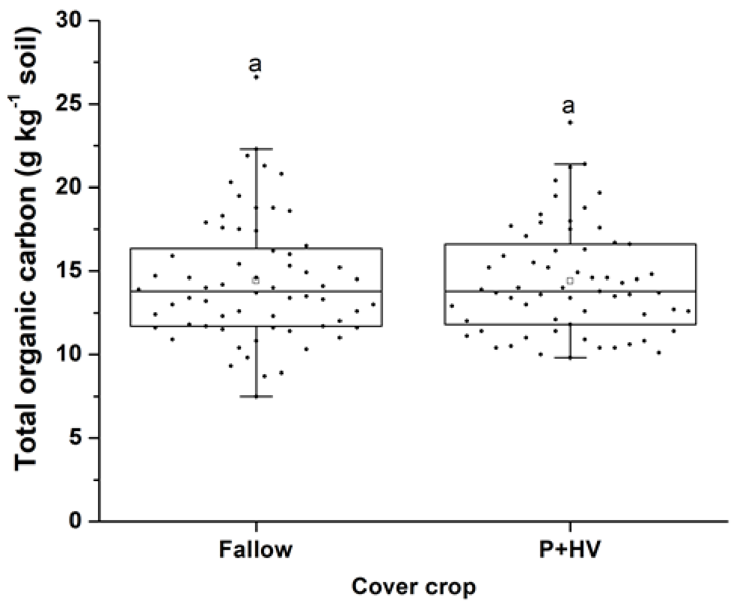


FIGURE 24 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on total organic carbon (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

A.

B.

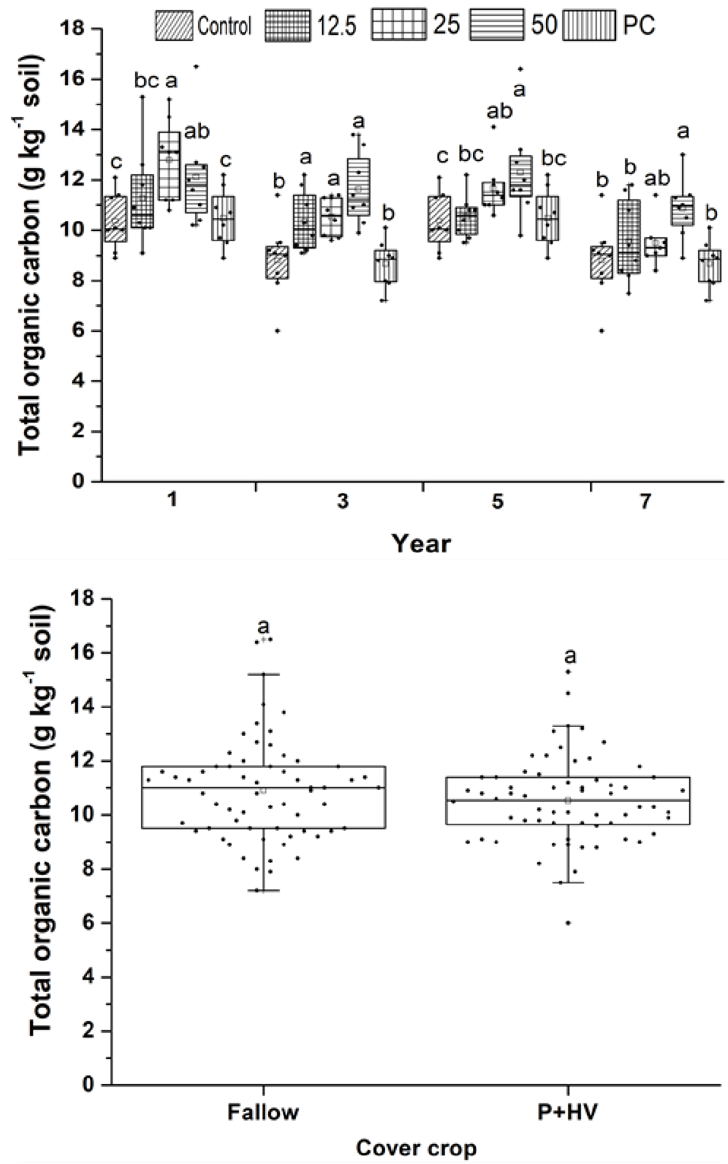


FIGURE 25 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on total organic carbon (panels A and B, respectively) in 0-30 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

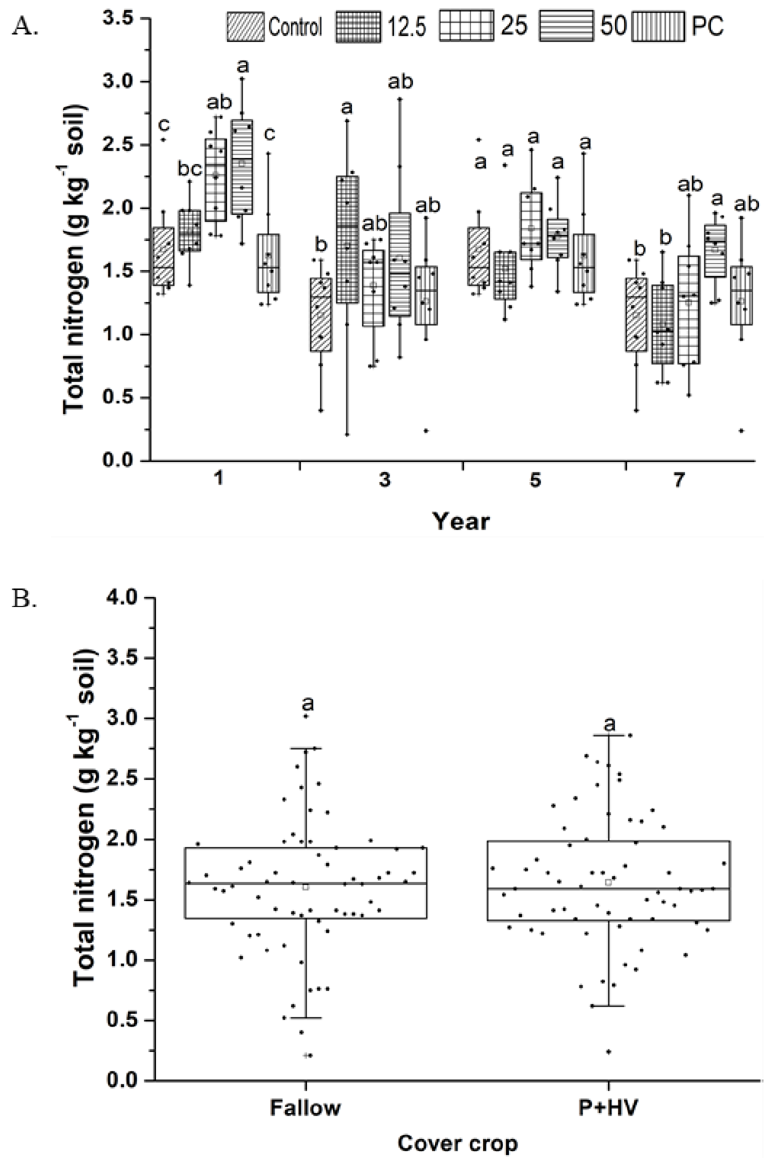


FIGURE 26 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on total nitrogen (A and B, respectively) in 0-10 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

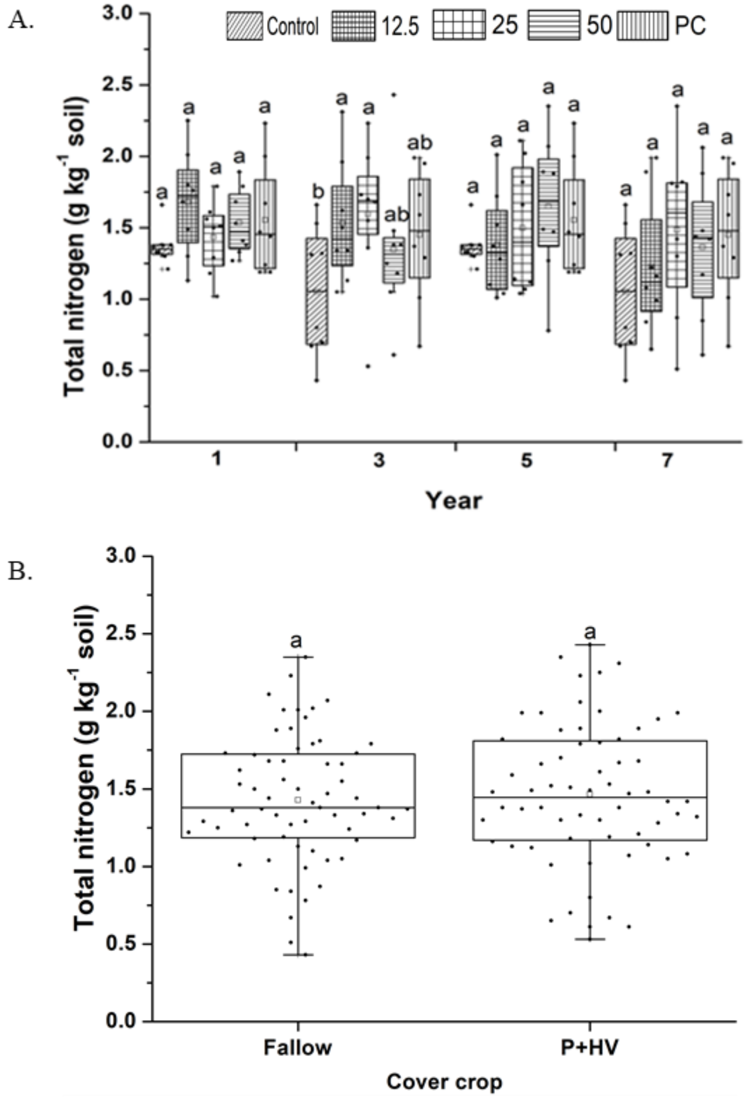


FIGURE 27 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on total nitrogen (A and B, respectively) in 0-30 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

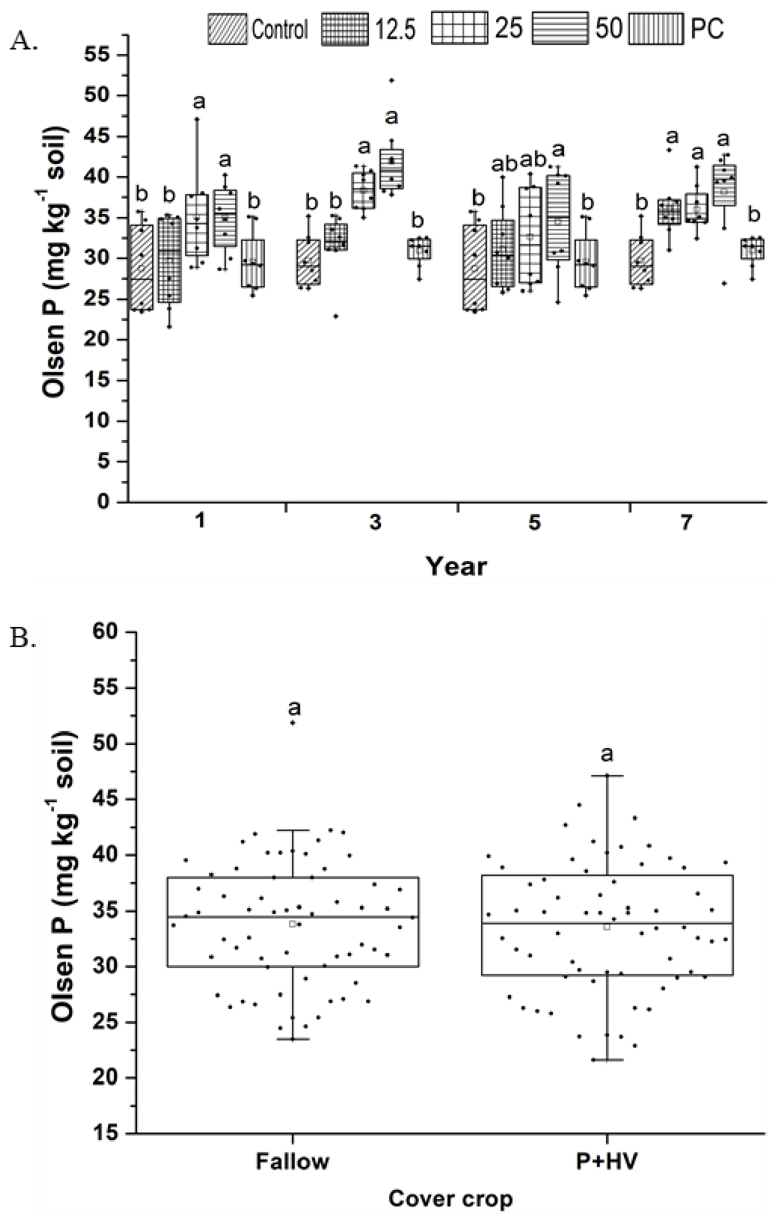


FIGURE 28 Main effects of compost (1, 3, 5, and 7 years) and cover crop (1 and 3 years) effects on Olsen P (A and B, respectively) in 0-30 cm at Blue Creek. Treatments with the same lower-case letters are not significantly different according to Tukey (0.05). PC = anhydrous ammonia.

CHAPTER III

PHOSPHORUS FRACTIONS IN ORGANIC DRYLAND SOILS FOLLOWING A ONE-TIME COMPOST APPLICATION

ABSTRACT

Low soil phosphorus (P) availability is a current challenge in organic dryland winter wheat systems in the Intermountain West, U.S. The goal of this study was to evaluate changes in inorganic and organic P pools following a one-time application of manure compost and its potential influence on short-term (3 yr) P bioavailability. Steer manure compost at 0, 25, and 50 Mg DW ha^{-1} was applied to two organic dryland sites with varying soil characteristics in northern Utah, USA, in a randomized complete block design. Potential phosphatase assays, a laboratory aerobic incubation study, and soil P fractionations were carried out to assess the transformation of P 1 and 3 years after a one-time compost application. Pathway analysis was performed to quantify the relationships among P pools. At 0-10 cm, compost application resulted in increased acid phosphatase at Snowville (67.3 vs 42.7 µg *p*-nitrophenol g^{-1} soil, p=0.0003), while alkaline phosphatase increased at Blue Creek (124 vs 49 µg *p*-nitrophenol g^{-1} soil, p=0.0185). Pathways of P differed between the sites as the path coefficient between compost P and labile P_i was significant at Snowville and not at Blue Creek. The residual P pool was a sink of soil P at Snowville but a source at Blue Creek. This study shows the variable impact of compost on the P cycle in organic dryland soils under winter wheat-fallow cultivation and could help farmers in making important decisions about sustainable long-term soil management practices.

Keywords: phosphorus, one-time compost, organic dryland, winter wheat-fallow, long-term, path analysis

1 | INTRODUCTION

The use of compost is a potential option for increasing the small readily available P pool for higher yield in organic dryland winter wheat-fallow (WW-F) systems in the semi-arid Intermountain West (IW). Neutral to alkaline soils are typical of organic dryland farms in the IW and low P availability is chiefly due to low use of fertility inputs, high sorption onto soil mineral surfaces, and precipitation of soil solution P (Wandruszka, 2006). Applied compost can increase P availability in WW-F systems where options of inexpensive organic soil inputs are limited (Rick et al. 2011). Greater P availability for plant use has been linked to increased photosynthetic capacity, dry matter accumulation, yield and decreased plant stress in WW systems (Chen et al., 2019; Rehm et al., 2003). Justifying the use of compost, however, is difficult for organic dryland WW-F farmers because of the high cost associated with the purchase and transportation of compost, and the inability to recoup the cost in the short-term (Reeve et al. 2012). However, Reeve et al. (2012) showed that the problem of P availability can be mitigated in the long-term by a single application of a relatively high amount of manure compost (50 Mg ha^{-1} DW compost) as it improved and maintained the availability of P and increased crop yield 16 years after application (Reeve et al., 2012). Although, the one-time use of compost in semi-arid WW-F systems offers promise to enhance P availability, its impact on soil P pools, which in part control P availability to plants, are not well understood. Understanding the effects of compost on soil P pools in organic WW-F systems is important considering the

spatial variability in soil characteristics and in helping the farmers make informed decisions.

Despite being present in large amounts in soils, P is known to be slightly soluble and low in availability to plants (Braschi et al., 2003; Sharma et al., 2013). This is because P can be sorbed onto clay surfaces and also complexed by Fe, Al, or Ca to form insoluble compounds complexes (Wandruszka, 2006). In organic dryland WW-F systems, P-availability is mainly reduced due to the precipitation of insoluble Ca-P as the soils are known to be rich in calcium carbonate (Braschi et al., 2003). Management practices that reduce P sorption and complexation, as well as increase P mineralization, can increase readily available P. For example, enriching a calcareous soil with organic matter has been shown to increase P solubilization by as much as 1.65 times (Braschi et al., 2003). Thus, the use of compost, which is rich in organic matter, can alter the chemical reactions that mediate the sorption and desorption of P in soils (Braschi et al., 2003). When compost decomposes in the soil, P sorption is decreased by low-molecular-weight organic acids that compete with the P binding sites (Yan et al., 2018). Furthermore, compost and manures can lower soil pH in alkaline soils, which affect $CaCO_3$ solubility and in turn P precipitation (Yan et al., 2016, 2018). However, maintaining P availability in the long-term in WW-F systems following compost application is a complex process that is affected by the compost effects on soil P pools, soil properties, and environmental perturbations. As P exists both in labile and non-labile inorganic (P_i) and organic (P_o) forms in soils, its transformation from one form to another could be rapid or gradual (DeLuca et al., 2015).

When applied to the soil, compost-P can end up in either the labile P pools or non-labile P pools, which may affect the potential short- or long-term effects of compost on P availability (González Jiménez et al., 2019; Tiessen et al., 1984; Zheng et al., 2004). The ultimate sink of the compost P or effects of the compost on soil P sorption/desorption depends greatly on the soil mineralogy, type, pH, exchangeable Ca concentrations and the decomposition rate of the organic material (Braos et al., 2020; Eghball, 2002; Kunito et al., 2012; Margenot et al., 2015; Penn et al., 2005; Ziadat et al., 2010). In a study evaluating the impact of compost on P pools, P added with compost preferentially enriched the labile P_i pool in soils with pH 5.2 to 7.7 (Gagnon et al., 2012). Elsewhere, Zheng et al. (2004) reported that the application of liquid manure had greater impacts on the labile P_o pools compared to the labile P_i pools in a soil with pH 5.6. Therefore, it is unknown if compost application will influence labile and non-labile P pools in neutral dryland WW-F soils in the same manner as in alkaline dryland soils. If the labile P pools are mostly affected immediately after compost application, then P will become available in excess to the plants in the short-term, thus potentially reducing its long-term impact. However, if the non-labile P pools are mainly affected following compost application, it could enhance the long-term benefits of compost on P availability.

To determine the short-term (3-yr) effects of a one-time application of compost on soil P pools and the relationships between the P pools, we assessed the effects of compost on labile and non-labile P pools in two dryland organic WW-F soils. We then determined the relationship between the compost P and soil P pools. The objectives of this study were to understand i) the biological mineralization of P, and ii) the effect of compost P on P

pools and the relationship between the P pools, 3 years after the one-time application of compost to organic dryland WW-F in the IW. We hypothesized that the effect of compost P will be greater in non-labile pools in soils with pH 8.0 and labile pools in soils with neutral pH.

2 | MATERIALS AND METHODS

2.1 | Study sites and treatments

Two long-term experiments in organic dryland winter wheat-fallow rotation were initiated at the Utah State Agricultural Experimental Station in Blue Creek, Utah (41°56’ N, 112°25’ W) in 2011 and a cooperator farmer’s field near Snowille, Utah (41°53’ N, 112°46’ W) in 2016. The climate of the region is semi-arid, but the sites have varying microenvironment conditions and soil characteristics.

The Blue Creek site was previously used for commercial fertilizer trials and was transitioned to organic beginning in 2011 and was certified organic in 2017. The soil is classified as a Parleys silt loam (fine-silty, mixed, superactive, mesic Calcic Argixerolls) based on the USDA soil classification and belongs to the soil order Mollisols with a slope of 6-10 %. The total annual precipitation and total annual potential evapotranspiration for 2016-17 and 2018-19 cropping cycles are 515 and 455 mm, and 1133 and 1114 mm, respectively (Utah Climate Center, 2020). The second experimental site at Snowville was established in 2016 on a certified organic dryland farm. The site was certified organic since the early 1990s and has retained its organic certification. The soil is calcareous Thiokol silt loam (fine-silty, mixed, active, mesic Sodic Calcixerepts) based on USDA soil classification and belongs to the soil order Inceptisol with a slope of 0-1 %. The total

annual precipitation and total annual evapotranspiration for 2016-17 and 2018-19 cropping cycles are 342 and 296 mm, and 1107 and 1071 mm, respectively (Utah Climate Center, 2020). Snowville has an aridity index between 4.3 to 4.7 while Blue Creek's index is between 2.8 and 3.2. Regions with higher aridity index are generally drier (Arora, 2002).

At Blue Creek, fresh additions of compost were applied to previously unamended plots within the existing RCBD in 2016. At this site, compost rate (0, 12.5, 25, and 50 Mg DW ha^{-1}) was the whole plot, and cover crop (winter pea/hairy vetch and fallow control) was the split-plot while in Snowville cover crop (winter pea *plus* hairy vetch and fallow) was the whole plot, and compost (0, 12.5, 25, and 50 Mg DW ha^{-1}) was the split-plot. For this experiment, samples were collected from the plots that received 0, 25, and 50 Mg DW ha^{-1} compost once in 2016. Wheat was planted in November at 78 kg ha^{-1} and two tillage passes were carried out to control weeds in May and June in the fallow plots. In August, the plots were disked to about 15-20 cm to turn over residues.

2.2 | Soil sampling

Initial soil samples (0 to 30 cm) were collected and analyzed for chemical properties in April 2011 (Blue Creek) or September 2015 (Snowville). The initial soil characteristics at Blue Creek were pH 6.8, soil organic carbon and total nitrogen, 9.6 and 1.32 g kg^{-1}, respectively, and Olsen P, 38.1 mg kg^{-1}. At Snowville the initial soil characteristics were pH 8.5, soil organic carbon and total nitrogen 10.7 and 1.28 g kg^{-1} respectively, and Olsen P, 4.98 mg kg^{-1}. Soil samples were collected from both sites in April/May during the 2016-2017 and 2018-2109 crop cycles prior to crop harvest. Six soil cores were randomly taken

within each plot across 0 to 10 and 10 to 30 cm depths using a soil probe 2.45 cm in diameter. The soil cores taken per plot were combined by depth and thoroughly homogenized, and a sub-sample was taken, placed in a polythene bag and transported to the laboratory on ice. The soil samples were sieved through a 2 mm-mesh sieve, air-dried, and stored at room temperature until analysis.

2.3 | Soil phosphatases assay and bioavailable P

To characterize the enzyme activities associated with organic P mineralization, potential soil acid and alkaline phosphomonoesterase (Tabatabai, 1994) and phosphodiesterase (Browman & Tabatabai, 1978) activities were quantified using a colorimetric *p*-nitrophenyl-ester-based method. Briefly, for the determination of phosphomonoesterases, 1.0 g of air-dried soil was placed in 15 mL centrifuge tubes and mixed with 4.0 mL modified universal buffer (MUB) (pH 6.5 for acid and pH 11 for alkaline), and 1.0 mL disodium *p*-nitrophenyl hexahydrate solution (excluding controls), vortexed and incubated at 37˚C for 24 hours. After incubation, the reaction was stopped by adding 1.0 mL of 0.5 M $CaCl_2$ and 4.0 mL 0.5 M NaOH to both samples and controls. Thereafter, disodium *p*-nitrophenyl phosphate solution was added to controls only. For phosphodiesterase assay, tris-hydroxymethl-aminomethane (THAM, pH 8.0) was added as the buffer solution followed by 1.0 mL *bis*-*p*-nitrophenyl phosphate (BPNP) solution (excluding controls), vortexed and incubated at 37˚C for 24 hours. The reaction was stopped using 1.0 mL of 0.5 M $CaCl_2$ and 4.0 mL 0.1 THAM-0.5 M NaOH (pH 12). Thereafter, samples were vortexed and centrifuged for 5 mins at 4000 rpm. The concentration of the *p*-nitrophenol released from both assays was determined by

absorbance at 405 nm with a microplate reader (SpectraMax M2, Molecular Devices, Sunnyvale, California). Control readings were subtracted from each sample and the µg p-nitrophenol g^{-1} dwt was quantified using a standard curve.

To assess potential microbial activity effects on bioavailability of P, bioavailable P index (BioP) was determined as described by Thien and Myers (1992) and modified by Appelhans et al. (2016). Approximately 4 g of soil was weighed into 60 cm^3 sterilized vials and incubated with 2 mL 10:1 C + N solution (0.44 M dextrose and 0.24 M NH_4Cl) for 7 days at 35 ˚C to create a biological sink for P. After incubation, the samples were divided into two sets. To set A (unfumigated) samples, 40 mL 0.5 M $NaHCO_3$ was added and labile inorganic P (LP_i) and total extractable P (TP_e) were determined in the extracts. For total extractable P determination, 5 mL of the extract was placed in a digestion flask and 0.8 g $K_2S_2O_8$ and 2 mL 5.5 M H_2SO_4 were added and digested for 30 mins at 150 ˚C until a clear solution was formed (Bowman, 1989). Labile organic P (LP_o) was calculated as the difference between total extractable P and inorganic P. Soils in set B were fumigated using 2 mL hexanol for 36 h and left to evaporate for another 12 h (Schneider et al., 2017). Thereafter, the soil was extracted using 40 mL 0.5 M $NaHCO_3$. The extracted inorganic P after fumigation is a combination of inorganic P and microbial P (LP_{i+mic}) released from microbial cells after lysis with hexanol. Microbial P was determined as the difference between LP_{i+mic} and P_i and a recovery factor of 0.4 was applied (Mclaughlin et al., 1986).

$LP_o = TP_e - LP_i$

$P_{mic} = (LP_{i+mic}) - LP_i$

$BioP = LP_o + P_{mic} + LP_i$

2.4 | Sequential phosphorus fractionation

To quantify the P concentration in the different P pools, soil samples were sequentially extracted using a P fractionation procedure described by (Hedley et al., 1982) and modified by (Mao et al., 2015). Briefly, 1 g of air-dried soil was placed in a 50 ml centrifuge tube and sequentially extracted using 20 mL 0.5 M $NaHCO_3$ (pH 8.5), 50 mL 0.5 M NaOH and 50 mL 1 M HCl. Thereafter, residual P was determined by combusting the soil at 550 ˚C and extracted with HCl. In each of these steps, the solvents selectively isolate P pools of different solubilities. The total P (TP) in each fraction was determined by digesting 5 mL aliquots with potassium persulfate and sulfuric acid at 150 ˚C (Nelson, 1987). Organic P was calculated as the difference between the TP and inorganic P (P_i).

The different P_i and P_o pools extracted and grouped based on increasing recalcitrance include: (1) labile P_i ($NaHCO_3$-P_i), which includes loosely adsorbed P_i by Al-Fe bound P, (2) moderately labile P_i (NaOH-P_i), which includes moderately sorbed P_i by Al-Fe bound P, (3) labile organic P_o ($NaHCO_3$-P_o + NaOH-P_o), (4) stable P (HCl-P_i+P_o), which includes Ca bound P, and (5) residual P, which includes organometallic complexes. Total inorganic P was the sum of all inorganic P pools and residual P, while total organic P was the sum of all the organic P pools. The TP was the sum of all the seven P pools (Cross & Schlesinger, 1995; González Jiménez et al., 2019; Mao et al., 2015; Zheng et al., 2001).

The orthophosphate concentration in all extracts was determined using the malachite green colorimetric procedure at 630 nm (D'Angelo et al., 2001). To quantify the concertation of P_i in digested samples, the pH of the digested extracts was adjusted with 5 drops of *p*-nitrophenol and 4 N NaOH before the determination for the orthophosphate concentration using malachite green colorimetric procedure (Nelson, 1987).

2.5 | Statistical analysis

To analyze the main effect of a one-time compost application on P enzymes, potential bioavailable P, and P pools, the data was checked for normality and homogeneity of variance and transformed where necessary. Each site and depth were analyzed separately. The data was analyzed as one-way ANOVA with repeated measure. The fixed factor effect in the model was compost and year after application was included as repeated measure. The random effects were block and plot. The analysis was done using PROC GLIMMIX in SAS Studio University Edition (version 9.4, SAS Institute, Cary, NC, USA). Path analysis was used to investigate relationships between the P pool sizes and manure added P. Conceptual models were developed after González Jiménez et al. (2019) with manure compost P as the independent variable (exogenous) and P pools as the dependent variables (endogenous and exogenous) (Figure 3). The data was transformed using either log or square root transformations to normalize the data. Path analysis comprises of linear regression equations and the coefficients referred to as path coefficients (β). The conceptualized model for each site was tested and modified by either dropping non-significant paths or including significant paths and standardized units were calculated for the paths. Chi-square Test, Bentler-Bonett NFI, Bentler Comparative Fit Index, and Root

Mean Square Error of Approximation (RMSEA) were used to assess the fitness of the conceptual model to the graphical representation. Path analysis was carried out using R studio, Version 1.2.5019 (RStudio, Inc) using both “lavaan” and “semPlot” packages (Rosseel, 2012).

3 | RESULTS AND DISCUSSION

3.1 | Effects of compost on soil phosphatase enzymes

The amount of potential phosphomonoesterase activity varied between the two sites. At Snowville, lower acid phosphatase activity was measured at the 0-10 and 10-30 cm depth compared to Blue Creek. Conversely, greater alkaline phosphatase activity was measured at Snowville compared to Blue creek at both depths (Tables 2 and 3). Acid phosphatase is known to be predominant in soils with pH 7 or less while alkaline phosphatase is predominant in soils with alkaline pH i.e. greater than 7 (Dick et al., 2000; Eivazi & Tabatabai, 1977; Nannipieri et al., 2011). Our result showed that compost had a significant effect on acid phosphatase (p=0.000) at Snowville and alkaline phosphatase (p=0.019) at Blue Creek in the top 10 cm soil layer (Table 2). At the 10 to 30 cm soil depth, acid phosphatase at 50 Mg DW ha^{-1} (73.1 µg *p*-nitrophenol g^{-1} soil) at Snowville was greater (p=0.019) than the control and 25 Mg DW ha^{-1} compost rates (50.3 and 51.2 µg *p*-nitrophenol g^{-1} soil) while there was no significant compost effect on alkaline phosphatase (Table 3). Whereas, at Blue Creek, compost application did not have a significant impact on either acid or alkaline phosphatase at the 10 to 30 cm soil depth (Table 2). This suggests that the compost effect on the inherently more active phosphomonoesterase enzyme is less pronounced than on the less active type of

phosphomonoesterase enzyme. The greater effects of compost on acid phosphatase suggest that compost contributed strongly to biological transformation of P at Snowville compared to Blue Creek. This could be due to the inherent high organic P mineralization at Blue Creek as reflected in the higher amount of acid phosphatase. Earlier studies have demonstrated that acid phosphatase mineralizes organic P more compared with alkaline phosphatase (Dick & Tabatabai, 1978).

The phosphodiesterase activity at Snowville ranged from 30.7 to 34.9 and 31.7 to 33.9 µg *p*-nitrophenol g^{-1} soil at the 0 to 10 and 10 to 30 cm soil depths respectively, while at Blue Creek it ranged from 5.5 to 11 and 8.5 to 10.3 µg *p*-nitrophenol g^{-1} soil at the 0 to 10 and 10 to 30 cm soil depths, respectively (Table 4). The lower phosphodiesterase activity compared to acid and alkaline phosphatase is consistent with earlier studies (Eivazi & Tabatabai, 1977; Nannipieri et al., 2011; Turner & Joseph Wright, 2014). At Blue Creek, phosphodiesterase activity at the top 10 cm soil depth was highest at 50 Mg DW ha^{-1} and was different from control plots. The data were averaged over the two years due to a lack of a compost x year interaction, indicating rapid transformation of organic P under amended plots. Compost did not have a significant effect on phosphodiesterase activity at 10 to 30 cm soil depth at Blue Creek and at both soil depths at Snowville. Similarly, adsorption of phosphodiester compounds such as DNA has been shown to increase with increasing concentration of calcium in soil solutions, which forms a cationic bridge between negatively charged clay surfaces and DNA (Poly et al., 2000). Phosphodiesterase precedes phosphomonoesterases in organic P transformation, apparently indicating enhanced mineralization of organic P at Blue Creek

(Browman & Tabatabai, 1978; Nannipieri et al., 2011; Turner & Haygarth, 2005). Dissimilar phosphodiesterase response to compost amendment may be due to enzyme stabilization on soil surfaces, changes in the scale of microbial activity or abiotic conditions such as soil pH, and moisture (Margenot et al., 2018). Soil enzymes can be adsorbed onto clay particles leading to a reduction in their activity (Olsson et al., 2012).

3.2 | Potential bioavailable P content

At the 0 to 10 cm soil depth, compost increased potential BioP at Blue Creek ($p=0.02$) and Snowville ($p=0.013$) (Figure 1), while at the 10 to 30 cm soil depth, compost addition increased potential BioP at Blue Creek but not at Snowville (Figure 2). Comparing the two years, potential BioP at Blue creek was higher ($p=0.001$) during year 3 than year 1 but there were no differences ($p=0.617$) between the years at Snowville. Compost effect on potential BioP was higher at Blue Creek (90-173 mg kg^{-1}) compared to Snowville (23-64 mg kg^{-1}). Likewise, at 10 to 30 cm soil depth, Blue Creek (62-125 mg kg^{-1}) had higher potential bioavailable P than Snowville (24-37 mg kg^{-1}). This result supports our hypothesis that the potential P bioavailability following compost application will be greater in soils with higher soil fertility and annual precipitation due to lower microbial P immobilization. The Blue Creek site, which is relatively more fertile with higher annual precipitation and lower calcium carbonate, has higher bicarbonate-extractable P_i (mean 30 mg kg^{-1}) and lower risk of P loss via precipitation or immobilization. However, the Snowville site, which is drier with higher calcium carbonate content, has a mean of 7 mg kg^{-1} bicarbonate-extractable P_i. An earlier study by Duda et al. (2013) showed that bioavailable P was higher (77-115 mg kg^{-1}) in

grassland soils with high soil organic matter and bicarbonate-extractable P_i (34.5-123 mg kg^{-1}) compared with soils with low available P (1.3-6.0 mg kg^{-1}; BioP: 7.9 to 24.4 mg kg^{-1}). Appelhans et al. (2016) also reported lower bioavailable P (8.1-24 mg kg^{-1}) across 7 sites under a no-till rotation of corn-soybean–double-cropped wheat cultivation with bicarbonate-extractable P_i between 4.8 and 7.4 mg kg^{-1}.

In our study, the contribution of inorganic P to BioP was highest at both sites at the 0 to 10 cm soil depth (Figure 1). Whereas at 10 to 30 cm, inorganic P was the major contributor at Blue Creek while organic P and microbial P were the major contributors to BioP at Snowville (Figure 2). Duda et al. (2013) found that Pmic contributed more to BioP, indicating that microorganisms can access P adsorbed to soil surfaces and immobilize it. The higher contribution of inorganic P to BioP suggests that microorganisms had access to more P than required for functioning, as such, the excess P is released back into the soil environment.

3.3 | Effect of compost application on soil total P pools

Sequential fractionation procedure, despite its limitations, has been widely used to study the P forms in soils by separation into operationally defined pools (Fan et al., 2019; Hedley et al., 1982; Negassa & Leinweber, 2009). Compost effect on total P persisted in the top 10 cm at both sites while a significant increase at the 10 to 30 cm soil depth was observable only at Snowville. Over the two cropping cycles, total P increased from 1035 to 1379 mg P kg^{-1} at Snowville and 880 to 1444 mg P kg^{-1} at Blue creek at the 0 to 10 cm soil depth (Table 5). The soil total P at Snowville was higher under 50 Mg DW ha^{-1} (1118 mg P kg^{-1}) compared to the control and 25 Mg DW ha^{-1} (927 and 985 mg P kg^{-1})

treatments at the 10 to 30 cm depth but there were no differences at Blue Creek (Table 6). A significant increase in soil total P has been reported in the presence of large applications of organic amendments. In a 16-year study with repeated application of cattle manure at 30 Mg DW ha^{-1}, the application of 1.6 Mg P ha^{-1} increased soil total P (Whalen & Chang, 2001). Similarly, in a 5-year study with repeated application of cattle manure, (Qian et al., 2004) reported an addition of 622 kg P ha^{-1} from 32 Mg DW ha^{-1} cattle manure. Our results showed that when 25 and 50 Mg DW ha^{-1} compost were added the P input was 0.58 Mg P ha^{-1} and led to an average of 0.413 Mg P ha^{-1} increase in total P in the 0 to 10 cm depth across both sites. At Snowville compost application at 50 Mg DW ha^{-1} increased the soil total P by 0.22 Mg P ha^{-1}. The lack of measurable increases in total P at 10 to 30 cm depth at Blue Creek could be linked to a combination of surface loss of compost derived P due to water erosion as the Blue Creek site is located on a slight slope while Snowville is nearly level (Farias et al., 2018) and the initial total P as observed in control plots.

3.4 | Distribution of soil P fractions

Compost P applied was in excess of the winter wheat P requirement for more than eight growing seasons (869 and 1739 kg P ha^{-1}) (Reeve et al., 2012). In general, P pools responded differently to compost applications across the two sites. We hypothesized that the effect of compost P will be greater in non-labile pools in soils with pH 8.0 and labile pools in soils with neutral pH due to a higher rate of P cycling because of the more conducive environmental condition for microbial activities in the latter. The magnitude of change in labile P_i pool concentration at 0 to 10 cm was comparable across both sites

(Table 5). Compost addition had a persistent effect on labile P_i at both sites, which made up 2-3 % of the total P at Snowville and 3-4 % of the total P at Blue Creek. At Snowville, labile P_i was increased by 17 and 20 mg kg^{-1} over the control while at Blue Creek labile P_i was increased by 18 and 27 mg kg^{-1} over the control at the 0-10 cm depth. Similarly, significant increases in labile P_i were also observed at 10 to 30 cm at Snowville (2.3 and 7.1 mg kg^{-1}) and Blue Creek (4.4 and 8.6 mg kg^{-1}) in response to compost. Increases in labile P_i concentration were higher at Blue Creek which has a higher baseline Olsen P concentration (31.6 mg kg^{-1}) than at Snowville (8.7 mg kg^{-1}). The differences in increases in the labile inorganic P pool reflects the variation in mineralization of compost P.

Moderately labile P_i contributed 3.2-4.4 % and 6.0-9.7 % of total P at Snowville and Blue Creek, respectively. Moderately labile P_i did not show any change after the single application of compost across the two sites. Few changes to the moderately labile pool after five years of continuous manure application have been reported by Qian et al. (2004). Similarly, changes in the labile P_o pool were not statistically significant at either site. Irrespective of the site, stable P contributed most to total P, about 73 % observed at Snowville and 53-73 % at Blue Creek. Our results showed that stable P was significantly increased by compost addition across both sites at the 0 to 10 cm depth. At the 10 to 30 cm depth, significant (p=0.035) increase was observed in the stable P at Snowville but not at Blue Creek following compost application. This suggests that P inputs via compost application may have little or no impact on the forms of P at 10- to 30-cm depth at Blue Creek (Sharpley & Moyer, 2000). The variation in the magnitude of compost effect

between the sites on the stable P pool at the 10 to 30 cm depth could be explained by differences in the sorption and retention capacities between the soils.

Previous studies have reported increases in labile P_i and total P pools following manure or manure compost application and little or no changes in moderately labile P_i and stable P pools (Hao et al., 2008; Kashem et al., 2004; Qian et al., 2004). Increased concentrations of the stable P pools at Blue Creek suggests a rapid rate of compost decomposition and P transformation. This means the long-term impact of compost is likely to be short-lived at Blue Creek. Thus, compost P has the potential to have long-term benefits particularly in drier sites of dryland soils (Matar, 1977).

3.5 | Pathways of P pools

Data generated from P fractionation was used in path analysis to distinguish the direct and indirect relationships between the P pools and compost P. We hypothesized that since soil properties controlling P solubility varied between the sites, the pathways of P pools will be different between the studied soils (Figure 3). Our results show that the pathways of P transformation and manure compost P are apparently different between the two soils studied as shown in Figures 4 and 5. The standardized path coefficients which describe the interrelationships between the manifest variables are adjacent to the arrows (Figure 4-5).

Manure compost P had different effects on labile P_i pools at both sites. The effect of compost P on labile P_i was significant at Snowville (β=0.24, p=0.04) compared with Blue Creek (β=0.11, p=0.17), thus suggesting that the contribution of compost P to the

replenishment of the labile P_i pool is greater in more marginal dryland soils (Figures 4-5). The stable P pool acted as a source for labile P_i pool, with a greater contribution at Blue Creek (β=0.82, $p<0.001$) than Snowville (β=0.57, $p<0.001$), probably because of the formation of Ca-P precipitates at Snowville. In semi-arid dryland soils, the solubility of Ca compounds controls the availability of P, which is mediated by pH, redox potential, and microbial activities (Reddy et al., 2015).

The direct relationship between manure compost applied P and moderately labile P_i was not significant at either site. However, the direct relationship between moderately labile P_i and labile P_o was inverse and significant (β=-0.31, p=0.02) at Blue Creek but not at Snowville. There was a significant direct relationship (β=0.53, $p<0.001$) between moderately labile P_i and stable P at Snowville but not at Blue Creek. The labile P_o acted as a sink for manure compost P at both sites. At Snowville, 67 % of the variation in labile P_o could be explained by manure compost ($p<0.001$) compared to about 32 % at Blue creek (p=0.03), suggesting that compost P influence on organic P pools is greater in more marginal dryland soils. Similar results were reported by Zheng et al. (2002) following the application of liquid dairy manure in a short-term barley-forage rotation. The labile P_o was negatively related to stable P at Snowville (β=-0.38, $p<0.01$), and to residual P Blue Creek (β=-0.31, $p<0.02$) (Figures 4-5). Earlier studies have shown residual P to act as a source for labile P_o pools in Mollisols (Zheng et al., 2004).

The stable P pool acted as a sink for manure compost applied P (β=-0.47, $p< 0.001$) at Snowville while there was no direct or indirect relationship between the stable P pool and manure compost P pool at Blue Creek. The results also indicated that residual P acted

as a sink for moderately labile P_i and labile P_o (β=0.38, $p<0.001$ and β=0.57, $p<0.001$, respectively) at Snowville. Furthermore, the direct relationship between stable P and residual P was not significant but the indirect relationship through the moderately labile P_i pool was significant (β=0.20, p=0.014). This shows that P transformation between resilient pools occurs in low P soils and indicates the tendency of available inorganic P to be immobilized in more occluded P pools, which may potentially become available in the long-term.

Thus, the long-term potential benefits of compost P is likely to be greater in low P soils, where rapid transfer of P into resilient P pools occurs in the short-term, compared to soils with high available P, where rapid transfer into labile P pools occurs. The potential for P immobilization and sorption is greater in soils with low available P because of high alkaline pH compared to soils with relatively higher available P and neutral pH. Significant changes in labile $NaHCO_3$-P_i and P_o following the long-term application of organic and conventional fertilizers in a calcareous soil has also been reported to be mediated by initial soil P concentration (Romanyà & Rovira, 2007) but a threshold is yet to be defined. As microbial demand for P is low, additional P added via compost tends to be mineralized than immobilized in soils with adequate P sufficiency levels and any immobilized P can become available rapidly. Furthermore, in alkaline soils with high P sorption capacity and potential microbial immobilization, changes in soil structure and moisture availability following compost application can affect oxidation-reduction reactions and alter P sorption and availability over time (Pierzynski et al., 2015).

4.0 | CONCLUSION

Determining which P pools are more responsive to compost could assist organic dryland WW-F farmers in making important decisions as they decide between investing in compost or land for long-term economic gains. Understanding the short-term bioavailability of P in agricultural systems with low soil fertility inputs and bioavailable P is important in making economically viable long-term management decisions. The focus of this study was to assess changes in P pools and how it is affected by soil properties following a single application of compost in organic dryland winter wheat-fallow systems in the IW. In the soils with low available P, the potential bioavailable P was lesser, indicating that microbial release of P is strongly influenced by variation in adsorption capacity between the soils. The pathways of transformation of P pools were also dissimilar between the sites and indicated that in soils where available soil P was high, the potential long-term effects of compost on legacy P may be suppressed. In the more marginal dryland soil, compost P had a direct effect on labile P_i but not at Blue Creek. Potential trends in the pathways of P cycling between the sites may have been impeded due to the short period of the study. Consequently, further studies are needed to capture undetected P transfer pathways with time following manure compost application in organic dryland winter wheat-fallow systems. In conclusion, by investigating changes in P pools and pathways, our work shows that the effect of a one-time compost application on long-term P availability in organic dryland grain agriculture is controlled by variation in localized climate and soil characteristics with potential for long-term benefits in drier areas with alkaline pH.

REFERENCES

Appelhans, S. C., Melchiori, R. J., Barbagelata, P. A., & Novelli, L. E. (2016). Assessing organic phosphorus contributions for predicting soybean response to fertilization. *Soil Science Society of American Journal*, *80*, 1688–1697. doi:10.2136/sssaj2016.04.0130.

Arora, V. K. (2002). The use of the aridity index to assess climate change effect on annual runoff. *Journal of Hydrology*, *265*, 164–177. doi:10.1016/S0022-1694(02)00101-4.

Bowman, R. A. (1989). A sequential extraction procedure with concentrated sulfuric acid and dilute base for soil organic phosphorus. *Soil Science Society of American Journal*, *53*, 362–366. doi:10.2136/sssaj1989.03615995005300020008x.

Braos, L. B., Bettiol, A. C. T., Santo, L. G. D., Ferreira, M. E., & Cruz, M. C. P. (2020). Dynamics of phosphorus fractions in soils treated with dairy manure. *Soil Research*, *58*(3), 289–298. https://doi.org/10.1071/SR18325

Braschi, I., Ciavatta, C., Giovannini, C., & Gessa, C. (2003). Combined effect of water and organic matter on phosphorus availability in calcareous soils. *Nutrient Cycling in Agroecosystems*, *67*(1), 67–74. https://doi.org/10.1023/A:1025143809825

Browman, M. G., & Tabatabai, M. A. (1978). Phosphodiesterase activity of soils. *Soil Science Society of American Journal*, *42*, 284–290. doi:10.2136/sssaj1978.03615995004200020016x.

Chen, X.-X., Zhang, W., Liang, X.-Y., Liu, Y.-M., Xu, S.-J., Zhao, Q.-Y., Du, Y.-F., Zhang, L., Chen, X.-P., & Zou, C.-Q. (2019). Physiological and developmental traits associated with the grain yield of winter wheat as affected by phosphorus fertilizer management. *Scientific Reports*, *9*(1), 16580. https://doi.org/10.1038/s41598-019-53000-z

Cross, A. F., & Schlesinger, W. H. (1995). A literature review and evaluation of the Hedley fractionation: applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma*, *64*, 197–214. doi:10.1016/0016-7061(94)00023-4.

D’Angelo, E., Crutchfield, J., & Vandiviere, M. (2001). Rapid, sensitive, microscale determination of phosphate in water and soil. *Journal of Environmental Quality*, *30*, 2206–2209. doi:10.2134/jeq2001.2206.

DeLuca, T. H., Glanville, H. C., Harris, M., Emmett, B. A., Pingree, M. R. A., de Sosa, L. L., Cerdá-Moreno, C., & Jones, D. L. (2015). A novel biologically-based approach to evaluating soil phosphorus availability across complex landscapes. *Soil Biology and Biochemistry*, *88*, 110–119. https://doi.org/10.1016/j.soilbio.2015.05.016

Dick, W. A., Cheng, L., & Wang, P. (2000). Soil acid and alkaline phosphatase activity as pH adjustment indicators. *Soil Biology and Biochemistry*, *32*, 1915–1919. doi:10.1016/S0038-0717(00)00166-8.

Dick, W. A., & Tabatabai, M. A. (1978). Hydrolysis of organic and inorganic phosphorus compounds added to soils. *Geoderma*, *21*(3), 175–182. https://doi.org/10.1016/0016-7061(78)90025-3

Duda, G. P., Guerra, J. G. M., Pereira, M. G., Anjos, L. H. C. dos., & Ribeiro, M. R. (2013). Phosphorus bioavailable evaluation in different soil classes from Brazil. *Semina: Ciências Agrárias*, *34*(4), 1563–1576. https://doi.org/10.5433/1679-0359.2013v34n4p1563

Eghball, B. (2002). Soil Properties as Influenced by Phosphorus- and Nitrogen-Based Manure and Compost Applications. *Agronomy Journal*, *94*(1), 128. https://doi.org/10.2134/agronj2002.0128

Eivazi, F., & Tabatabai, M. A. (1977). Phosphatases in soils. *Soil Biology and Biochemistry*, *9,* 167–172. doi:10.1016/0038-0717(77)90070-0.

Entz, M. H., Guilford, R., & Gulden, R. (2001). Crop yield and soil nutrient status on 14 organic farms in the eastern portion of the northern Great Plains. *Canadian Journal of Plant Science*, *81*(2), 351–354. https://doi.org/10.4141/P00-089

Fan, Y., Zhong, X., Lin, F., Liu, C., Yang, L., Wang, M., Chen, G., Chen, Y., & Yang, Y. (2019). Responses of soil phosphorus fractions after nitrogen addition in a subtropical forest ecosystem: Insights from decreased Fe and Al oxides and increased plant roots. *Geoderma*, *337*, 246–255. https://doi.org/10.1016/j.geoderma.2018.09.028

Farias, V. L. da S., Filho, M. V. M., de Paula, D. T., & Siqueira, D. S. (2018). Modeling of phosphorus losses by water erosion. *Journal of the Brazilian Association of Agricultural Engineering 38*, 149–157. doi:10.1590/1809-4430-eng.agric.v38n1p149-157/2018.

Gagnon, B., Demers, I., Ziadi, N., Chantigny, M. H., Parent, L.-É., Forge, T. A., Larney, F. J., & Buckley, K. E. (2012). Forms of phosphorus in composts and in compost-amended soils following incubation. *Canadian Journal of Soil Science*, *92*(5), 711–721. https://doi.org/10.4141/cjss2012-032

González Jiménez, J. L., Healy, M. G., & Daly, K. (2019). Effects of fertiliser on phosphorus pools in soils with contrasting organic matter content: A fractionation and path analysis study. *Geoderma*, *338,* 128–135. https://doi.org/10.1016/j.geoderma.2018.11.049

Hao, X., Godlinski, F., & Chang, C. (2008). Distribution of phosphorus forms in soil following long-term continuous and discontinuous cattle manure applications. *Soil Science Society of American Journal*, *72*, 90–97. doi:10.2136/sssaj2006.0344.

Hedley, M. J., Stewart, J. W. B., & Chauhan, B. S. (1982). Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of American Journal*, *46*, 970–976. doi:10.2136/sssaj1982.03615995004600050017x.

Kashem, M. A., Akinremi, O. O., & Racz, G. J. (2004). Phosphorus fractions in soil amended with organic and inorganic phosphorus sources. *Canadian Journal of Soil Science, 84*, 83–90. doi:10.4141/S03-018.

Kunito, T., Tsunekawa, M., Yoshida, S., Park, H. D., Toda, H., Nagaoka, K., & Saeki, K. (2012). Soil properties affecting phosphorus forms and phosphatase activities in japanese forest soils: soil microorganisms may be limited by phosphorus. *Soil Science, 177*, 39–46. doi:10.1097/SS.0b013e3182378153.

Mao, X., Xu, X., Lu, K., Gielen, G., Luo, J., He, L., Donnison, A., Xu, Z., Xu, J., Yang, W., Song, Z., & Wang, H. (2015). Effect of 17 years of organic and inorganic fertilizer applications on soil phosphorus dynamics in a rice–wheat rotation cropping system in eastern China. *Journal of Soils and Sediments*, *15*, 1889–1899. doi:10.1007/s11368-015-1137-z.

Margenot, A. J., Calderón, F. J., Bowles, T. M., Parikh, S. J., & Jackson, L. E. (2015). Soil organic matter functional group composition in relation to organic carbon, nitrogen, and phosphorus fractions in organically managed tomato fields. *Soil Science Society of American Journal*, *79*, 772–782. doi:10.2136/sssaj2015.02.0070.

Margenot, A. J., Sommer, R., & Parikh, S. J. (2018). Soil phosphatase activities across a liming gradient under long-term managements in Kenya. *Soil Science Society of American Journal*, *82*, 850–861. doi:10.2136/sssaj2017.12.0420.

Mclaughlin, M., Alston, A., & Martin, J. (1986). Measurement of phosphorus in the soil microbial biomass: A modified procedure for field soils. *Soil Biology and Biochemistry*, *18*, 437–443. doi:10.1016/0038-0717(86)90050-7.

Nannipieri, P., Giagnoni, L., Landi, L., & Renella, G. (2011). Role of phosphatase enzymes in soil. In E. Bünemann, A. Oberson, & E. Frossard (Eds.), *Phosphorus in Action* (pp. 215–243). Berlin, Heidelberg: Springer. doi:10.1007/978-3-642-15271-9_9.

Negassa, W., & Leinweber, P. (2009). How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: A review. *Journal of Plant Nutrition and Soil Science*, *172*, 305–325. doi:10.1002/jpln.200800223.

Nelson, N. S. (1987). An acid-persulfate digestion procedure for determination of phosphorus in sediments. *Communications in Soil Science and Plant Analysis*, *18*, 359–369. doi:10.1080/00103628709367826.

Olsson, R., Giesler, R., Loring, J. S., & Persson, P. (2012). Enzymatic hydrolysis of organic phosphates adsorbed on mineral surfaces. *Environmental Science and Technology*, *46*, 285–291. doi:10.1021/es2028422.

Penn, C. J., Mullins, G. L., & Zelazny, L. W. (2005). Mineralogy in Relation to Phosphorus Sorption and Dissolved Phosphorus Losses in Runoff. *Soil Science Society of America Journal*, *69*(5), 1532–1540. https://doi.org/10.2136/sssaj2004.0224

Pierzynski, G. M., McDowell, R. W., & Sims, J. T. (2015). Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In J. T. Sims, & A. N. Sharple (Eds.), *Phosphorus: Agriculture and the Environment* (pp. 51-86). Mandison, WI: SSSA. doi:10.2134/agronmonogr46.c3.

Poly, F., Chenu, C., Simonet, P., Rouiller, J., & Jocteur Monrozier, L. (2000). Differences between linear chromosomal and supercoiled plasmid DNA in their mechanisms and extent of adsorption on clay minerals. *Langmuir, 16,* 1233–1238. doi:10.1021/la990506z.

Qian, P., Schoenau, J. J., Wu, T., & Mooleki, P. (2004). Phosphorus amounts and distribution in a Saskatchewan soil after five years of swine and cattle manure application. *Canadian Journal of Soil Science, 84,* 275–281. doi:10.4141/S03-016.

Reddy, K. R., Wetzel, R. G., & Kadlec, R. H. (2005). Biogeochemistry of phosphorus in wetlands. In J. T. Sims, & A. N. Sharple (Eds.), *Phosphorus: Agriculture and the Environment* (pp. 263–316). Mandison, WI: SSSA. https://doi.org/10.2134/agronmonogr46.c9

Reeve, J. R., Endelman, J. B., Miller, B. E., & Hole, D. J. (2012). Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. *Soil Science Society of American Journal, 76,* 278–285. doi:10.2136/sssaj2011.0123.

Rehm, G. W., Sims, A. L., & Lamb, J. A. (2003). Influence of rate and placement of phosphate fertilizer on growth and yield of hard red spring wheat in diverse tillage systems. *Nutrient Cycling in Agroecosystems*, *67*(1), 75–83. https://doi.org/10.1023/A:1025169825754

Rick, T. L., Jones, C. A., Engel, R. E., & Miller, P. R. (2011). Green manure and phosphate rock effects on phosphorus availability in a northern Great Plains dryland organic cropping system. *Organic Agriculture*, *1*(2), 81–90. https://doi.org/10.1007/s13165-011-0007-2

Romanyà, J., & Rovira, P. (2007). Labile phosphorus forms in irrigated and rainfed semiarid Mediterranean grassy crops with long-term organic or conventional farming practices. *European Journal of Agronomy*, *27*(1), 62–71. https://doi.org/10.1016/j.eja.2007.02.001

Rosseel, Y. (2012). *lavaan: An R package for structural equation modeling and more Version 0.5-12 (BETA).*

Schneider, K. D., Voroney, R. P., Lynch, D. H., Oberson, A., Frossard, E., & Bünemann, E. K. (2017). Microbially-mediated P fluxes in calcareous soils as a function of water-extractable phosphate. *Soil Biology and Biochemistry, 106*, 51–60. doi:10.1016/j.soilbio.2016.12.016.

Sharma, S. B., Sayyed, R. Z., Trivedi, M. H., & Gobi, T. A. (2013). Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *Springer Plus*, *2*(1), 587. https://doi.org/10.1186/2193-1801-2-587

Tabatabai, M. A. (1994). Soil enzymes. In P. S. Bottomley, J. S. Angle, & R. W. Weaver (Eds.), *Methods of Soil Analysis: Part 2—Microbiological and Biochemical Properties* (pp. 775–833). Mandison, WI: SSSA. https://doi.org/10.2136/sssabookser5.2.c37

Thien, S. J., & Myers, R. (1992). Determination of bioavailable phosphorus in soil. *Soil Science Society of American Journal*, *56*, 814–818. doi:10.2136/sssaj1992.03615995005600030023x.

Tiessen, H., Stewart, J. W. B., & Cole, C.V. (1984). Pathways of phosphorus transformations in soils of differing pedogenesis. *Soil Science Society of American Journal*, *48*, 853–858. doi:10.2136/sssaj1984.03615995004800040031x.

Turner, B. L., & Haygarth, P. M. (2005). Phosphatase activity in temperate pasture soils: Potential regulation of labile organic phosphorus turnover by phosphodiesterase activity. *Science and Total Environment*, *344*, 27–36. doi:10.1016/j.scitotenv.2005.02.003.

Turner, B. L., & Joseph Wright, S. (2014). The response of microbial biomass and hydrolytic enzymes to a decade of nitrogen, phosphorus, and potassium addition in a lowland tropical rain forest. *Biogeochemistry*, *117*, 115–130. doi:10.1007/s10533-013-9848-y.

Wandruszka, R. von. (2006). Phosphorus retention in calcareous soils and the effect of organic matter on its mobility. *Geochemical Transaction*, *7*, 1–8. doi:10.1186/1467-4866-7-6.

Whalen, J. K., & Chang, C. (2001). Phosphorus accumulation in cultivated soils from long-term annual applications of cattle feedlot manure. *Journal of Environmental Quality*, *30*(1), 229–237. https://doi.org/10.2134/jeq2001.301229x

Yan, Z., Chen, S., Dari, B., Sihi, D., & Chen, Q. (2018). Phosphorus transformation response to soil properties changes induced by manure application in a calcareous soil. *Geoderma*, *322*, 163–171. https://doi.org/10.1016/j.geoderma.2018.02.035

Yan, Z., Chen, S., Li, J., Alva, A., & Chen, Q. (2016). Manure and nitrogen application enhances soil phosphorus mobility in calcareous soil in greenhouses. *Journal of Environmental Management*, *181*, 26–35. https://doi.org/10.1016/j.jenvman.2016.05.081

Zheng, Z., MacLeod, J. A., Sanderson, J. B., & Lafond, J. (2004). Soil phosphorus dynamics after ten annual applications of mineral fertilizers and liquid dairy manure: fractionation and path analyses. *Soil Science*, *169*, 449–456. doi:10.1097/01.ss.0000131225.05485.25.

Zheng, Z., Simard, R. R., Lafond, J., & Parent, L. E. (2001). Changes in phosphorus fractions of a Humic Gleysol as influenced by cropping systems and nutrient sources. *Canadian Journal of Soil Science*, *81*, 175–183. doi:10.4141/S00-666.

Zheng, Z., Simard, R. R., Lafond, J., & Parent, L. E. (2002). Pathways of soil phosphorus transformations after 8 years of cultivation under contrasting cropping practices. *Soil Science Society of American Journal*, *66*, 999–1007. doi:10.2136/sssaj2002.9990.

Ziadat, F. M., Taimeh, A. Y., & Hattar, B. I. (2010). Variation of soil physical properties and moisture content along toposequences in the arid to semiarid area. *Arid Land Research and Management*, *24*, 81–97. doi:10.1080/15324981003635396.

TABLES

Table 1. Means (n=4) and analysis of variance of acid and alkaline phosphomonoesterases at 0 to 10 cm depth 3 yr after a single compost application.

Site	Compost	Acid phosphatase	Alkaline phosphatase
	(Mg DW ha $^{-1}$)	ug *p*-nitrophenol g^{-1} soil	
Blue Creek[z]	0	178	49b
	25	202	87ab
	50	219	124a
Snowville	0	42.7c	230
	25	62.2b	266
	50	67.3a	279
	Effects	**ANOVA**	
Blue Creek	Treatment	NS	**0.0185**
	Year	**<.0001**	0.0707
	Treatment*Year	NS	NS
Snowville	Treatment	**0.0003**	NS
	Year	**<.0001**	**0.0244**
	Treatment*Year	NS	NS

[z]Tukey's HSD (*P* < 0.05) for comparing means within columns.

Table 2. Means (n=4) and analysis of variance of acid and alkaline phosphomonoesterases at 10 to 30 cm depth 3 yr after a single compost application.

Site	Compost	Acid phosphatase	Alkaline phosphatase
	(Mg DW ha $^{-1}$)	ug *p*-nitrophenol g^{-1} soil	
Blue Creek[z]	0	105	61
	25	98	70
	50	118	65
Snowville	0	50.3b	195
	25	51.2b	209
	50	73.1a	219
	Effects	ANOVA	
Blue Creek	Treatment	NS	NS
	Year	NS	**<.0001**
	Treatment*Year	NS	NS
Snowville	Treatment	**0.0187**	NS
	Year	**0.0031**	NS
	Treatment*Year	NS	NS

[z]Tukey's HSD (*P* < 0.05) for comparing means within columns.

Table 3. Means (n=4) and analysis of variance of phosphodiesterase at 10 to 30 cm depth 3 yr after a single compost application.

Site	Year	Compost (Mg DW ha^{-1})	Phosphodiesterase ug *p*-nitrophenol g^{-1} soil 0-10 cm	10-30 cm
Blue Creek[z]	1	0	5.10b	6.27
		25	8.10ab	3.55
		50	10.1a	7.54
	3	0	6.09b	10.7
		25	12.3ab	10.8
		50	12.7a	13
Snowville	1	0	32.7b	27.4
		25	30.9b	24.3
		50	42.5a	27.8
	3	0	28.7	37.6
		25	33.3	39
		50	27.4	40.1
		Effects	ANOVA	
Blue Creek		Treatment	0.0308	NS
		Year	NS	<.0001
		Treatment*Year	NS	NS
Snowville		Treatment	NS	NS
		Year	0.0173	0.0001
		Treatment*Year	0.0333	NS

[z]Tukey's HSD ($P < 0.05$) for comparing means within column

Table 4. Means (n=4) and analysis of variance of P fractions at 0 to 10 cm depth.

Site	Compost	Labile-Pi	Moderately labile-Pi	Labile-Po	Stable-P	Residual-P	Total-Pi	Total-Po	Total-P
	(Mg DW ha $^{-1}$)	mg P kg^{-1} soil							
Blue Creek[z]	0	31.6b	85.3	121.7	593b	49.2	595b	285b	880b
	25	49.9a	85.9	143.1	888a	53.7	767a	453ab	1221a
	50	58.1a	86.4	152.9	1091a	55.4	766a	678a	1444a
Snowville	0	8.7b	45.1	171.9	782b	27.5	688	347b	1035b
	25	25.9a	41.5	188.3	986a	36	719	557a	1277a
	50	28.6a	43.7	208.1	1063a	35	692	687a	1379a
	Year								
Blue Creek	1	46.4	85.5	119	863	68.5	712	470	1183
	3	46.7	86.3	159	851	37	707	474	1180
Snowville	1	18.4	49.8	197	971	35.5	711	560	1271
	3	23.7	37	182	916	30.2	688	501	1189
	Effects	ANOVA							
Blue Creek	Treatment	<.0001	NS	NS	0.0012	NS	0.0002	0.0108	0.0024
	Year	NS	NS	0.0237	NS	<.0001	NS	NS	NS
	Treatment*Year	NS	NS	NS	NS	NS	NS	NS	NS
Snowville	Treatment	0.0002	NS	NS	0.0093	NS	NS	0.0023	0.0021
	Year	0.0064	0.0003	0.0232	NS	0.0027	0.0137	NS	NS
	Treatment*Year	NS	NS	NS	NS	NS	NS	NS	NS

[z]Tukey's HSD ($P < 0.05$) for comparing means within columns.

Table 5. Means (n=4) and analysis of variance of P fractions at 10 to 30 cm depth.

Site	Compost	Labile-Pi	Moderately labile-Pi	Labile-Po	Stable-P	Residual-P	Total-Pi	Total-Po	Total-P
	(Mg DW ha $^{-1}$)	mg P kg^{-1} soil							
Blue Creek[z]	0	31b	84.4	176.9	587	52.1	629	302	931
	25	35.4ab	81.4	198.6	692	58.9	662	405	1066
	50	39.6b	85	196.2	759	60.6	697	392	1039
Snowville	0	1.91b	36	190.9	667b	30.7	567b	360	927b
	25	4.24b	34.5	200.3	717ab	30.1	610ab	376	985b
	50	8.93a	35.9	248.8	787a	37	633a	485	1118a
Site	Year								
Blue Creek	1	37.8	87.5	166	725	71.8	668	420	1088
	3	32.9	79.7	215	633	42.5	656	305	961
Snowville	1	3.45	37.5	220	756	36.4	575	478	1053
	3	6.61	33.5	207	691	28.8	632	326	967
				ANOVA					
Blue Creek	Treatment	0.0300	NS	NS	NS	NS	NS	NS	NS
	Year	0.0021	NS	0.0433	NS	<.0001	NS	0.0071	NS
	Treatment*Year	NS	NS	NS	NS	NS	NS	NS	NS
Snowville	Treatment	0.0053	NS	NS	0.0354	NS	0.0085	NS	0.0061
	Year	0.0229	NS	NS	NS	0.0039	0.0014	0.0035	0.0213
	Treatment*Year	NS	NS	NS	NS	NS	NS	NS	NS

[z]Tukey's HSD ($P < 0.05$) for comparing means within columns.

FIGURES

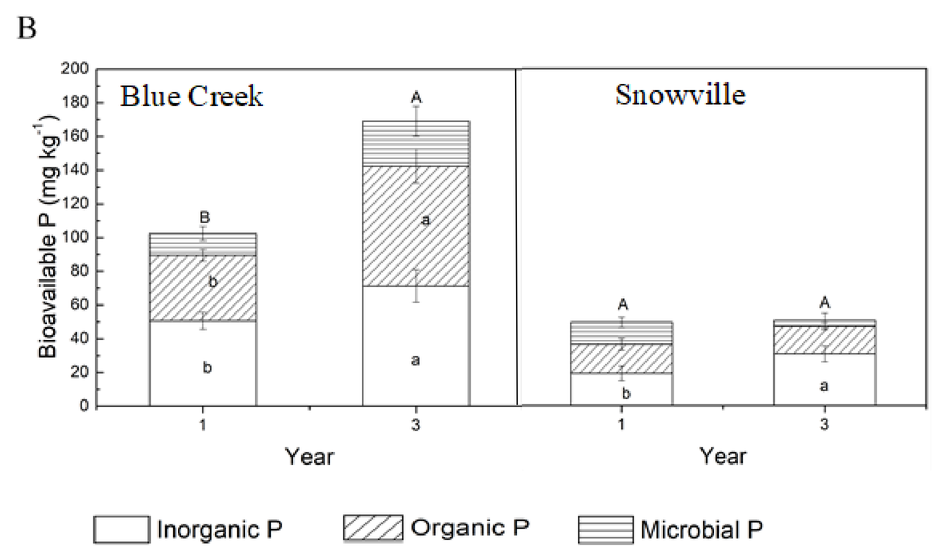


Figure 1. Bioavailable P in each of the sites at 0-10 cm showing the main effects of compost (A) and year (B).

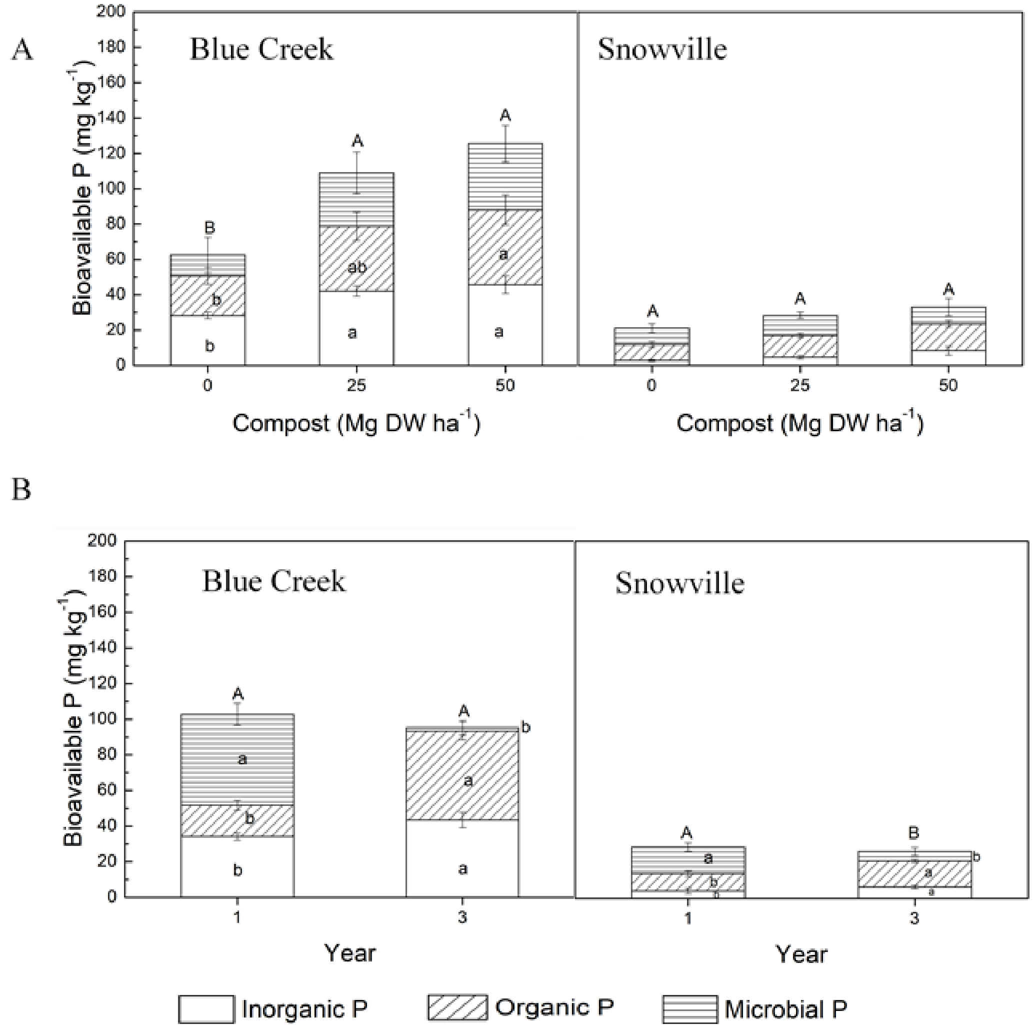


Figure 2. Bioavailable P in each of the sites at 10-30 cm showing the main effects of compost (A) and year (B).

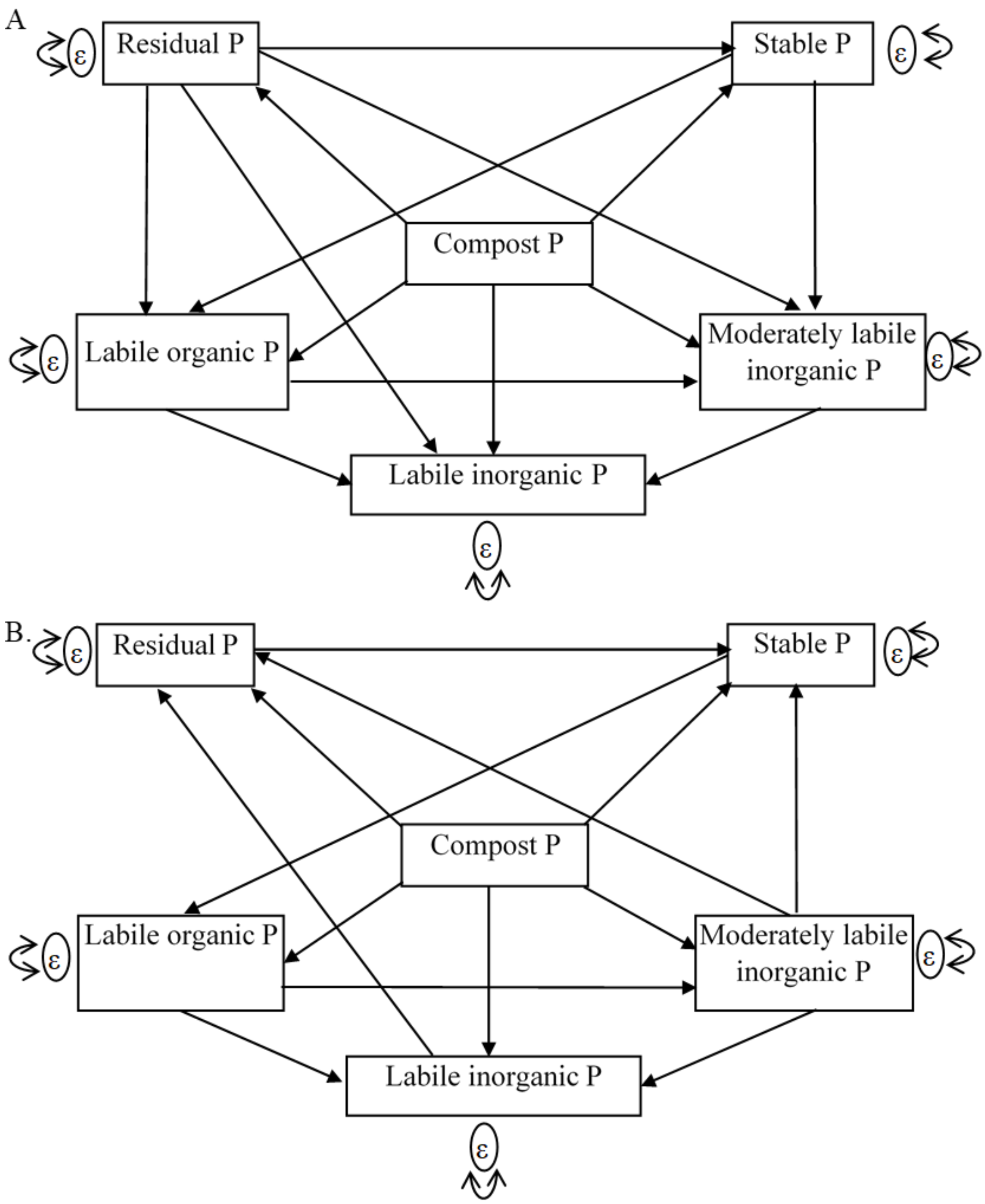
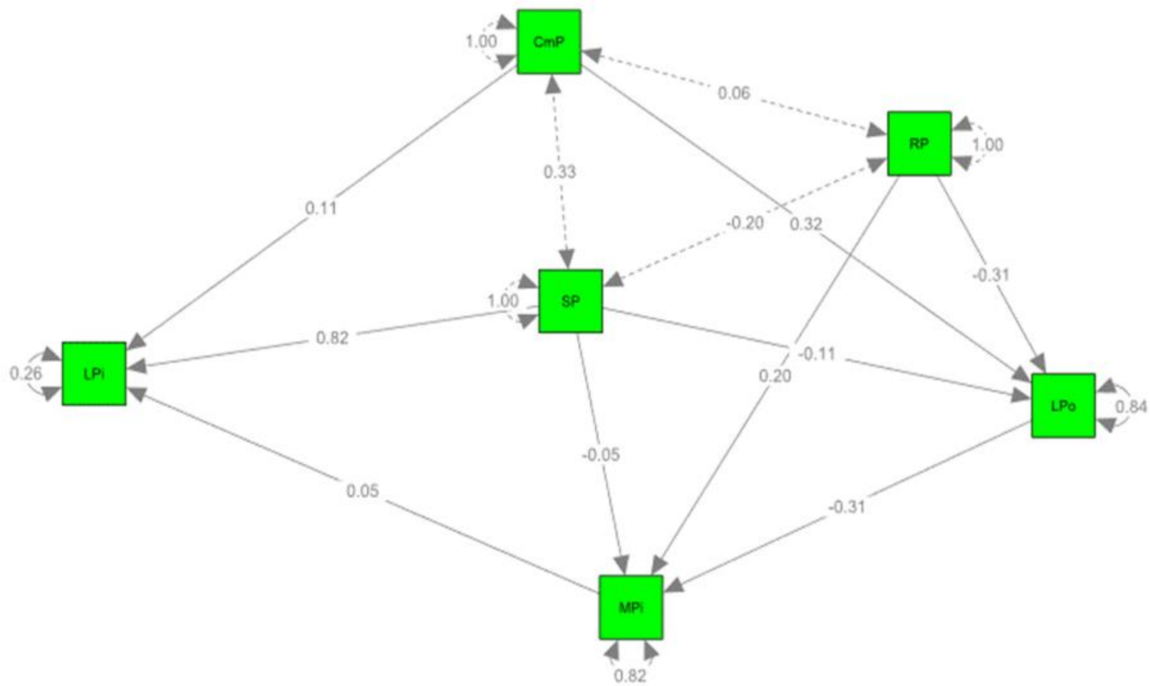
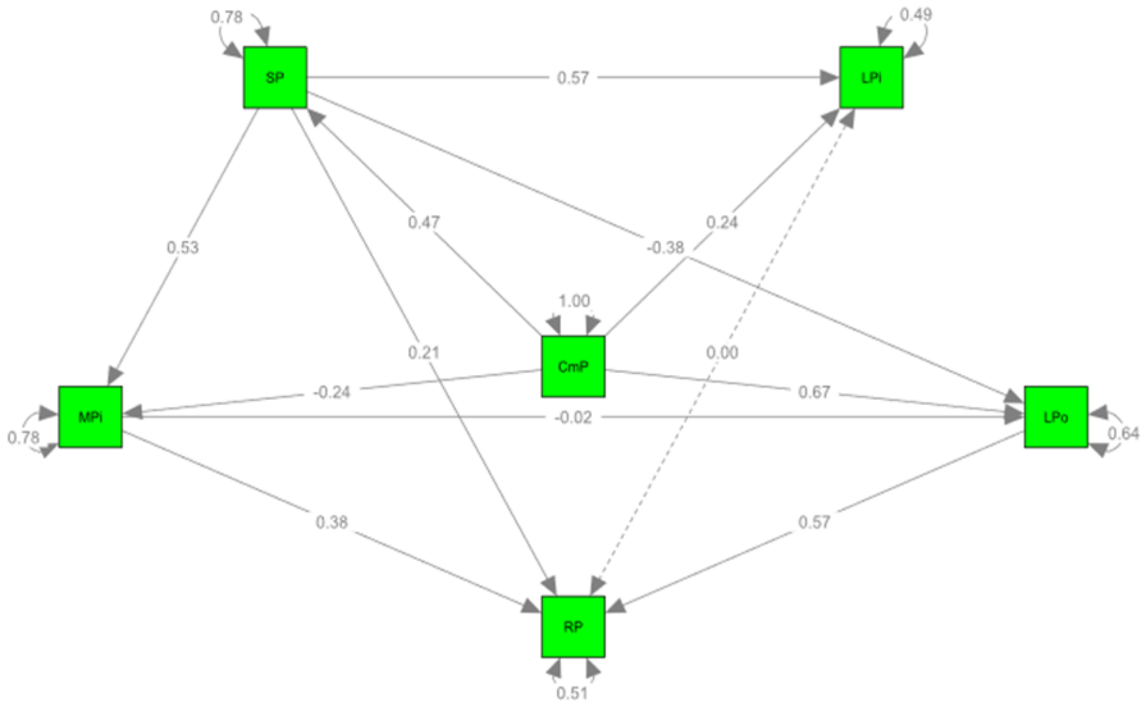


Figure 3. A proposed conceptual model for P pathways at Blue Creek (panel A) and Snowville (panel B). Errors (ε) represent the variance of each manifest variable (modified after González Jiménez et al. 2019).



$\chi^2 = 0.708$, df = 3, p =0.871, RMSEA = 0.000

Figure 4. Path analysis model showing the relationships between P pools at Blue Creek site. The numbers next to the path arrows are standardized path coefficients, which indicates the effect size between the manifest variables. The continuous dashed arrows indicate a correlation between variables that are not related directly in the model. Model fit parameters are shown below the diagram. Chi/df = RMSEA: Root mean square error of approximation. The pools in the diagram are compost P (CmP), labile inorganic P (LPi), moderately inorganic P (MPi), labile organic P (LP_o), stable P (SP), and residual P (RP).



$\chi^2 = 3.88$, df = 4, p =0.421, RMSEA = 0.000

Figure 5. Path analysis model showing the relationships between P pools at Snowville site. The numbers next to the path arrows are standardized path coefficients, which indicates the effect size between the manifest variables. The continuous dashed arrows indicate a correlation between variables that are not related directly in the model. Model fit parameters are shown below the diagram. Chi/df = RMSEA: Root mean square error of approximation. The pools in the diagram are compost P (CmP), labile inorganic P (LPi), moderately inorganic P (MPi), labile organic P (LP_o), stable P (SP), and residual P (RP).

CHAPTER IV

INCREASE IN SURFACE AND SUBSOIL ORGANIC CARBON FRACTION CONCENTRATIONS FOLLOWING COMPOST APPLICATION IN DRYLAND WHEAT-FALLOW SYSTEMS

ABSTRACT

Long-term field experiments can provide pertinent information relating to the effects of soil management practices on organic carbon (OC) dynamics in agroecosystems. Determining and understanding how soil management practices alter surface and subsoil OC pools in intensively cultivated semi-arid soils is important for the adoption of sustainable soil management practices. We quantified the effects of a one-time compost (0, 25, and 50 Mg DW ha^{-1}) application to three fields (Historical, Snowville, and Blue Creek) under organic dryland winter wheat-fallow (WW-F) in northern Utah, U.S.A. Soil samples were collected at four depths (0-10, 10-30, 30-60, and 60-90 cm) 1 and 3 years after compost application at the Snowville (SN) and Blue Creek (BC) sites, and 24 years later at the Historical site (HT). Organic C in bulk soil and soil fractions, namely, particulate organic matter (POM), sand associated organic matter (SMA), mineral associated organic matter (MAOM), and dissolved organic matter (DOM) were analyzed. We observed a significant increase in OC concentration in the POM and MAOM pools in the surface soil at HT and both the surface and subsoils at SN and BC. The OC in the POM pool increased by 4.6-fold (30-60 cm) at SN and 3.8-fold (60-90 cm at BC). Similarly, the OC in MAOM increased by an average of 1.7-fold in the subsoil at SN and BC. The OC stock in the soil fractions and bulk soil were significantly

higher in the compost amended plots at HT at the 10-30 cm depth. Including changes in OC in soil fractions in subsoil will aid if the understanding of the effects of management practices on soil C dynamics in cultivated drylands.

Keywords: compost, soil organic carbon, organic carbon fractions, winter wheat, dryland

INTRODUCTION

Maintaining soil organic carbon (SOC, used as a proxy for soil organic matter, SOM) is considered important for sustaining soil productivity and crop yield in dryland agriculture (Rasmussen and Parton 1994; Dregne 2002; Machado, Rhinhart, and Petrie 2006). Of great concern are non-irrigated winter wheat-fallow (WW-F) systems in semiarid western U.S.A which are more susceptible to SOC loss because of the characteristic low production and inconsistent yield (Rasmussen, Albrecht, and Smiley 1998; Schillinger et al. 2006). Replacement of fallow with continuous cropping or use of organic amendments in cultivated drylands can enhance SOC storage and maintenance because it alters both the quantity and quality of SOC (Machado, Rhinhart, and Petrie 2006; Guo et al. 2019). Although the effects of soil and cropping strategies on SOC in dryland agriculture have been largely documented, the focus of these studies has been mainly on the total SOC, while the effects of these practices on SOC pools are less defined (Rasmussen, Albrecht, and Smiley 1998; Lal 2004; Álvaro-Fuentes et al. 2008). There is a need to better understand how soil management and cropping practices affect the storage and maintenance of SOC pools in cultivated poor drylands for continuous sustainable crop production.

Considerable changes in SOC due to management practices are usually greatest near the surface and decline with depth and there is a growing interest in understanding changes in subsoil (> 30 cm) OC and pools in agricultural soils (Syswerda et al. 2011; Tautges et al. 2019; Shahzad et al. 2019). Earlier studies on SOC in did not observe differences in total SOC at the 30-60 cm depth (Ghimire, Machado, and Rhinhart 2015; Ghimire, Machado, and Bista 2018). However, in a dryland experiment at Shanxi Province, China, Wang et al. (2019) reported that minimum tillage with residue incorporation increased OC content in small macroaggregates from 0-10 cm depth to the 60-80 cm depth layer by 1%–58% compared with conventional tillage with residue removal 13 years later. Due to the differences in the characteristics of SOC fractions and factors controlling surface and subsoil OC dynamics, OC in soil fractions may respond differently to soil management practices with depth. However, previous studies have focused on changes in subsoil total SOC in non-irrigated drylands, while limited studies have examined how soil management practices changes in SOC of soil fractions in the subsoils.

Long-term experiments (LTEs) evaluating changes in SOC have notably increased our understanding of the effects of soil management and cropping practices (Johnston and Poulton 2018). The oldest long-term study focused on understanding the effects of soil management and cropping practices on SOC in the semiarid western U.S.A was established in 1931 in Pendleton, OR (Rasmussen, et al., 1994). From the Pendleton LTE, it was reported that while the addition of C inputs can lead to a varying impact on SOC over time in some cases, changes in SOC were not detectable in other cases despite

the increase in crop yield (Rasmussen, Albrecht, and Smiley 1998; Machado 2011; Ghimire, Machado, and Rhinhart 2015; Ghimire, Machado, and Bista 2018). For instance, the 6-year average grain yield and straw dry weight following nitrogen fertilization in a conventionally tilled continuous spring wheat were greater than in the unfertilized plots in the Pendleton LTEs (Machado, Rhinhart, and Petrie 2006). However, there were no significant differences in the amount of SOC between the two treatments, even though there was a positive correlation between fertilization and shoot biomass returned (Machado, Rhinhart, and Petrie 2006). Also, from the Pendleton LTEs Ghimire et al. (2015) highlighted that differences in SOC content at 0-10 and 10-20 cm depth in undisturbed grasslands and cultivated WW-F plots with manure (11.2 Mg $ha^{-1}yr^{-1}$, DM 47.5%) application were not statistically significant during the 1931-2010 period despite significantly higher whole profile C stock (0-60 cm) under the former. In the Intermountain West (IW, UT) a study in an organic dryland WW-F revealed the significant positive effects of a single application of compost (50 Mg ha^{-1} DW) on yield and SOC at the 0-5 and 10-30 cm depth but not at 5-10 cm depth 16 years later (Reeve et al. 2012). These studies indicate while the effects of soil management and cropping strategies can be observed in crop yield, its effects on total SOC can be variable especially in subsoils.

Soil OC is made up of distinct fractions that vary in characteristics, pedo-function, and response to cropping strategies (Christensen 1992). Information on the nature and properties of pools isolated using different approaches have been presented in Christensen (1992), Baldock and Nelson (2000), Gregorich et al. (2006), Lavallee,

Soong, and Cotrufo (2019). Physical size separation has been widely used in studying SOC pool responses to soil management practices (Cambardella and Elliott 1992; Janzen et al. 1992; Lavallee, Soong, and Cotrufo 2019). The SOC pools isolated using this approach are usually divided into three: particulate organic matter (POM, > 53 µm), sand associated mineral organic matter (SMA, > 53 µm), and silt and clay mineral associated organic matter (MAOM, < 53 µm) (Baldock and Nelson 2000; Cambardella and Elliott 1992; Gregorich et al. 2006). The POM pool is a source of readily available nutrients to plants, which is mainly made up of fine root fragments, fungal hyphae, and other organic debris, is readily decomposable and more sensitive to management practices than total SOC (Álvaro-Fuentes et al. 2008; Cambardella and Elliott 1992). In an earlier study comparing the effect of tillage practices on changes in SOC, Wander et al. (1998) observed SOC was 25 % more under no-till compared to conventional tillage, whereas POM-C was 70 % greater. Assessing changes in POM and other SOC fractions may be a useful approach in understanding and accurately predicting SOC changes in dryland cropping systems following the adoption of soil management and cropping practices.

In cultivated dryland with characteristically low SOC, elucidating the effects of soil management practices on SOC fractions in surface and subsoil soils in the short- and long-term could affect management decisions and recommendations. Therefore, the objective of this study was to assess changes in total SOC and SOC fractions following a one-time compost application 1-, 3- and 24-years later in surface- and sub-soils in organic dryland WW-F systems in the IW. We hypothesized that in WW-F dryland soils with low SOC, where the effects of soil management practices on total SOC are subtle, the effects

of compost application on SOC will be higher in SOC fractions compared to total SOC, especially in the subsoils (30-90 cm).

MATERIALS AND METHODS

Study sites and treatments

The experiments were conducted at a cooperator farmer's field near Snowille, Utah (41°53' N, 112°46' W) with an elevation of 1,387 m and the Utah State Agricultural Experimental Station in Blue Creek, Utah (41°56' N, 112°25' W) with an elevation of 1,433 m. There are two experiments at Snowville and one at Blue Creek. At Snowville, the first experiment referred to as historical (HT) was established in 1994, while the second referred to as Snowville (SN) was established in 2016. The experiment at Blue Creek (BC) was started in 2011. All the sites are certified organic, and the cropping cycle is a winter wheat-annual fallow (WW-AF) system. HT and SN were certified organic in 1992 (Stukenholtz et al. 2002; Reeve et al. 2012) and BC was certified organic in 2017. The climate is semi-arid and characterized by hot, dry summers and wet winters. The average annual precipitation (2016-2019) at HT and SN was 319 mm, and potential annual evapotranspiration was 1107 mm. At BC, the average annual precipitation for the same period was 485 mm, and potential annual evapotranspiration was 1113 mm. The average annual high and low temperatures were 17 and 4 ºC, respectively, and were comparable across the sites (Utah Climate Center, 2020).

A detailed description of the soil properties and experimental setup at HT can be found in Stukenholtz et al. (2002) and Reeve et al. (2012). Briefly, the soil type is calcareous Thiokol silt loam (fine-silty, mixed, active, mesic Sodic Calcixerepts) based

on the USDA soil classification with an average pH of 8.5 and calcium carbonate equivalent of about 16-36 %. The experiment was arranged as a randomized complete block split-plot design with three replicates. Dairy manure compost, 0, and 50 Mg DW ha^{-1} were applied once in August 1994 across the plots (6.86 by 8.53 m) and variety was the split-plot.

The experiment at SN was established as a randomized complete block split-plot design, with cover crop (winter pea *plus* hairy vetch and fallow) as the whole plot, and compost (0, 12.5, 25, and 50 Mg DW ha^{-1}) as the split-plot applied once in 2016 and incorporated immediately. For this experiment, samples were collected from the plots that received 0, 25, and 50 Mg DW ha^{-1} steer manure compost. The split-plot size was 7.3 x 61.0 m. Juniper WW cultivar was planted in August at 67 kg/ha to a depth of 3.8 cm and harvested in July of the following year. The land was fallowed for the next 13 months before the planting of the next wheat crop. The wheat-fallow plots where tilled three times with a Flexicoil chisel plow with 0.45 m sweeps. The first tillage pass in mid-March was 10 cm deep, the second tillage pass in late May was to a depth of 7.62 cm, and the third pass was to a depth of 5 cm in early July.

The soil at BC is classified as a Parleys silt loam (fine-silty, mixed, superactive, mesic Calcic Argixerolls) based on USDA soil classification. At this site, the long-term study was designed as a randomized complete block split-plot design, with compost rate (0, 12.5, 25, and 50 Mg DW ha^{-1}) as the whole plot, and cover crop (winter pea *plus* hairy vetch and fallow control) as the split-plot. Steer manure compost was applied to unamended plots in 2016. Like the site at SN, plots that received only steer manure

compost (0, 25, and 50 Mg DW ha^{-1}) in 2016 were selected for this study. The whole plot size was 7.3 x 61.0 m. Juniper WW cultivar was planted in November at 78 kg/ha to a depth of 5 cm and harvested in September of the following year. The land was fallowed for the next 13-14 months before the planting of the next wheat crop. The wheat-fallow plots where tilled three times with a Flexicoil chisel plow with 40.64 cm wide sweeps. The first tillage pass was to a depth of 25 cm in mid-May and the second tillage pass to a depth of 25 cm in mid-June. The plots were disked in early August to a depth of 15 cm before the third chisel plow with sweeps to a depth of 7 cm in mid-October.

Soil Sampling and laboratory analysis

Initial soil samples (0 to 30 cm) were collected and analyzed for physical and chemical properties in April 2011 (BC) or April 2016 (SN) (Table 1). Soil samples were collected in late April/ early May at SN and BC during the 2016-2017 and 2018-2019 wheat rotations and at HT during the 2017-2018 wheat rotations. For the 0 to10 and 10 to 30 cm, four soil samples were collected using a soil auger (4.5 cm, i.d), composted, and thoroughly homogenized. Bulk density samples were collected using a slide hammer (4.5 cm, i.d). Soil cores at 0-90 cm depth were collected using a hydraulic truck-mounted Giddings probe (4.5 cm i.d) (Giddings Machine Company, Windsor, Colorado) and divided into 30 cm increments. The samples were divided into halves and one-part was used for C analysis and the other one-half was used in estimating bulk density. The soil core samples to be used for C analysis were combined and thoroughly homogenized, and a sub-soil was taken while the sample collected for bulk density was placed directly in polythene bags and transported to the laboratory on ice. The soil samples for C analysis

were sieved through a 2 mm-mesh sieve, air-dried, and stored at room temperature while the soil samples for bulk density were oven-dried at 105 ˚C for 24 h. Bulk density of the 0-90 cm depth was determined at SN and BC in 2019.

Total SOC

A subsample of air-dried soil was placed into 15 ml glass vials and grounded to < 150 µm using a rolling grinder with steel bars. The TC and IC were determined using the Primacs SNC total C and N analyzers (Skalar Inc., Buford, GA). Total organic C (TOC) was quantified as the difference between TC and IC.

SOC physical fractionation

In this study, SOC was separated using a simplified particle size fractionation approach to isolate three fractions, namely, (i) particulate organic matter (POM), (ii) mineral associated soil organic carbon in the sand fraction (>53 µm) (SMA), and (iii) mineral associated organic matter in the silt and clay (MAOM) (Cambardella and Elliott 1992; Dobarco and Van Miegroet 2014). Briefly, 20 g of air-dried soil (0 to 10, 10 to 30, 30 to 60 and 60 to 90 cm) was placed in 250 mL Nalgene bottles, 20 glass beads were added along with 100 mL deionized water and placed on a horizontal end-to-end shaker for 16 hours. The MAOM (<53 µm) was isolated by sieving through a 53 µm sieve and oven-dried at 50 ˚C, while the >53 µm fraction was further separated into POM and SMA using electrostatic attraction as described by (Kaiser, Ellerbrock, and Sommer 2009) and modified by (Dobarco and Van Miegroet 2014). A glass petri dish was electrostatically charged using a woolen cloth and placed at a distance of 1 cm to the coarse fraction. The

petri dish was visually inspected for possible soil mineral contaminations (e.g. quartz grains) which were carefully removed (Kaiser, Ellerbrock, and Sommer 2009). The fractions greater than 53 µm were grounded (<150 µm) using a roller-mill and TC and IC content were measured using a Skalar Primacs SLC Analyzer (Skalar, Inc., Breda, The Netherlands). The total organic carbon (TOC) was estimated as the difference between TC and IC.

Dissolved organic carbon

Dissolved organic carbon (DOC) was quantified in 30 cm increments to 90 cm depth. Approximately, 10 g of field-moist soil was placed in 50 mL polypropylene centrifuge tubes and 45 mL of deionized water was added. The soil suspension was placed on a horizontal end-to-end shaker for 16 hours. Thereafter, the soil suspension was filtered through 0.45 µm glass fiber filters (Sterilitech Corporation, Kent, Washington), and froze at -4 ˚C when samples were not analyzed immediately, although, freezing and thawing of samples, can affect the concentration of DOC due to incomplete reconstitution (Jones and Willett 2006). Total carbon (TC) and inorganic carbon (IC) concentrations were measured using the TOCN-liquid analyzer (Shimadzu, Kyoto Prefecture, Japan) and the total organic carbon (TOC) was estimated as the difference between TC and IC.

Estimation of soil organic C stocks

Soil organic C stocks in the bulk soil and fractions were quantified as proposed by (Wei et al. 2013) as follows:

$$\text{SOC stocks (Mg ha}^{-1}\text{)} = \frac{DxBD \times OC}{10} \qquad (1)$$

where D is the thickness (cm) of the soil layer, BD is the bulk density (g cm^{-3}) and OC is the OC concentration (g kg^{-1}).

Organic C stocks in each of the size fraction from the four depths were calculated as follows:

$$M_i = \frac{DxBDxw_i}{10} \qquad (2)$$

$$OC_i \text{ stock (Mg ha}^{-1}) = \frac{M_i \times OC_i}{100} \qquad (3)$$

where M_i is the quantity in the *i*th size fraction (kg m^{-2}) and OC_i is the OC concentration of the *i*th size fraction (g kg^{-1} aggregate), and w_i is the proportion of the total soil in the *i*th size fraction (%). Bulk density samples collected in 2019 at SN were used in estimating SOC stock at HT.

STATISTICAL ANALYSIS

Because of differences in soil types and environmental conditions, each site was analyzed separately. Response variables were log or square root transformed before analysis to satisfy the assumptions of normality and constant variance. Data were analyzed for each depth separately and the whole-profile (0-90 cm). Compost treatment was included as a fixed effect factor, block as a random effect, and year after compost application included as repeated measure. Statistical analysis was performed using generalized linear mixed-effects models SAS (University Edition). The mean comparison was carried out using the adjusted Tukey’s method at p=0.05. Correlation analysis was

carried out using MAOM, SMA, POM, TOC, and DOC concentrations across the whole soil profile.

RESULTS

Organic carbon concentrations in soil fractions and bulk soil

The OC in the soil fractions and bulk soil, POM-OC, MAOM-OC, SMA-OC, and SOC generally decreased with depth across the three sites (Tables 3 and 4). At the 0-90 cm depth, POM-OC ranged from 14.3 to 84.1 g OC kg^{-1} at HT, 3.75 to 124 g OC kg^{-1} at SN, and 8.3 to 172 g OC kg^{-1} at BC. At the surface 0-10 and 10-30 cm depth, a significantly greater concentration of POM-OC was measured in compost amended plots at the three sites. Conversely, below the 30 cm depth, the POM-OC concentration was significantly greater at the 30-60 cm at SN and 60-90 cm depth at BC only. There was no significant difference between the effects of the two compost rates on POM-OC. Compost effects on POM-OC were generally higher in year 3 than 1 at SN and BC.

Similar to POM-OC, the MAOM-OC of the soil fractions decreased with depth. The MAOM-OC concentration in the 0-90 cm depth the values ranged from 1.6 to 19 g OC kg^{-1} at HT, 1.7 to 13.6 g OC kg^{-1} at SN, and 2.35 to 15.5 g OC kg^{-1} at BC. At the 0-10 cm depth, MAOM-OC concentration was significantly greater in compost amended plots at SN and BC, while there no significant differences at HT. At the 10-30 cm depth, however, MAOM-OC concentration was significantly higher in compost amended soils HT and SN but nit at BC. Below the 30 cm depth, MAOM-OC concentration was higher in compost amended plots at 30-60 and 60-90 cm depth at BC and only at 30-60 cm depth at SN. No significant difference was observed in MAOM-OC concentration at the

30-60 cm between the treatments at HT. Overall, MAOM-OC concentrations were greater in year 3 than 1 at SN and year 1 than 3 at BC.

The SMA-OC concentration values ranged from 4.3 to 6.9 g OC kg^{-1} at HT, 1.8 to 6.4 g OC kg^{-1} at SN and 2.28 to 8.18 g OC kg^{-1} at BC in the 0-90 cm depth. At the 0-10 cm depth, SMA-OC concentration was significantly greater under compost amended plots at SN and BC. However, at the 10-30 cm depth, SMA-OC concentration was significantly different at SN but not at BC. There were no significant differences between the SMA-OC concentration at HT at the 0-10 and 10-30 cm depth. Further down in the 30-60 and 60-90 cm depth, there was no significant variation in the SMA-OC concentration at the three sites. In general, SMA-OC concentrations were greater in year 3 than 1 at SN and year 1 than 3 at BC.

In the 0-90 cm depth, total SOC concentration values ranged from 2.7 to 13.7 g kg^{-1} at HT, 2 to 17.8 g kg^{-1} at SN, and 5.25 to 20 g kg^{-1} at BC. The total SOC concentration was only significantly greater at the 10-30 cm depth at HT, and in the 0-10, and 10-30 cm depth at SN, and 0-10 cm depth at BC. The total SOC concertation was generally higher in year 1 than 3 at both SN and BC sites expect at the 30-60 cm depth at SN.

Soil organic carbon stocks

Soil organic carbon stocks for the soil fractions and bulk soil are presented in Tables 3 and 5. At the long-term HT, the OC stock in the soil fractions and bulk soil were significantly greater in compost amended plots at the 10-30 cm depth. There were no

significant differences in the OC stocks in the soil fractions and bulk soil at the 0-10 and 30-60 cm depth at this site. Among the soil fractions at SN, MAOM stock increased with compost application at 0-10, 10-30, and 30-60 cm depth, SMA stock at 0-10 and 10-30 cm depth, and POM stock at 0-10 cm depth. At BC, compost rates influenced the MAOM stock at the 60-90 cm depth, POM stocks at the 0-10, and 10-30 cm depth while there no differences in SMA stock across the depths. The total SOC stocks were significantly greater in compost amended plots at the 0-10 and 10-30 cm depth at SN and 0-10 cm depth at BC. At BC the OC stocks in the soil fractions and bulk soil were greater in year 1 than 3. Conversely, at SN, the OC stocks in the soil fractions were greater in year 3 than 1 except for POM-OC stock. The SOC stocks at SN were also greater in year 1 than 3.

Differences in the whole-profile SOC stocks values are presented in Figure 1. The whole-profile total SOC stock ranged from 45.4 to 47.6 Mg ha^{-1} at HT, 45.9 to 68.1 Mg ha^{-1} at SN, and 77.1 to 100 Mg ha^{-1} at BC. Among the soil fractions, whole-profile MAOM-OC and SMA-OC stocks were not significantly different at HT and BC while compost application increased the OC stock in the two fractions at SN. The whole-profile POM-OC stock at SN and BC were higher under compost amended plots while there were no differences between the compost treatments at HT. Compost application at 25 and 50 Mg ha^{-1} DW had comparable effects on SOC stocks in the soil fractions and bulk soil at SN and BC with greater values observed at the highest rate.

Dissolved organic carbon

In the 0-90 cm depth DOC ranged from 31.9 to 84.8 mg kg^{-1} at SN, 39.1 to 148 mg kg^{-1} at BC, and 37.3 to 43.8 mg kg^{-1} (0-60 cm) at HT (Table 6). At the long-term HT site, the effect of compost on DOC at the 0-30 and 30-60 cm depth were not statistically significant. The DOC concentrations at SN and BC were significantly higher in compost amended plots at the 0-30 cm depth. At the 30-60 cm depth, DOC was highest in control plots at SN while at BC there were no differences between the treatments. The DOC concentration at the 60-90 cm depth was not significantly different at both sites. Across all depths, DOC concentrations were generally higher in year 3 than 1.

DISCUSSION

Cropping practices can greatly impact SOC by altering both the decomposition and C input rates. The aim of the study was to understand the temporal effects of a one-time compost addition on surface and subsoil OC storage in cultivated organic dryland soils in the IW UT. Changes in OC concentrations of POM-OC, MAOM-OC, SMA-OC, and bulk soil were studied 1 and 3 years after compost application at SN and BC, and 24 months later at HT.

SOC fractions can be separated by chemical or physical approaches, with the physical approach preferred because chemical separation can lead to selective solubilization of SOC (Elliott and Cambardella 1991). Physical fractionation includes particle size and density separation of soil primary organomineral particles (Christensen 1992). The > 53 µm fractions, POM and SMA, are defined as labile SOM fractions (Baldock and Nelson 2000). The POM contains plants and animal remains at various stages of decomposition as well as seeds, spores, pollens, charcoal, and phytoliths

(Baldock and Nelson 2000; Gregorich et al. 2006). The SMA is made up of humified organic materials that are found on the surfaces of sand mineral particles. Both the POM and SMA are known to have different physical and chemical characteristics as SMA has a higher density than POM and is a minor contributor to total SOC (Dobarco and Van Miegroet 2014). The <53 µm size, i.e. MAOM, is made up of microscopic fragments of organic materials that have been chemically transformed by soil microorganisms or leached from plant materials and is less susceptible to decomposition compared to the POM and SMA (Cambardella and Elliott 1992; Lavallee, Soong, and Cotrufo 2019). One limitation of particle size fractionation is the potential presence of traces of unprotected very fine root hairs (15-17 µm) in MAOM (Gregorich et al. 1994). Nevertheless, particle size fractionation has been preferred to density fractionation due to the toxic nature of the chemicals used in the latter and its potential to alter the chemical forms of C in the isolated pools (Plaza et al. 2019).

We hypothesized that in WW-F dryland soils with low SOC, where the effects of soil management practices on total SOC are subtle, the effects of compost application on SOC will be higher in SOC fractions compared to total SOC, especially in the subsoils (30-90 cm). Results from this study show that increasing C input through compost addition had greater effects on SOC in POM and MAOM compared with total SOC in surface and subsoils in the WW-AF systems. At SN and BC, between a 1.8- and 2.4-fold increase was observed in the OC content in the soil fractions at the surface soils, while in the subsoils the increase was between 1.8- to 3.9-fold. Similarly, the SOC stocks in the soil fractions at the surface and subsoils increased by 1.4- to 8.6-fold, especially in the

POM and MAOM fractions. The effect of the one-time application of compost on OC in soil fractions in subsoils 3 years later illustrates that the impact of soil management practices on C dynamics is not restricted to the surface layers only. Wang et al. (2019) documented that tillage practices affected the OC in soil fractions at the 60-80 cm depth in a dryland farming in Shouyang, China. Similarly, Sainju and Lenssen (2011) reported the effects of annual-forage cropping sequences on particulate total carbon as deep as 90-120 cm in a dryland experiment in Montana, U.S.A. The main sources of C in subsoils are dissolved organic carbon, root exudates, and root litter (Lorenz and Lal 2005). Given that the impact of compost on DOC was restricted to the top 30 cm in our study, the increase in OC in soil fractions in subsoils could be attributed to increased root biomass and root exudates. Although root biomass in subsoils was not measured in this study, wheat roots in drylands can get up to 120 cm to use the soil water reserve (Chaudhary and Bhatnagar 1980; Xue et al. 2003). Earlier studies have shown that roots are an important source of POM (Cambardella and Elliott 1992). The values of POM and MAOM were strongly correlated with SOC at HT. POM is known to be labile and an important source of nutrients for soil microorganisms. Recent studies also suggest that OC in MAOM can be accessed by soil microorganisms (Jilling et al. 2018).

The use of manure and manure-compost can mitigate SOC loss in cultivated dryland soils. Three years after, compost amended plots had between 48 and 81 % greater SOC stocks at the 0-10 and 10-30 cm depth. Surprising, 24 years later, total SOC stock at the 10-30 cm depth at HT was 14 % higher in compost amended plots than control plots. While changes were not noticeable in total SOC in the subsoil, our study showed that

compost increase subsoil MAOM and POM OC stocks at SN and BC. This indicates that soil management practices affect deep soil OC. Thus, it is important to consider changes in subsoil SOC fractions evaluating the impact of soil management practices in cultivated drylands. The higher SOC stock found at the 10-30 cm depth at HT indicates the ability of dryland soils to preserve accrued SOC following compost application. (Duchaufour 1976) suggested that SOM can be biologically stabilized by reactive $CaCO_3$. Furthermore, the results show a positive significant relationship exist between the OC content in the soil fractions and the total SOC. Thus, if a soil management practice increases any OC SOM pool, we can conclude it enhances SOM.

Similarly, SOC stocks in the 0-90 cm profile were also found to increase by 14 to 48 % three years after in plots that received 8.5 and 16 Mg C ha^{-1} once at SN and BC. Twenty-four years later, however, there was no significant difference in the whole-profile SOC between compost amended plots and control plots at HT. This is consistent with the results of the Pendleton LTE that reported a significant increase in total SOC stocks the surface soil (0-20 cm) and whole-profile (0-60 cm) in plots amended with 22 Mg ha^{-1} manure (1.7 Mg C ha^{-1}) every two years compared to unamended control plots (Ghimire, Machado, and Rhinhart 2015). Earlier studies by Reeve et al. (2012) at the HT site reported that the effects of the 50 Mg ha^{-1} DW compost on SOC in the surface soil (0-5 cm) can last at least 16 years. Increasing and maintaining SOC in cultivated drylands will require either annual addition of 0.85 Mg C ha^{-1} yr^{-1} (Ghimire, Machado, and Rhinhart 2015) or the one-time addition of 16.5 Mg C ha^{-1} every two decades.

Overall, studies on changes in SOC carbon in cultivated dryland should not be restricted to total SOC alone. Lack of observable changes in SOC does not necessarily mean soil management practices are not affecting SOC at least from the standpoint of the observed long-term effects on subsoil POM- and MAOM-OC. There is a need for extensive studies on the effects of soil management practices and cropping systems on SOC fractions in subsoils. Long-term experiments studying the changes in SOC fractions compared to total SOC would aid in understanding the effects of management practices on soil C dynamics in cultivated drylands. This will contribute towards the adoption of soil management practices that will contribute to the sustainability of WW-F systems.

CONCLUSION

Changes in surface and subsoil OC in soil fractions and total SOC were determined at three cultivated dryland soils following the one-time application of compost. Our study showed that OC in POM and MAOM in the WW-AF soils were higher 24 years later reflecting the persistent effect of compost, increased wheat residue, and root biomass on labile and mineral protected organic carbon. The short-term (<3 years) compost effect on the SOC pools in subsoils was also observed. Based on these findings, it is evident that soil management practices can impact subsoil OC. It then becomes important for studies to consider the effects of management practices on SOC fractions and not total SOC alone. This is of importance in cultivated organic dryland soils where yield is constrained, in part, due to low SOC. A little increase in SOC could potentially have great effects on soil resilience in a region faced with soil degradation and water stress and promote the economic sustainability of non-irrigated organic wheat

production. Future studies can also examine if the quality of OC in the soil fractions vary with time across different sites.

References

Álvaro-Fuentes, J., M.V. López, C. Cantero-Martinez, and J.L. Arrúe. 2008. Tillage effects on soil organic carbon fractions in mediterranean dryland agroecosystems. *Soil Science Society of America Journal* 72 (2):541–547.

Baldock, J.A., and P.N. Nelson. 2000. Soil organic matter. In *Handbook of Soil Science*, ed. M.E. Sumner, B25–B84. Boca Raton, FL, USA: CRC Press.

Cambardella, C.A., and E.T. Elliott. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal* 56 (3):777–783.

Chaudhary, T.N., and V.K. Bhatnagar. 1980. Wheat root distribution, water extraction pattern and grain yield as influenced by time and rate of irrigation. *Agricultural Water Management* 3 (2):115–124.

Christensen, B.T. 1992. Physical fractionation of soil and organic matter in primary particle size and density separates. In *Advances in Soil Science*, ed. B.A. Stewart, 1–90. Advances in Soil Science. New York, NY: Springer New York.

Dobarco, M., and H. Van Miegroet. 2014. Soil organic carbon storage and stability in the aspen-conifer ecotone in montane forests in Utah State, USA. *Forests* 5 (4):666–688.

Dregne, H.E. 2002. Land degradation in the drylands. *Arid Land Research and Management* 16 (2):99–132.

Duchaufour, P. 1976. Dynamics of organic matter in soils of temperate regions: Its action on pedogenesis. *Geoderma* 15 (1):31–40.

Elliott, E.T., and C.A. Cambardella. 1991. Physical separation of soil organic matter. *Agriculture, Ecosystems & Environment* 34 (1–4):407–419.

Ghimire, R., S. Machado, and P. Bista. 2018. Decline in soil organic carbon and nitrogen limits yield in wheat-fallow systems. *Plant and Soil* 422 (1):423–435.

Ghimire, R., S. Machado, and K. Rhinhart. 2015. Long-term crop residue and nitrogen management effects on soil profile carbon and nitrogen in wheat–fallow systems. *Agronomy Journal* 107 (6):2230–2240.

Gregorich, E.G., M.H. Beare, U.F. McKim, and J.O. Skjemstad. 2006. Chemical and biological characteristics of physically uncomplexed organic matter. *Soil Science Society of America Journal* 70 (3):975–985.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data Set to assess soil organic matter quality in agricultural soils. *Canadian Journal of Soil Science* 74 (4):367–385.

Guo, Z., Z. Zhang, H. Zhou, D. Wang, and X. Peng. 2019. The effect of 34-year continuous fertilization on the soc physical fractions and its chemical composition in a vertisol. *Scientific Reports* 9 (1):2505. https://doi.org/10.1038/s41598-019-38952-6

Janzen, H.H., C.A. Campbell, S.A. Brandt, G.P. Lafond, and L. Townley-Smith. 1992. Light-fraction organic matter in soils from long-term crop rotations. *Soil Science Society of America Journal* 56 (6):1799–1806.

Jilling, A., M. Keiluweit, A.R. Contosta, S. Frey, J. Schimel, J. Schnecker, R.G. Smith, L. Tiemann, and A.S. Grandy. 2018. Minerals in the rhizosphere: overlooked mediators of soil nitrogen availability to plants and microbes. *Biogeochemistry* 139 (2):103–122.

Johnston, A.E., and P.R. Poulton. 2018. The importance of long-term experiments in agriculture: their management to ensure continued crop production and soil fertility; the Rothamsted experience. *European Journal of Soil Science* 69 (1):113–125.

Jones, D.L., and V.B. Willett. 2006. Experimental evaluation of methods to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil. *Soil Biology and Biochemistry* 38 (5):991–999.

Kaiser, M., R.H. Ellerbrock, and M. Sommer. 2009. Separation of coarse organic particles from bulk surface soil samples by electrostatic attraction. *Soil Science Society of America Journal* 73 (6):2118-2130. https://doi:10.2136/sssaj2009.0046

Lal, R. 2004. Carbon sequestration in dryland ecosystems. *Environmental Management* 33:528-524. http://link.springer.com/10.1007/s00267-003-9110-9.

Lavallee, J.M., J.L. Soong, and M.F. Cotrufo. 2019. Conceptualizing soil organic matter into particulate and mineral-associated forms to address global change in the 21st century. *Global Change Biology* 26 (1):261-273 https://doi.org/10.1111/gcb.14859

Lorenz, K., and R. Lal. 2005. The depth distribution of soil organic carbon in relation to land use and management and the potential of carbon sequestration in subsoil horizons. In *Advances in Agronomy,* 88:35–66. Academic Press. https://doi.org/10.1016/S0065-2113(05)88002-2

Machado, S. 2011. Soil organic carbon dynamics in the pendleton long-term experiments: implications for biofuel production in pacific northwest. *Agronomy Journal* 103 (1):253–260.

Machado, S., K. Rhinhart, and S. Petrie. 2006. Long-term cropping system effects on carbon sequestration in eastern Oregon. *Journal of Environmental Quality* 35 (4):1548–1553.

Plaza, C., B. Giannetta, I. Benavente, C. Vischetti, and C. Zaccone. 2019. Density-based fractionation of soil organic matter: effects of heavy liquid and heavy fraction washing. *Scientific Reports* 9 (1):1–7.

Rasmussen, P.E., S.L. Albrecht, and R.W. Smiley. 1998. Soil C and N changes under tillage and cropping systems in semi-arid pacific northwest agriculture. *Soil and Tillage Research* 47 (3):197–205.

Rasmussen, P.E., Collins, H.P., and Smiley, R.W. 1994. Long-term management effects on soil productivity and crop yield in semi-arid regions of eastern Oregon. *Oregon Agricultural. Experimental Stationn Special Bulletin 675*. Pendleton, OR.: Columbia Basin Agriccultural Research.

Rasmussen, P.E., and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow: I. Inputs, yield, and soil organic matter. *Soil Science Society of America Journal* 58 (2):523–530.

Reeve, J.R., J.B. Endelman, B.E. Miller, and D.J. Hole. 2012. Residual effects of compost on soil quality and dryland wheat yield sixteen years after compost application. *Soil Science Society of America Journal* 76 (1):278–285.

Sainju, U.M., and A.W. Lenssen. 2011. Dryland soil carbon dynamics under alfalfa and durum-forage cropping sequences. *Soil and Tillage Research* 113 (1):30–37.

Schillinger, W.F., R.I. Papendick, S.O. Guy, P.E. Rasmussen, and C. van Kessel. 2006. Dryland Cropping in the Western United States. In *Dryland Agriculture*, ed. G. A. Peterson, P. W. Unger and W. A. Payne. Madison, WI, USA: ASA, SSSA, CSSA.

Shahzad, T., F. Anwar, S. Hussain, F. Mahmood, M.S. Arif, A. Sahar, M.F. Nawaz, et al. 2019. Carbon dynamics in surface and deep soil in response to increasing litter addition rates in an agro-ecosystem. *Geoderma* 333:1–9.

Stukenholtz, P.D., R.T. Koenig, D.J. Hole, and B.E. Miller. 2002. Partitioning the nutrient and nonnutrient contributions of compost to dryland-organic wheat. *Compost Science & Utilization* 10 (3):238–243.

Syswerda, S.P., A.T. Corbin, D.L. Mokma, A. Kravchenko, and G.P. Robertson. 2011. Agricultural management and soil carbon storage in surface vs. deep layers. *Soil Science Society of American Journal* 75 (1):92-101.https://doi.org/10.2136/sssaj2009.0414

Tautges, N.E., J.L. Chiartas, A.C.M. Gaudin, A.T. O'Geen, I. Herrera, and K.M. Scow. 2019. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. *Global Change Biology* 25 (11):3753–3766.https://doi.org/10.1111/gcb.14762

Wander, M.M., M.G. Bidart, and S. Aref. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. *Soil Science Society of America Journal* 62 (6):1704–1711.https://doi.org/10.2136/sssaj1998.03615995006200060031x

Wang, B., L. Gao, W. Yu, X. Wei, J. Li, S. Li, X. Song, G. Liang, D. Cai, and X. Wu. 2019. Distribution of soil aggregates and organic carbon in deep soil under long-term conservation tillage with residual retention in dryland. *Journal of Arid Land* 11 (2):241–254.https://doi.org/10.1007/s40333-019-0094-6

Wei, X., M. Shao, W.J. Gale, X. Zhang, and L. Li. 2013. Dynamics of aggregate-associated organic carbon following conversion of forest to cropland. *Soil Biology and Biochemistry* 57:876–883.

Xue, Q., Z. Zhu, J.T. Musick, B.A. Stewart, and D.A. Dusek. 2003. Root growth and water uptake in winter wheat under deficit irrigation. *Plant and Soil* 257 (1):151–161.https://doi.org/10.1023/A:1026230527597

Table 1. Initial physical and chemical properties at the 0 to 30 cm depth under a winter wheat-annual fallow (WW-AF) experiment at Snowville (SN) and Blue Creek (BC).

	Sand	Silt	Clay	Textural class	pH	SOC	TN	Olsen P
	———	% ———				—— g kg^{-1} ——		mg kg^{-1}
SN	14 (1.45)[†]	69 (1.40)	17(0.72)	Silt Loam	7.2	9.60	1.32	38.1
BC	19 (1.07)	56 (0.59)	25 (0.51)	Silt Loam	8.5	10.7	1.28	5.20

[†]Standard errors in parentheses

Table 2. Soil bulk densities at different depths under a winter wheat-annual fallow (WW-AF) experiment at Snowville and Blue Creek.

	Bulk density					
	Mg m^{-3}					
Depth	Snowville			Blue Creek		
cm	0	25	50	0	25	50
0-10	1.25a[a]	1.21a	1.04b	1.15a	1.10a	1.08a
10-30	1.27a	1.19a	1.18a	1.16a	1.16a	1.15a
30-60	1.25a	1.24a	1.14a	1.27a	1.23a	1.26a
60-90	1.14a	1.16a	1.29a	1.23a	1.27a	1.20a

[a] Means within the same row with the same lower-case letter are not significantly different according to adjusted Tukey (.05).

Table 3. Organic carbon concentrations and stock in soil fractions and bulk soil at the historical site (HT) in 0-60 cm depth 24 years after compost application (n=3).

Depth	Compost	MAOM	SMA	POM	TOC	MAOM	SMA	POM	TOC
cm	Mg DW ha^{-1}	g OC kg^{-1} fraction			g kg^{-1}	——— Mg OC ha^{-1} ———			
0-10	0	14.6a	5.90a	54.6b[a]	12.4a	12.0a	2.03a	2.81a	15.0a
	50	19.0a	6.90a	84.1a	13.7a	15.1a	2.54a	4.51a	16.6a
10-30	0	8.80b	4.30a	19.4b	7.50a	16.6b	1.87b	1.27b	18.1b
	50	11.4a	5.60a	34.4a	8.60a	20.0a	3.14a	2.48a	20.7a
30-60	0	1.60a	4.40a	14.3a	3.30a	5.15a	1.30a	0.33a	12.3a
	50	2.70a	4.40a	18.9a	2.70a	8.59a	1.99a	0.65a	10.3a
	Source of variation	ANOVA							
0-10	Compost	NS[†]	NS	**	NS	NS	NS	NS	NS
10-30		**	NS	**	NS	*	*	**	*
30-60		NS	NS	NS	NS	NS	NS	NS	NS

[§] MAOM = mineral associated organic matter, SMA = mineral associated organic matter in sand fraction, POM = particulate organic matter, and SOC = total soil organic carbon.

[a] Means within the same column with the same lower-case letter are not significantly different according to adjusted Tukey (.05). * Significant at the .05 probability level, **Significant at the .01 probability level. **Significant at the .001 probability level, [†] NS, nonsignificant.

Table 4. Main effects of compost and year on OC concentrations in soil fractions and bulk soil at Snowville (SN) and Blue Creek (BC) in 0-90 cm depth (n=3).

Depth	Compost	Snowville				Blue Creek			
		MAOM[§]	SMA	POM	TOC	MAOM	SMA	POM	TOC
cm	Mg DW ha^{-1}	g OC kg^{-1} fraction							
0-10	0	7.50b[a]	2.90b	67.2b	10.0b	10.8b[a]	3.94b	97.7b	11.1b
	25	12.8a	6.30a	111a	16.4a	14.8a	7.29ab	140ab	15.9a
	50	13.6a	5.50a	124a	17.8a	15.5a	8.18a	172a	20.0a
10-30	0	5.50b	1.80b	35.4b	9.40b	6.76a	2.28a	29.4b	10.0a
	25	12.2a	5.00a	52.2ab	12.1a	7.25a	3.01a	60.9a	12.9a
	50	12.0a	6.40a	73.6a	13.6a	8.01a	2.65a	74.5a	12.8a
30-60	0	1.80b	2.50a	5.50b	1.60a	4.08b	4.08a	8.30a	5.58a
	25	2.50ab	3.90a	23.6a	2.00a	4.63ab	3.61a	16.7a	6.59a
	50	3.40a	2.70a	19.6a	2.10a	6.14a	4.19a	20.0a	7.20a
60-90	0	1.70a	1.90a	3.75a	2.00a	2.35b	4.08a	8.30b	5.36a
	25	3.10a	2.40a	5.63a	3.70a	3.64ab	5.03a	16.8a	5.25a
	50	3.60a	3.20a	6.23a	4.40a	3.99a	4.84a	31.2a	6.31a
	Year								
0-10	1	10.2b	3.33b	78.6b	15.4a	16.3a	8.64a	129a	17.3a
	3	12.3a	6.44a	123a	14.1a	11.1b	4.29b	144a	14.1b
10-30	1	6.87b	4.55a	48.2b	13.1a	9.13a	1.71a	42.2b	13.8a
	3	12.9a	4.25a	59.2a	10.2b	5.56b	3.58b	67.7a	9.95b
30-60	1	1.50b	2.13b	4.07b	6.33a	3.81b	6.49a	14.1b	7.43a
	3	3.62a	3.94a	28.4a	4.94b	6.08a	1.43b	16.0b	5.48b
60-90	1	0.94b	1.87	4.61	3.34	4.02a	6.26a	33.9a	7.43a
	3	4.25a	3.09	17.6	3.31	2.63b	2.87b	3.58b	3.86b

	Sources of variation				ANOVA				
0-10	Compost	**	**	**	**	*	*	*	**
	Year	*	***	***	NS[†]	**	***	NS	**
	Compost*Year	NS	NS	NS	NS	NS	NS	NS	NS
10-30	Compost	**	**	*	**	NS	NS	**	NS
	Year	***	NS	*	**	**	***	**	**
	Compost*Year	NS	NS	NS	NS	NS	NS	NS	NS
30-60	Compost	*	NS	**	NS	*	NS	NS	NS
	Year	***	**	***	**	**	***	NS	**
	Compost*Year	NS	NS	NS	NS	NS	NS	NS	NS
60-90	Compost	NS	NS	NS	NS	*	NS	**	NS
	Year	*	NS	NS	NS	**	***	***	***
	Compost*Year	NS	NS	NS	NS	NS	NS	NS	NS

[§] MAOM = mineral associated organic matter, SMA = mineral associated organic matter in sand fraction, POM = particulate organic matter, and SOC = total soil organic carbon.

[a] Means within the same column with the same lower-case letter are not significantly different according to adjusted Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level. **Significant at the .001 probability level,

[†] NS, nonsignificant.

Table 5. The main effects of compost and year on bulk soil and soil fraction OC stock at Snowville and Blue Creek in 0-90 cm depth.

		Snowville				Blue Creek			
Depth	Compost	MAOM[§]	SMA	POM	TOC	MAOM	SMA	POM	TOC
cm	Mg DW ha^{-1}	Mg OC ha^{-1}							
0-10	0	6.56b[a]	0.98b	2.29b	12.5b	9.59a	0.97a	2.40b	12.9b
	25	9.93a	2.40a	7.01a	20.1a	12.4a	1.50a	5.34ab	17.5ab
	50	9.95a	1.39a	7.42a	18.7a	12.4a	2.00a	8.23a	21.7a
10-30	0	10.0b	1.18b	1.50a	23.7b	12.9a	0.90a	0.75b	23.3a
	25	20.4a	3.29a	2.70a	29ab	13.8a	1.02a	2.63a	29.6a
	50	20.4a	3.96a	5.55a	32.2a	15.1a	1.06a	3.19a	29.6a
30-60	0	5.69b	0.92a	0.21a	6.00a	18.0a	1.55a	0.38a	21.2a
	25	7.39ab	1.79a	1.07a	7.47a	19.1a	1.16b	0.51a	24.8a
	50	10.6a	0.89a	0.88a	7.31a	22.0a	1.85a	0.75a	26.6a
60-90	0	5.19a	0.54a	0.08a	7.28a	10.6b	1.55a	0.36b	19.8a
	25	6.81a	0.43a	0.18a	9.64a	18.2a	1.66a	0.75b	20.5a
	50	6.12a	1.06a	0.30a	13.2a	13.2ab	2.15a	2.57a	22.3a
	Year								
0-10	1	7.66b	1.14b	5.71a	17.9a	13.6a	1.90a	7.02a	19.1a
	3	9.96a	2.03a	5.43a	16.3a	9.37b	1.08b	3.63b	15.6b
10-30	1	11.1b	3.11a	4.21a	31.8a	17.2a	0.56b	3.48a	32.0a
	3	22.7a	2.51a	2.30b	24.8b	10.6b	1.42a	0.90b	23.0b
30-60	1	4.58b	0.5b	0.42b	3.48b	20.2a	2.20a	0.85a	27.9a
	3	11.2a	1.89a	1.02a	10.4a	19.2a	0.84b	0.24a	20.6b
60-90	1	3.20b	0.45a	0.26b	15.4a	19.6a	2.02a	2.40a	27.5a
	3	13.1a	0.96a	0.12b	7.56a	8.37b	1.50b	0.05b	14.2b

	Sources of variation	ANOVA							
0-10	Compost	*	**	*	*	NS[†]	NS	*	**
	Year	**	**	NS	NS	**	*	***	**
	Compost*Year	NS	NS	NS	NS	NS	NS	NS	NS
10-30	Compost	**	**	**	*	NS	NS	**	NS
	Year	**	NS	**	**	*	*	**	**
	Compost*Year	NS	NS	NS	NS	NS	NS	NS	NS
30-60	Compost	*	NS	NS	NS	NS	*	NS	NS
	Year	**	*	*	*	NS	***	NS	**
	Compost*Year	NS	NS	NS	NS	*	NS	NS	NS
60-90	Compost	NS	NS	NS	NS	*	NS	**	NS
	Year	**	NS	NS	NS	***	**	**	**
	Compost*Year	NS	NS	NS	NS	NS	NS	**	NS

[§] MAOM = mineral associated organic matter, SMA = mineral associated organic matter in sand fraction, POM = particulate organic matter, and SOC = total soil organic carbon.

[a] Means within the same column with the same lower-case letter are not significantly different according to adjusted Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, [†] NS, nonsignificant.

Table 6. The main effects of compost and year on the dissolved organic carbon (DOC) content at the Historical, Snowville, and Blue Creek sites at 0-90 cm depth (n=4).

Depth cm	Compost Mg DW ha^{-1}	Historical	Snowille DOC (mg kg^{-1})	Blue Creek
0-30	0	43.8a[a]	45.5b	96.5ab
	25	-	56.7ab	148a
	50	39.7a	67.6a	141a
30-60	0	37.3a	84.8a	78.8a
	25	-	74.7ab	74.7a
	50	41.6a	57.5b	82.5a
60-90	0	-	56.1a	40.7a
	25	-	45.1a	49.9a
	50	-	31.9a	39.1a
	Year			
0-30	1	-	42.5b	99.4b
	3	-	70.7a	157a
30-60	1	-	51.0b	24.4a
	3	-	93.6a	133a
60-90	1	-	36.9a	10.8b
	3	-	57.9a	75.6a
	Source of variation		ANOVA	
0-30	Compost	NS	*	**
	Year	-	**	***
	Compost*Year	-	NS	NS
30-60	Compost	NS	**	NS
	Year	-	***	***
	Compost*Year	-	NS	NS
60-90	Compost	-	NS	NS
	Year	-	NS	***
	Compost*Year	-	NS	NS

[a] Means within the same column with the same lower-case letter are not significantly different according to adjusted Tukey (.05).

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level, † NS, nonsignificant.

- Not determined

Table 7. Correlation between the different organic carbon fractions across the three sites in the 0-90 cm depth. Significant values are asterisked.

Site		MAOM§	SMA	POM	TOC	DOC
	MAOM	1				
	SMA	0.61*	1			
Historical	POM	0.90***	0.56	1		
	TOC	0.79**	0.51	0.84**	1	
	DOC	0.14	-0.54	0.25	0.2	1
	MAOM	1				
	SMA	0.72***	1			
Snowville	POM	0.87***	0.72***	1		
	TOC	0.67***	0.47***	0.76***	1	
	DOC	0.17	0.34**	0.16	-0.15	1
	MAOM	1				
	SMA	0.52***	1			
Blue Creek	POM	0.79***	0.59***	1		
	TOC	0.85***	0.67***	0.89***	1	
	DOC	0.34**	-0.11	0.39**	0.28*	1

§ MAOM = mineral associated organic matter, SMA = mineral associated organic matter in sand fraction, POM = particulate organic matter, and SOC = total soil organic carbon.

* Significant at the .05 probability level, **Significant at the .01 probability level.

**Significant at the .001 probability level

Table S1. The main effects of compost and year on the mass fraction, mass contribution, and percentage contribution of fractions to soil organic carbon (SOC) ± standard deviation at the historical site (n=3).

Compost	Depth	Sum of fraction yield	Initial weight-fraction yield	Fractions	Mass			SOC					
(Mg DW ha^{-1})	(cm)	(g)	(g)		($g\ kg^{-1}$ soil)			($g\ OC\ kg^{-1}$ soil)			(% of total)		
				MOAM	677.0	±	31.6	9.9	±	1.4	71.0	±	6.3
	0-10	19.8	0.2	SMA	280.8	±	31.8	1.7	±	0.3	12.1	±	2.5
				POM	42.3	±	4.40	2.3	±	0.4	16.9	±	4.1
				MOAM	786.8	±	55.5	6.9	±	0.9	83.9	±	2.3
0	10-30	19.9	0.1	SMA	185.3	±	50.8	0.8	±	0.1	9.60	±	2.5
				POM	27.9	±	5.10	0.5	±	0.1	6.40	±	0.8
				MOAM	872.4	±	64.3	1.4	±	0.1	68.3	±	9.0
	30-60	19.8	0.3	SMA	118.3	±	64.9	0.5	±	0.3	25.1	±	11.8
				POM	9.3	±	1.60	0.1	±	0.0	6.60	±	2.8
				MOAM	652.9	±	6.50	12.4	±	1.2	68.2	±	3.0
	0-10	19.6	0.4	SMA	302.9	±	5.80	2.1	±	0.1	11.5	±	0.6
				POM	44.2	±	6.90	3.7	±	0.6	20.3	±	2.6
				MOAM	733.6	±	25.3	8.3	±	0.5	78.1	±	2.0
50	10-30	19.7	0.3	SMA	236.2	±	22.6	1.3	±	0.2	12.2	±	1.0
				POM	30.2	±	5.90	1.0	±	0.2	9.70	±	1.0
				MOAM	828.4	±	110.7	2.3	±	0.7	68.5	±	21.6
	30-60	19.9	0.1	SMA	156.5	±	106.8	0.8	±	0.8	23.7	±	23.5
				POM	15.1	±	4.50	0.3	±	0.1	7.80	±	2.1

Table S2. The main effects of compost and year on the mass fraction, mass contribution, and percentage contribution of fractions to soil organic carbon (SOC) ± standard deviation at Snowville (n=4).

Depth (cm)	Compost (Mg DW ha^{-1})	Fraction yield (g)	Initial weight-fraction yield (g)	Fraction	Mass (g kg^{-1} soil)	SOC (g OC kg^{-1} soil)	SOC (% of total)
0-10	0	19.1	0.9	MOAM	688.8 ± 36.8	5.2 ± 2.4	61.4 ± 16.2
				SMA	279.5 ± 30.7	1.0 ± 0.4	13.0 ± 4.90
				POM	31.7 ± 16.7	1.8 ± 0.5	25.6 ± 13.1
	25	18.9	1.1	MOAM	633.1 ± 68.7	8.1 ± 1.4	51.7 ± 5.30
				SMA	313.9 ± 64.4	1.9 ± 0.6	12.5 ± 3.90
				POM	53.0 ± 18.7	5.7 ± 2.0	35.7 ± 7.50
	50	19.5	0.5	MOAM	699.8 ± 55.1	9.5 ± 1.2	54.5 ± 10.6
				SMA	243.1 ± 40.8	1.3 ± 0.6	7.40 ± 2.80
				POM	57.1 ± 22.3	7.0 ± 2.8	38.1 ± 10.6
10-30	0	19.5	0.5	MOAM	726.5 ± 44.2	4.0 ± 2.1	76.2 ± 10.7
				SMA	255.4 ± 41.5	0.5 ± 0.2	9.50 ± 4.70
				POM	18.1 ± 7.90	0.6 ± 0.2	14.3 ± 8.6
	25	19.6	0.4	MOAM	693.1 ± 86.3	8.5 ± 3.7	74.5 ± 11.7
				SMA	283.4 ± 79.3	1.4 ± 0.4	14.5 ± 7.60
				POM	23.4 ± 10.6	1.1 ± 0.4	11.0 ± 4.80
	50	19.8	0.2	MOAM	708.3 ± 47.7	8.6 ± 3.0	67.6 ± 13.4
				SMA	261 ± 37.1	1.7 ± 0.5	13.6 ± 4.20

Depth	Compost	Fraction yield	Initial weight-fraction yield	Fraction	Mass			SOC					
(cm)	(Mg DW ha^{-1})	(g)	(g)		(g kg^{-1} soil)			(g OC kg^{-1} soil)			(% of total)		
				POM	30.8	±	14	2.3	±	1.7	18.8	±	11.4
30-60	0	19.9	0.1	MOAM	886.9	±	29	1.6	±	1.1	83.0	±	6.4
				SMA	96.1	±	29.2	0.3	±	0.2	13.8	±	5.8
				POM	17.0	±	11.4	0.1	±	0	3.10	±	1.8
	25	19.9	0.1	MOAM	858.6	±	85.6	2.1	±	0.8	74.2	±	16
				SMA	119.1	±	70.3	0.5	±	0.5	15.3	±	9.5
				POM	22.3	±	25.8	0.3	±	0.3	10.5	±	10.4
	50	19.4	0.7	MOAM	867.8	±	53.3	3.0	±	1.5	83.5	±	7
				SMA	115	±	55.5	0.3	±	0.1	9.40	±	4.1
				POM	17.1	±	5.9	0.3	±	0.2	7.10	±	4.6
60-90	0	19.9	0.1	MOAM	902.3	±	39	1.1	±	0.9	81.6	±	13.1
				SMA	84.8	±	36.4	0.20	±	0.1	15.2	±	9.8
				POM	12.9	±	14	0.01	±	0	3.20	±	3.7
	25	19.8	0.2	MOAM	929.6	±	30.9	2.0	±	1.5	91.8	±	4.7
				SMA	60.2	±	28.2	0.1	±	0	4.80	±	3.9
				POM	10.2	±	8.6	0.1	±	0.1	3.50	±	0.9
	50	19.9	0.1	MOAM	900.6	±	9.4	2.6	±	2.1	85.5	±	5.5
				SMA	86.2	±	15	0.3	±	0.2	9.00	±	3
				POM	13.2	±	8.2	0.1	±	0.1	5.50	±	4.4

Table S3. The main effects of compost and year on the mass fraction, mass contribution, and percentage contribution of fractions to SOC ± standard deviation at Blue Creek (n=4).

Depth	Compost	Fraction yield	Initial weight-fraction yield	Fraction	Mass			SOC					
(cm)	(Mg DW ha^{-1})	(g)	(g)		(g kg $^{-1}$ soil)			(g OC kg^{-1} soil)			(% of total)		
0-10	0	19.9	0.1	MOAM	768.9	±	34.2	8.3	±	1.5	75.5	±	9.3
				SMA	210.5	±	33.0	0.8	±	0.5	7.1	±	3.2
				POM	20.7	±	9.0	2.1	±	1.1	17.4	±	8.0
	25	19.8	0.2	MOAM	770.2	±	8.3	11.7	±	3.8	64.9	±	6.0
				SMA	193.4	±	12.7	1.3	±	0.7	7.0	±	2.1
				POM	36.4	±	15.9	5.2	±	2.4	28.1	±	5.6
	50	19.9	0.1	MOAM	734.4	±	49.3	11.1	±	2.6	56.6	±	9.7
				SMA	222.1	±	51.1	1.9	±	0.8	9.7	±	4.0
				POM	43.5	±	21.5	7.2	±	4.0	33.7	±	8.3
10-30	0	19.8	0.2	MOAM	818.5	±	29.8	5.5	±	1.4	88.2	±	5.1
				SMA	166.8	±	30.2	0.4	±	0.3	7.0	±	5.7
				POM	14.6	±	11.0	0.3	±	0.2	4.8	±	1.9
	25	19.8	0.2	MOAM	830.7	±	33.8	5.8	±	2.6	82.1	±	4.7
				SMA	152.1	±	32.9	0.4	±	0.2	6.8	±	3.4
				POM	17.2	±	12.2	0.8	±	0.4	11.1	±	4.6
	50	19.8	0.2	MOAM	806.1	±	32.1	6.7	±	2.4	79.5	±	8.0

Depth	Compost	Fraction yield	Initial weight-fraction yield	Fraction	Mass			OC					
(cm)	(Mg DW ha^{-1})	(g)	(g)		(g kg^{-1} soil)			(g OC kg^{-1} soil)			(% of total)		
				SMA	169.4	±	33.2	0.5	±	0.3	7.0	±	5.2
				POM	24.5	±	20.7	1.4	±	1.1	15.5	±	8.8
30-60	0	19.6	0.4	MOAM	811.9	±	28.8	3.3	±	1.2	79.6	±	15.3
				SMA	178.6	±	28.3	0.7	±	0.5	18.0	±	13.3
				POM	9.5	±	7.3	0.1	±	0.1	2.5	±	2.4
	25	19.6	0.4	MOAM	853.2	±	21.5	4.5	±	1.6	85.6	±	11.1
				SMA	136.6	±	16.5	0.5	±	0.4	11.2	±	9.2
				POM	10.2	±	7.7	0.1	±	0.1	3.2	±	2.5
	50	19.7	0.3	MOAM	833.1	±	43.2	4.6	±	1.6	82.5	±	14.1
				SMA	156.2	±	41.8	0.6	±	0.5	13.6	±	11.7
				POM	10.7	±	7.3	0.2	±	0.1	3.9	±	2.6
60-90	0	19.5	0.5	MOAM	849.4	±	55.8	2.0	±	0.9	81.4	±	9.9
				SMA	141.4	±	54.3	0.3	±	0.2	15.3	±	12.1
				POM	9.1	±	5.8	0.1	±	0.1	3.3	±	3.2
	25	19.6	0.4	MOAM	855.5	±	24.3	3.2	±	1.7	82.4	±	7.2
				SMA	134.7	±	25.0	0.3	±	0.1	10.2	±	6.8
				POM	9.8	±	9.8	0.4	±	0.8	7.4	±	9.4
	50	19.7	0.3	MOAM	840.2	±	24.8	3.2	±	0.8	82.2	±	10.0
				SMA	146.1	±	21.0	0.3	±	0.2	8.9	±	6.8
				POM	13.7	±	11.2	0.5	±	0.5	10.1	±	11.0

FIGURE

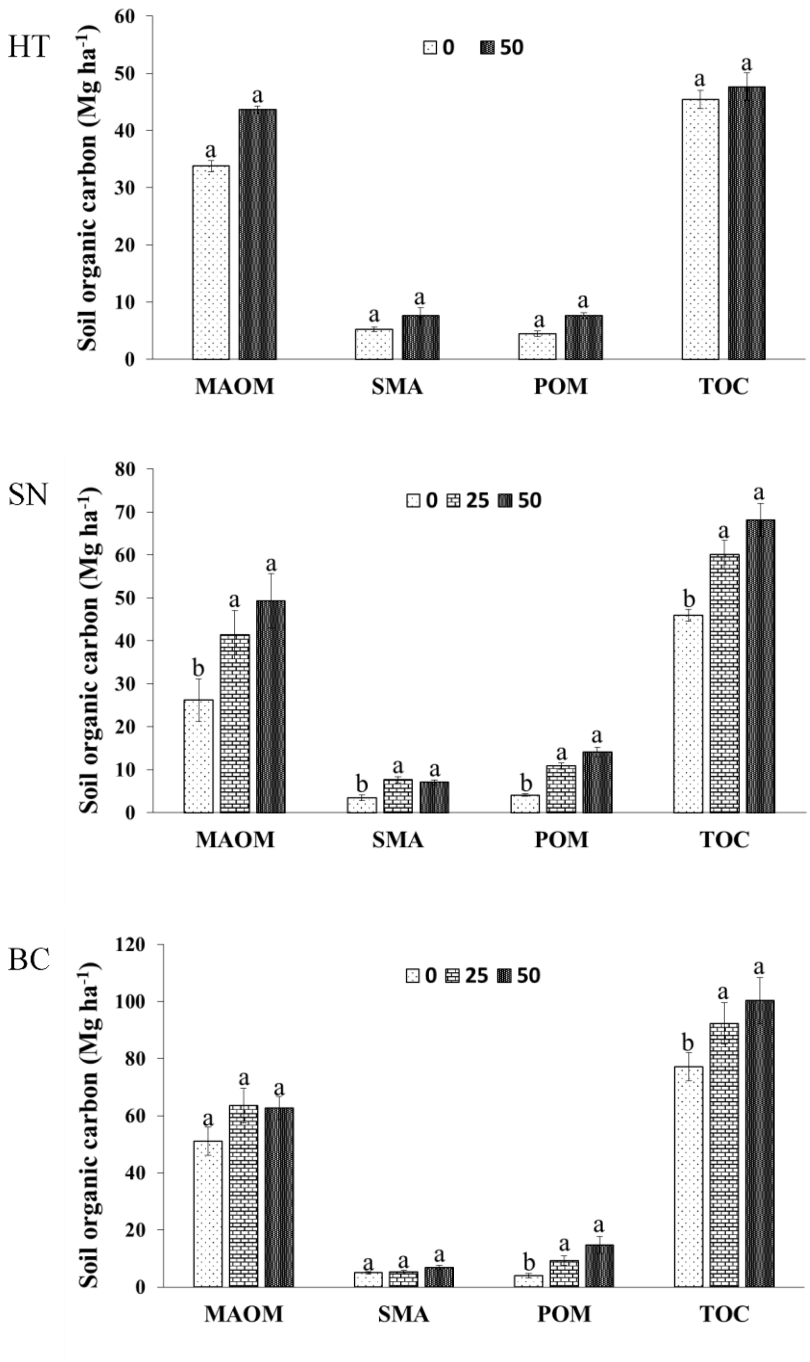


Figure 1. Soil organic carbon stock (0-90 cm) after 24 years (HT) and 3 years (SN and BC) of compost application in winter wheat-annual fallow (WW-AF). MAOM = mineral

associated organic matter, SMA = mineral associated organic matter in sand fraction, POM = particulate organic matter, and SOC = total soil organic carbon. HT = Historical plots (est. 1994), SN = Snowville plots (est. 2016), BC = Blue Creek plots (est. 2016). The same letter across SOC contents indicates no significant difference between treatments ($p < 0.05$).

CHAPTER V

CONCLUSION

Organic dryland wheat farmers are seeking sustainable soil management practices that are economically viable and environmentally friendly. Yield in organic dryland wheat is typically low and variable due to low soil fertility and precipitation. More so, organic dryland wheat farmers are faced with limited soil fertility options due to regulations, costs, and logistics. This study builds upon an earlier study by Reeve et al (2012) that reported the long-term benefits a single application of large quantities of compost on soil health and yield. Therefore, to provide more understanding on the observed long-term compost effect and to enable the farmers to make informed decisions, specific emphasis was placed on 1) understanding the effects of different rates of large quantities of single compost application and the inclusion of cover crops in fallow on soil health in two organic dryland soils of varying characteristics, 2) determining if variations in site characteristics can be used in predicting the effects of single-compost applications on phosphorus (P) cycling, 3) assess changes in surface and deep soil organic matter (SOM) pools.

For the first set of objectives, it was shown that there was a little synergy between cover crops and compost on soil health, as cover crops had minimal effects on soil health. This could be because the cover crops did not produce enough biomass to provide N to compensate for water use. When compared across sites, there appears to be variation in compost and cover crops response across sites. Cover crops increased dehydrogenase enzyme activity and readily mineralizable carbon at Snowville, which has a pH of 8.5 and

lower annual precipitation, compared with Blue Creek. The 25 and 50 Mg DW ha^{-1} compost rates had comparable effects on soil health. This finding is very important for organic dryland farmers in areas with very low annual precipitation and have limited restricted organic inputs to enhance soil health.

In the third chapter, it was shown that compost had varying effects on the biological cycling of P. Compost had a greater effect on organic P mineralization in soils where P is largely inaccessible as shown by higher acid phosphatase activity in Snowville and alkaline phosphatase activity at Blue Creek. Results from path analyses showed that the potential for rapid compost P mineralization and transfer into labile pools was greater in soils with relative higher fertility and annual precipitation compared with soils with low available P and pH 8.5. Thus, the long-term availability of compost applied P is likely to be greater in more marginal organic dryland soils.

Finally, compost application was found to affect surface and subsoil SOM pools. The results revealed that the one-time application of compost may be a good approach to build and maintain soil C in organic dryland WW-F systems in the IW. Results showed that 24 years after compost application at Snowville, POM-OC concentration was higher (0-10, and 10-30 cm) than control soils. Likewise, subsoil POM-OC and MAOM-OC were higher under compost amended soils across the sites. This shows that while changes in total SOC may be undetectable, OC changes in the SOM pools can be detected. Measuring changes in SOM pools may be a better approach to monitoring the effect of soil management practices on SOC. Further research is needed to determine if changes in quality of SOM pool is similar across different drylands WW-F systems.

Overall, the findings from this research clearly showed that the application of large quantities of compost is a good strategy for enhancing and maintaining soil health and C compared with the use of chicken manure, and inclusion of cover crops in fallow. Also, N additions through feather meal to compost did not offer a greater advantage to soil health, C, and P compared with compost only. The study recommends that for improving soil health in organic dryland agriculture 1) the effects of applying 25 Mg DW ha $^{-1}$ compost were comparable to using 50 Mg DW ha^{-1} compost, 2) the addition of cover crops had minimal effects on the benefits of compost, 3) long-term benefits if compost is potentially greater in soils with lower fertility, lower total annual precipitation, and with pH 8.5.

APPENDICES

APPENDIX A

SOIL WATER IN ORGANIC DRYLAND AGRICULTURE: EFFECTS OF A ONE-TIME COMPOST AND INCLUSION OF COVER CROPS DURING FALLOW

Understanding the effects of soil management practices on soil water in organic dryland agriculture is important for the adoption of sustainable practices with the potential to increase yield. The objective of this study was to evaluate how a one-time compost application and the inclusion of cover crops in the fallow rotation will affect soil water in two organic dryland grain soils with different microclimatic characteristics in Utah State. Soil water was monitored in 30 cm increments to a depth of 0.9 m (Snowville, 2 yr average annual precipitation is 290 mm) and 1.8 m (Blue Creek, 4 yr average annual precipitation is 485 mm) for 2 years (Snowville) and 4 years (Blue Creek). During the fallow rotation at Snowville, the gravimetric water content in the top 0.6 m of the soil decreased by about 0.05 to 0.1 g g^{-1} with the inclusion of cover crops, indicating a decrease in subsoil water availability under cover crops. Conversely, compost was found to increase soil water to 0.9 m depth in the early spring, indicating compost effect on deep soil water distribution. During the fallow rotation at Blue Creek, compost did not increase soil moisture storage, while cover crops decreased it by about 0.05 g g^{-1}. At Blue Creek, during the wheat rotation, significant effect of compost on water use was observed as deep as 1.2 m. The decline in soil water due to cover crop effect was detected earlier at Snowville, which has lower annual precipitation.

MATERIALS AND METHODS

The field layout and treatments are discussed in Chapter 2. At Snowville, the presence of calcium carbonate layer prevented the installation of access tubes, thus soil moisture was determined gravimetrically. Soil moisture was measured by collecting duplicate soil cores in each plot in 30 cm increments to 0.9 m depth during the fallow rotation in 2018 and 2019 (i.e. 2 and 4 years after compost application) from the north and south plots. Samples were collected fortnightly between the last week of April and the middle of June when sampling becomes restrictive due to the presence of calcium carbonate. Gravimetric soil water content was determined by oven-drying the soil for 24 hr at 105 ºC. At Blue Creek, 3 access tubes were installed in each plot. Soil water was measured in each tube in 30 cm intervals beginning from 0.3 m to 1.8 m using a neutron probe (Model 503 Hydroprobe, CPN International, Martinez, CA). Soil water in the 0.0 to 0.3 m depth was measured gravimetrically. The neutron probe was calibrated yearly using gravimetric moisture determined in the plot area.

The data were analyzed as described earlier in the statistical analysis section of CHAPTER TWO. The analysis was done using PROC GLIMMIX in SAS Studio University Edition (version 9.4, SAS Institute, Cary, NC, USA). Graphical presentations were made using Origin Pro 8.5 software (OriginLab, Northampton, MA, USA).

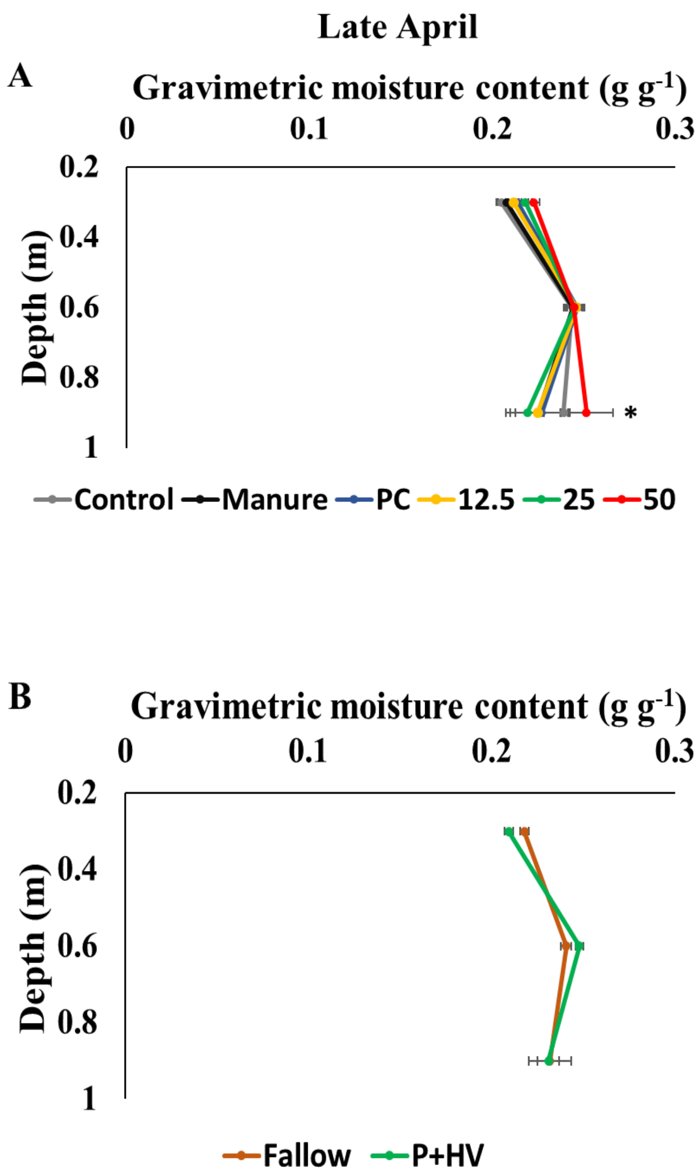
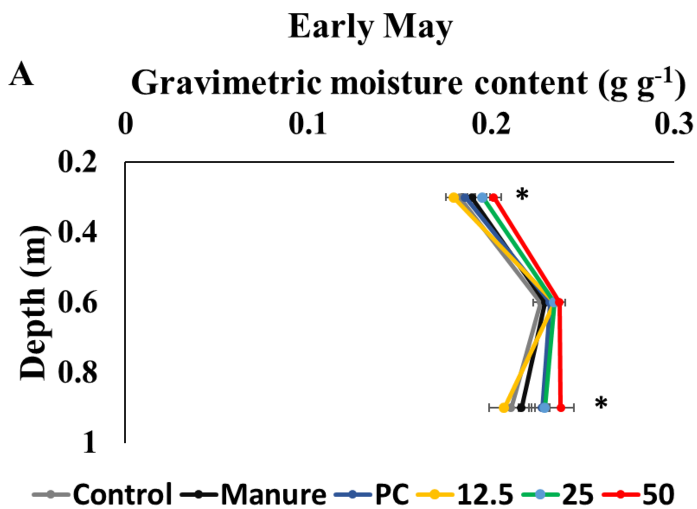


Figure A1: Main effects of compost (A) and cover crops (B) on soil water in late April averaged over 2 and 4 years (fallow rotation) after compost application at Snowville.

* Indicates significant differences using Tukey (0.05).



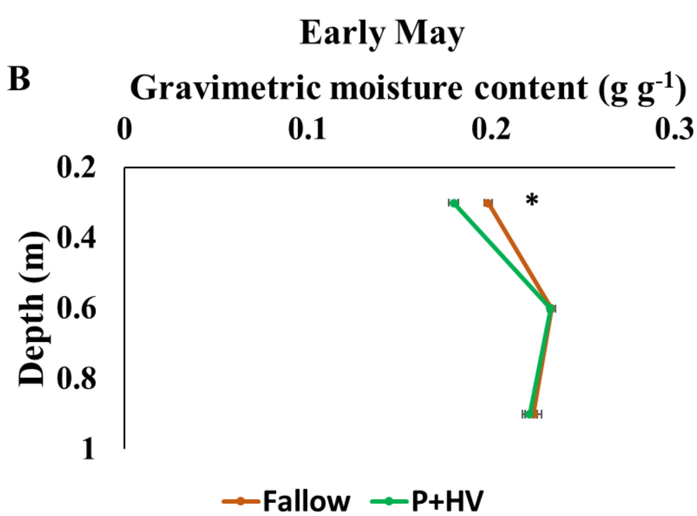
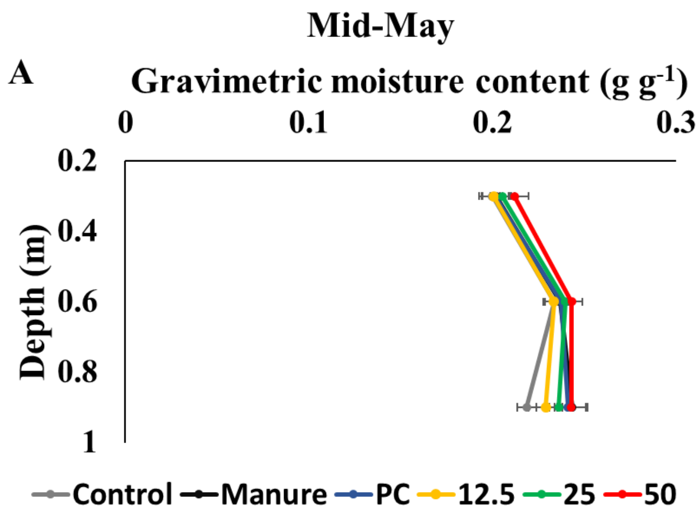


Figure A2: Main effects of compost (A) and cover crops (B) on soil water in early May averaged over 2 and 4 years (fallow rotation) after compost application at Snowville. * Indicates significant differences using Tukey (0.05).



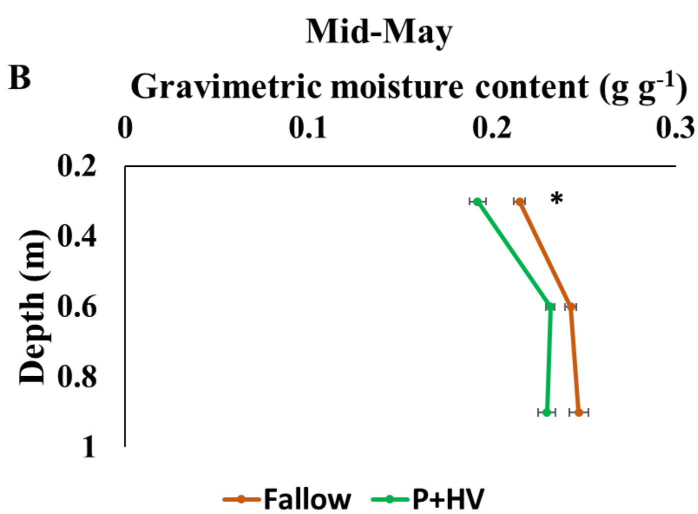
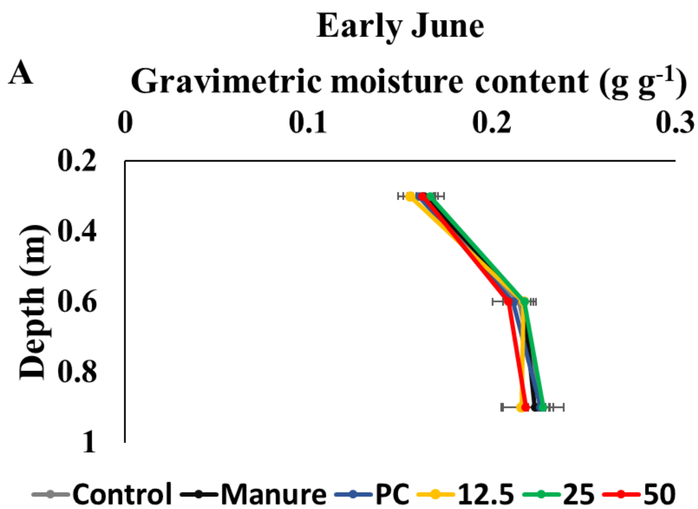


Figure A3: Main effects of compost (A) and cover crops (B) on soil water in mid-May averaged over 2 and 4 years (fallow rotation) after compost application at Snowville.

* Indicates significant differences using Tukey (0.05).



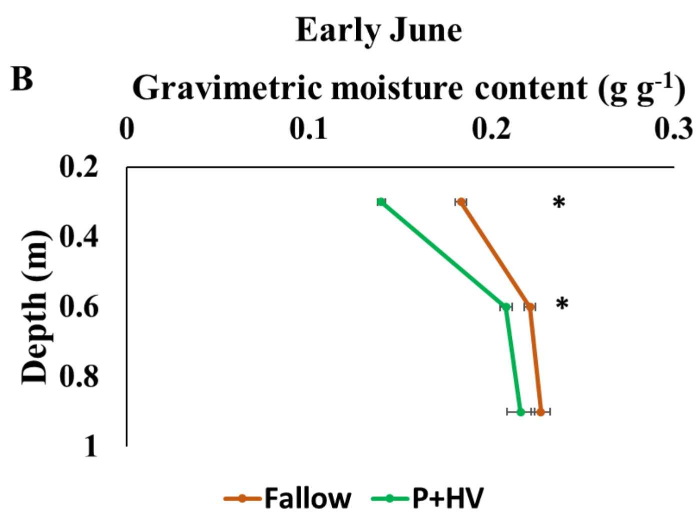
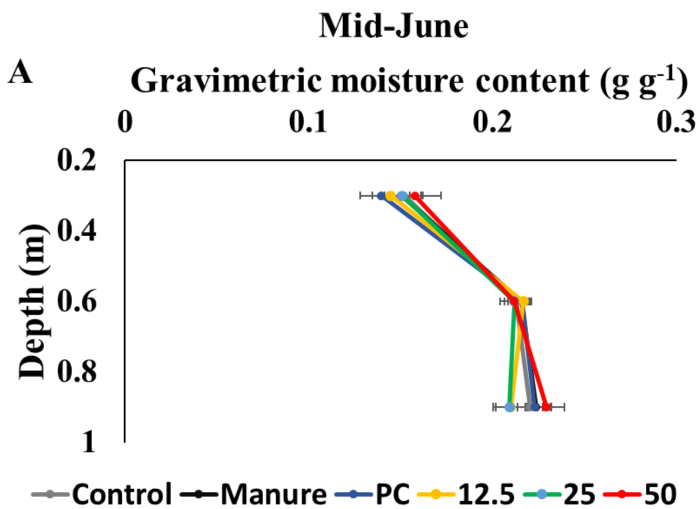


Figure A4: Main effects of compost (A) and cover crops (B) on soil water in early June averaged over 2 and 4 years (fallow rotation) after compost application at Snowville. * Indicates significant differences using Tukey (0.05).



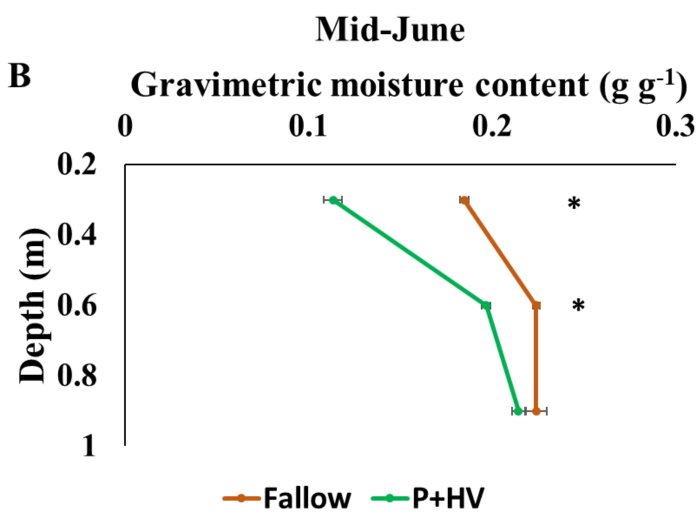


Figure A5: Main effects of compost (A) and cover crops (B) on soil water in mid-June averaged over 2 and 4 years (fallow rotation) after compost application at Snowville. * Indicates significant differences using Tukey (0.05).

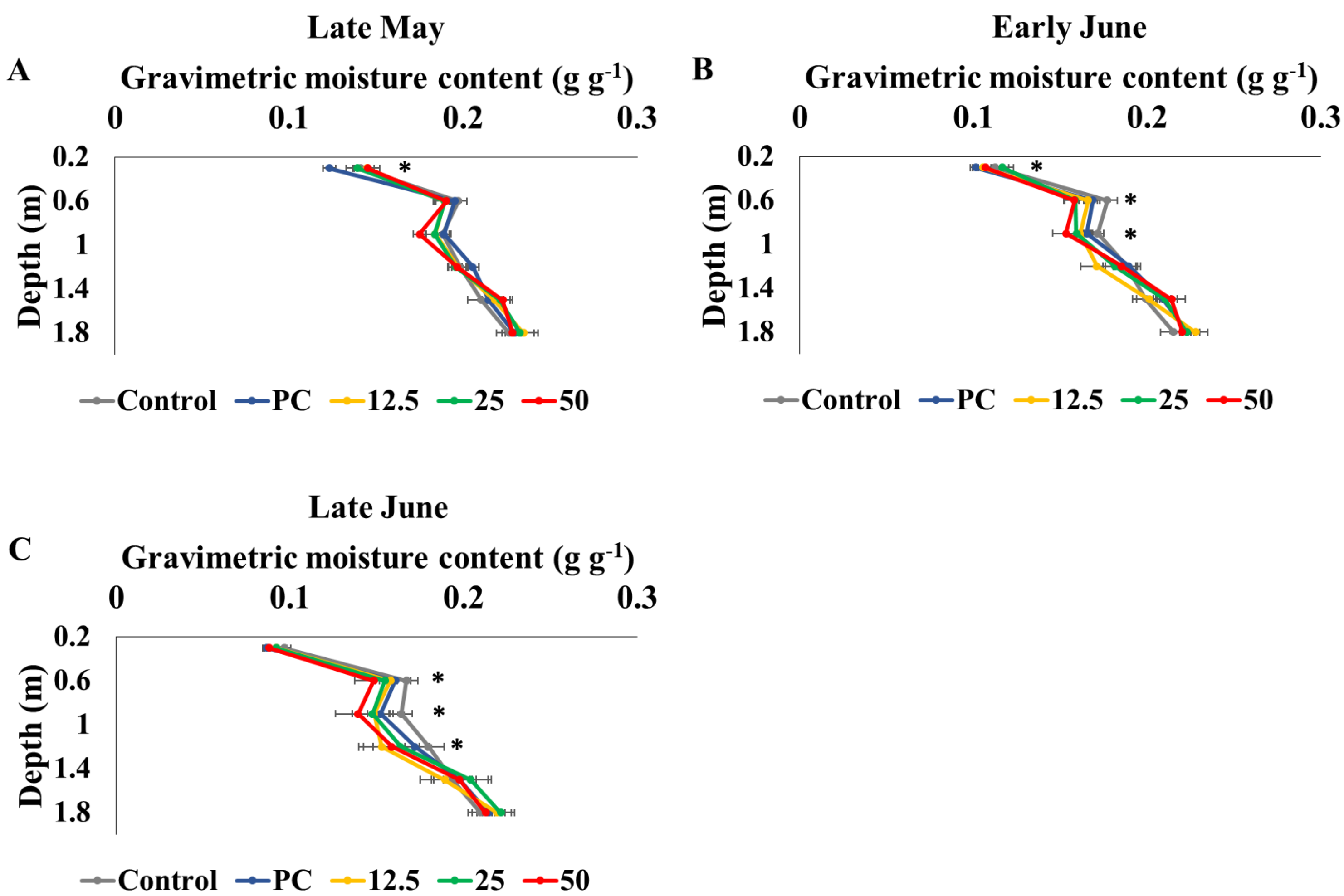


Figure A6: Main effects of compost 1 year (wheat rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

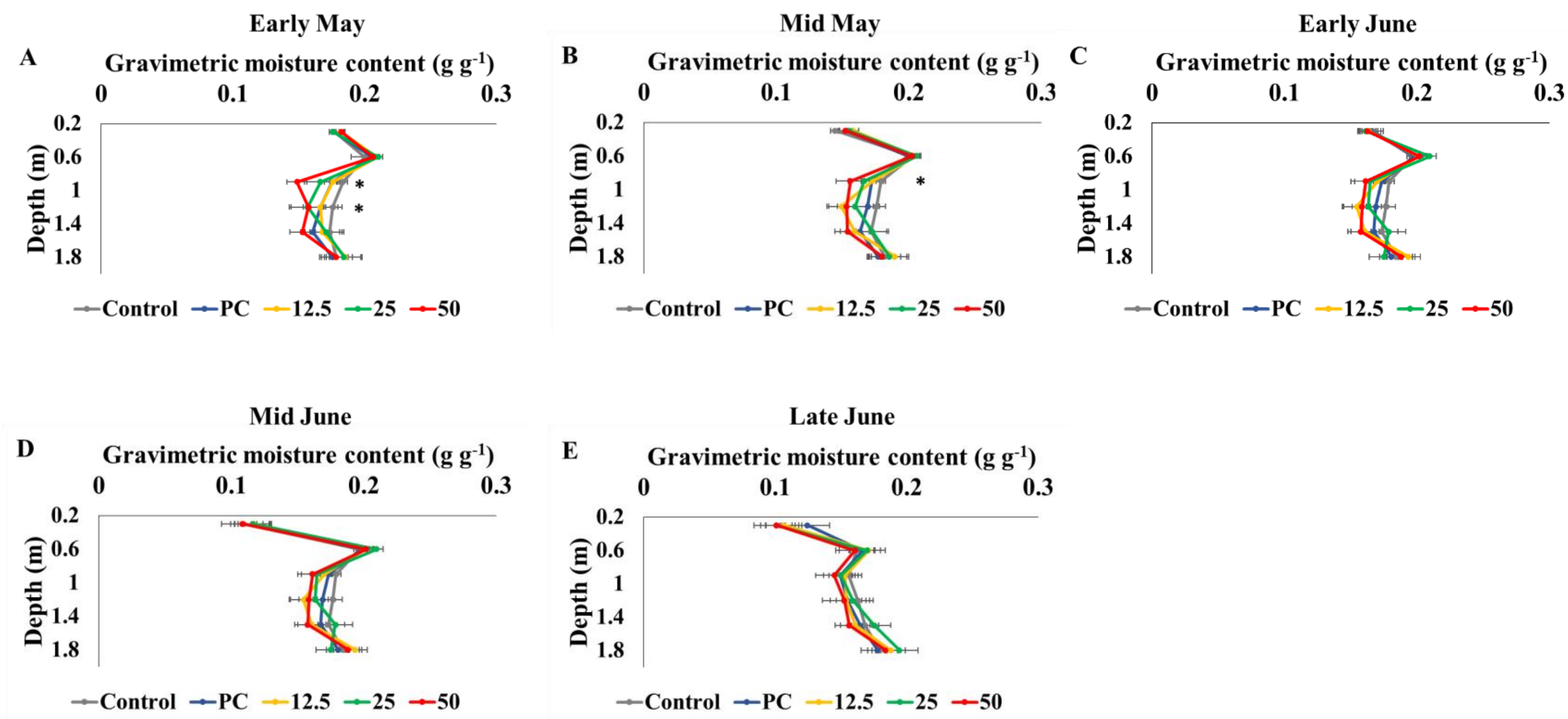


Figure A7: Main effects of compost 2 years (fallow rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

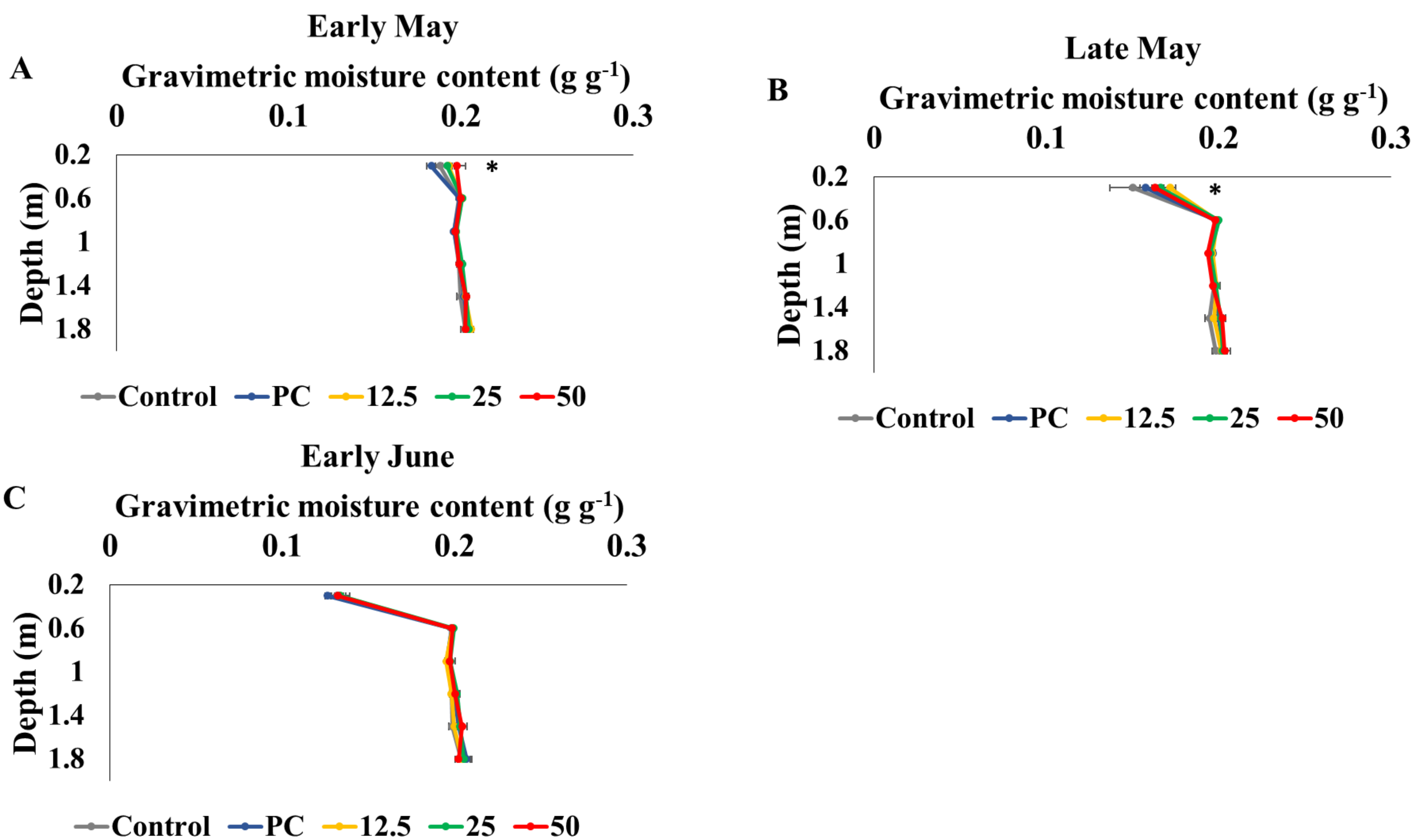


Figure A8: Main effects of compost 3 years (wheat rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

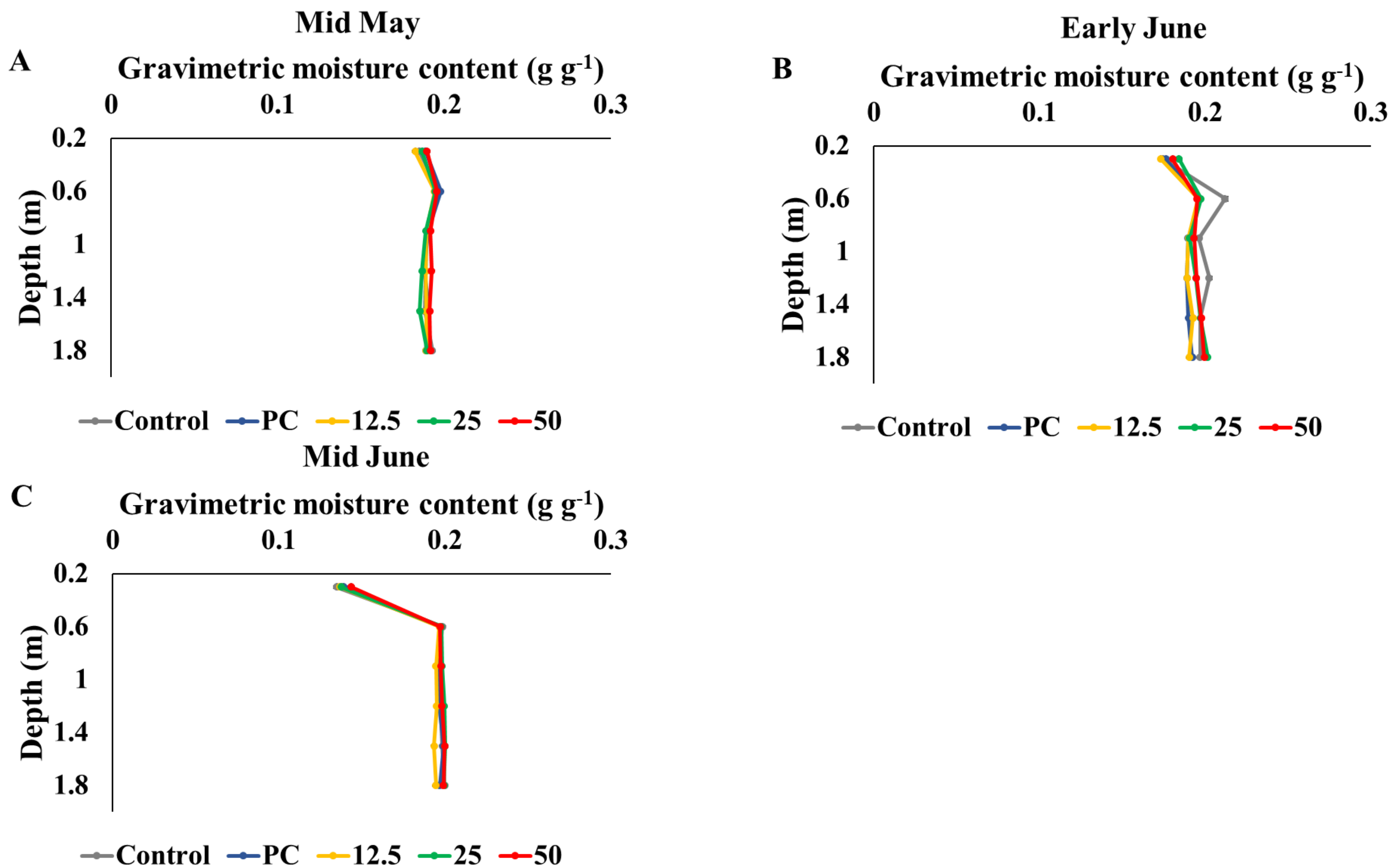


Figure A9: Main effects of compost 4 years (fallow rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

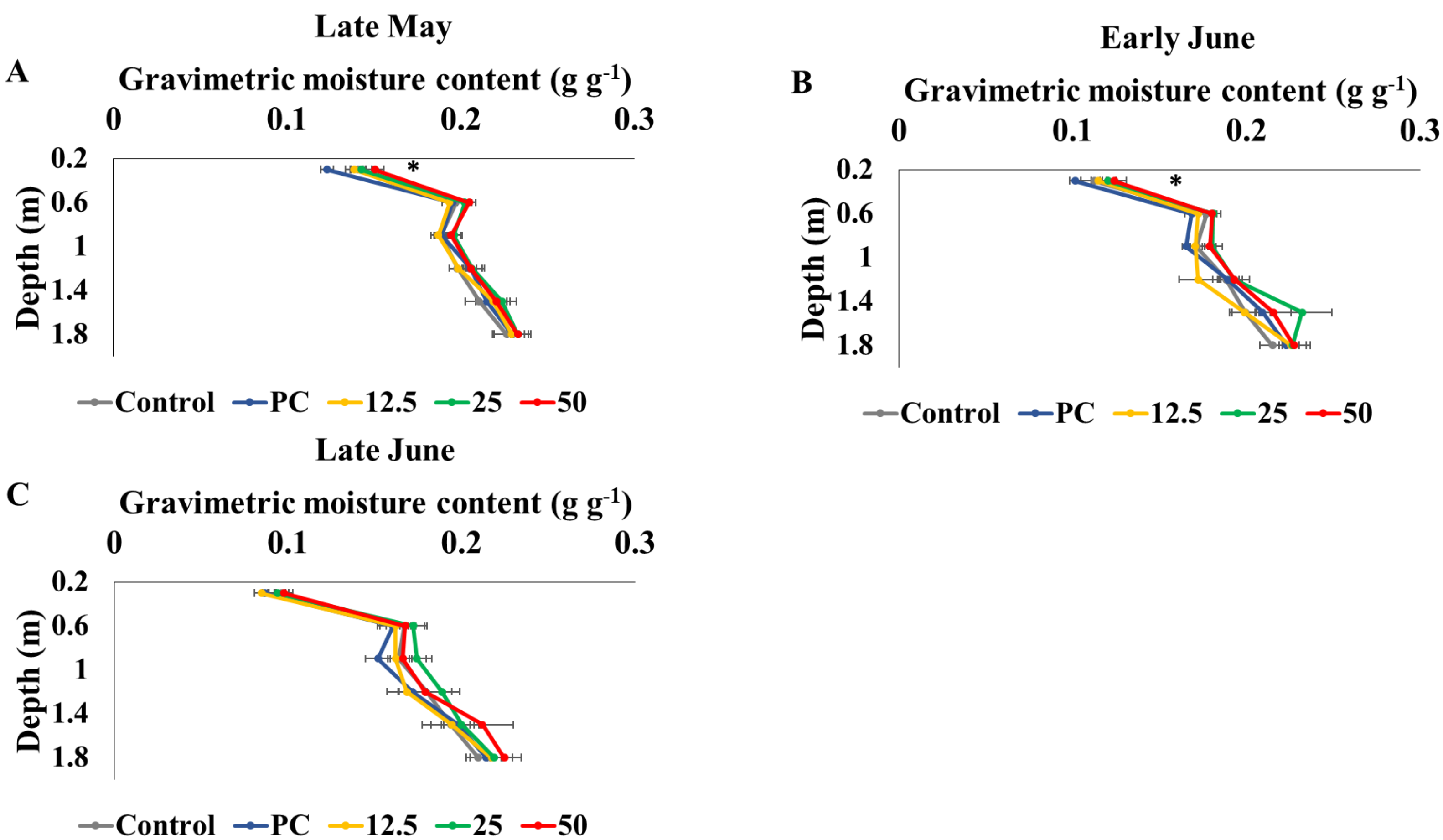


Figure A10: Main effects of compost 5 years (wheat rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

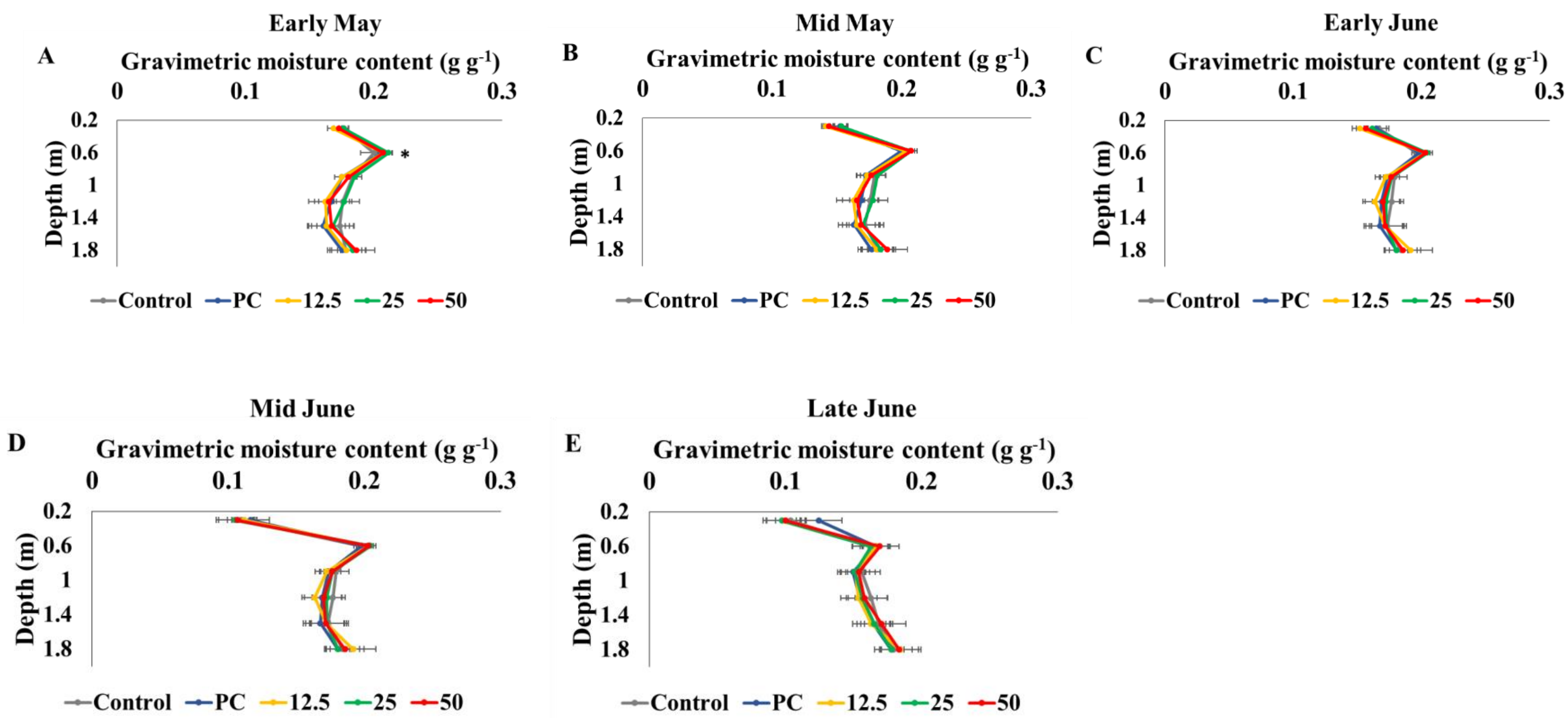


Figure A11: Main effects of compost 6 years (fallow rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

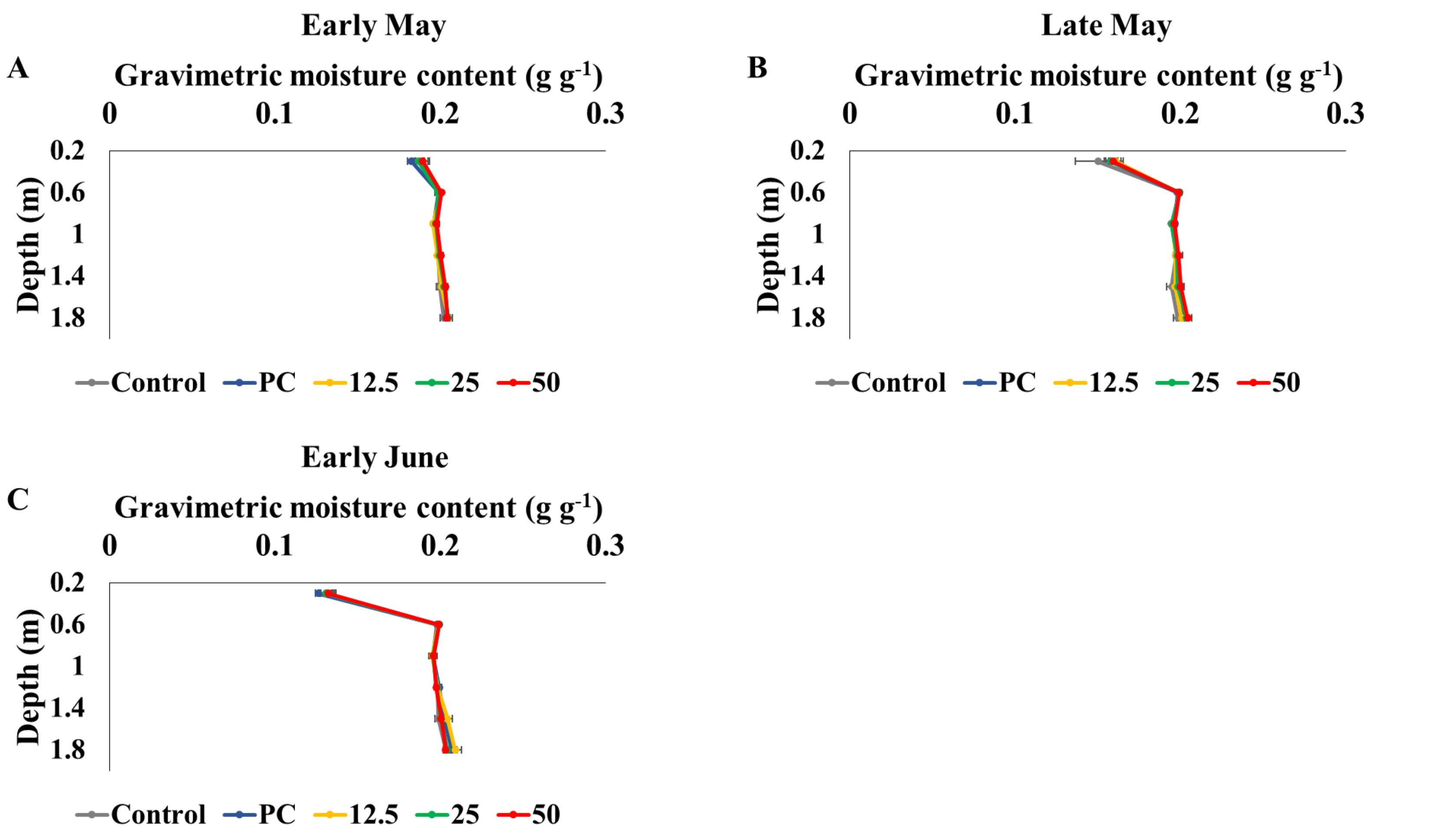


Figure A12: Main effects of compost 7 years (wheat rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

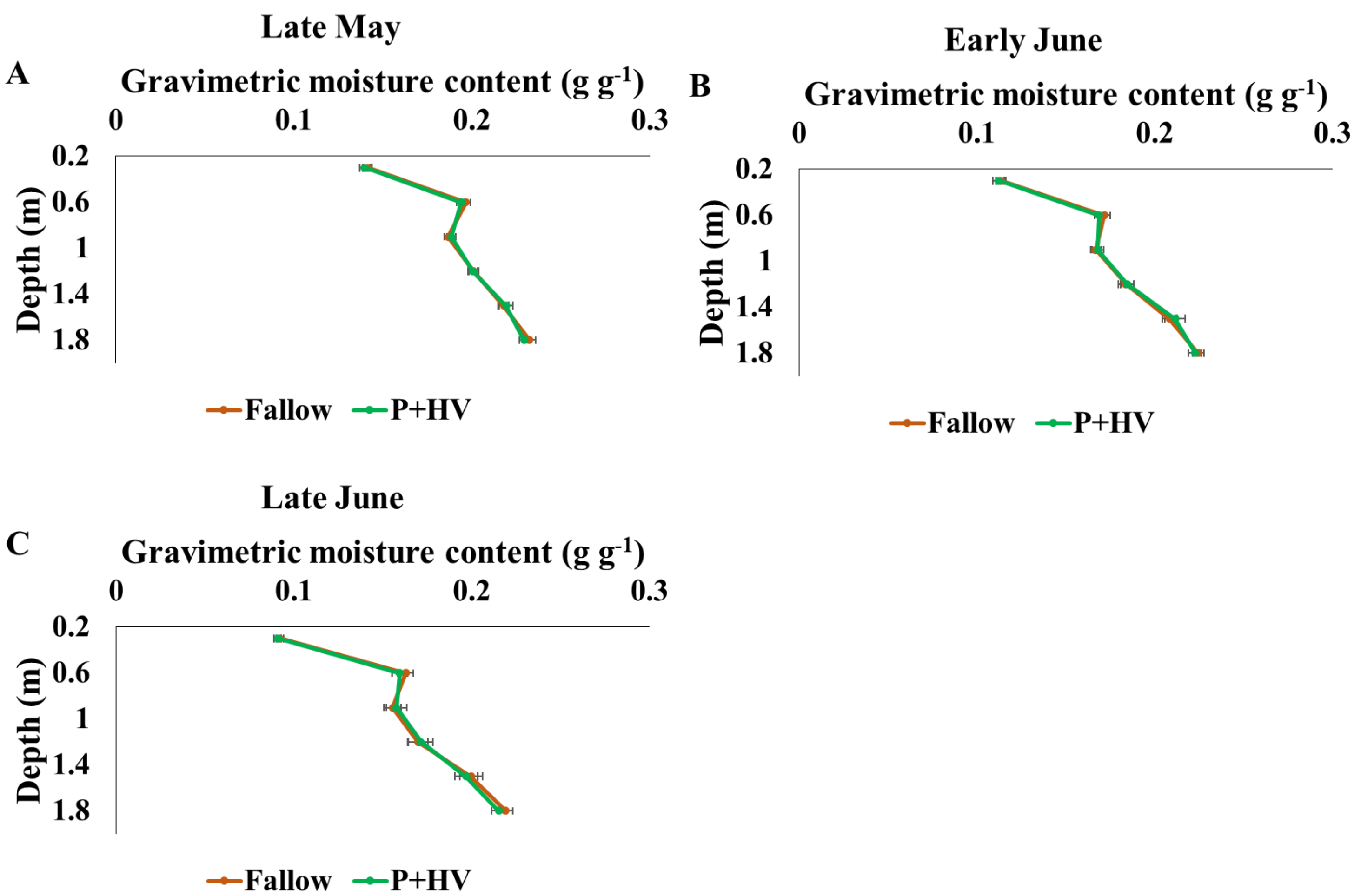


Figure A13: Main effects of cover crops 1 year (wheat rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

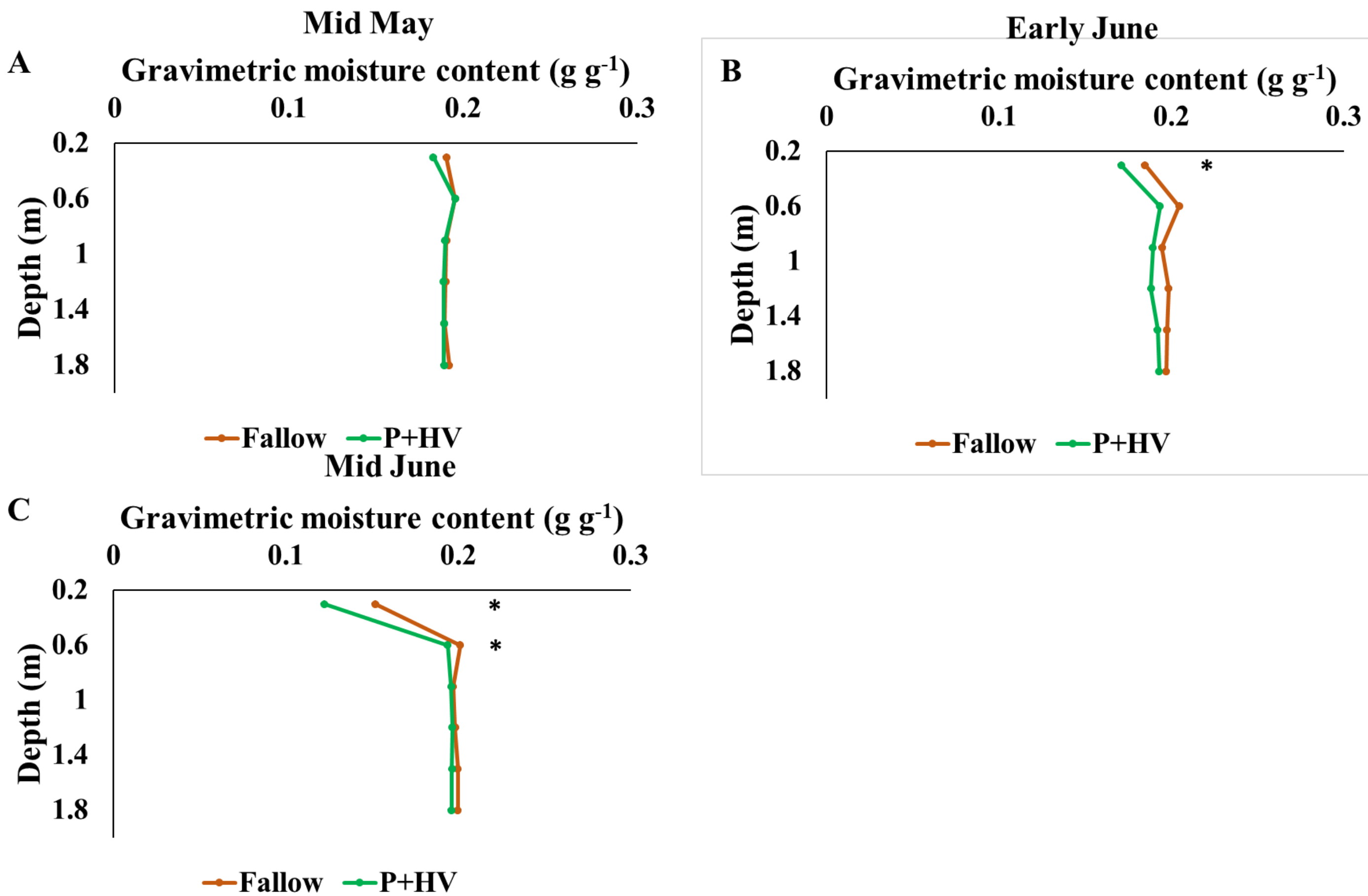


Figure A14: Main effects of cover crops 2 years (fallow rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

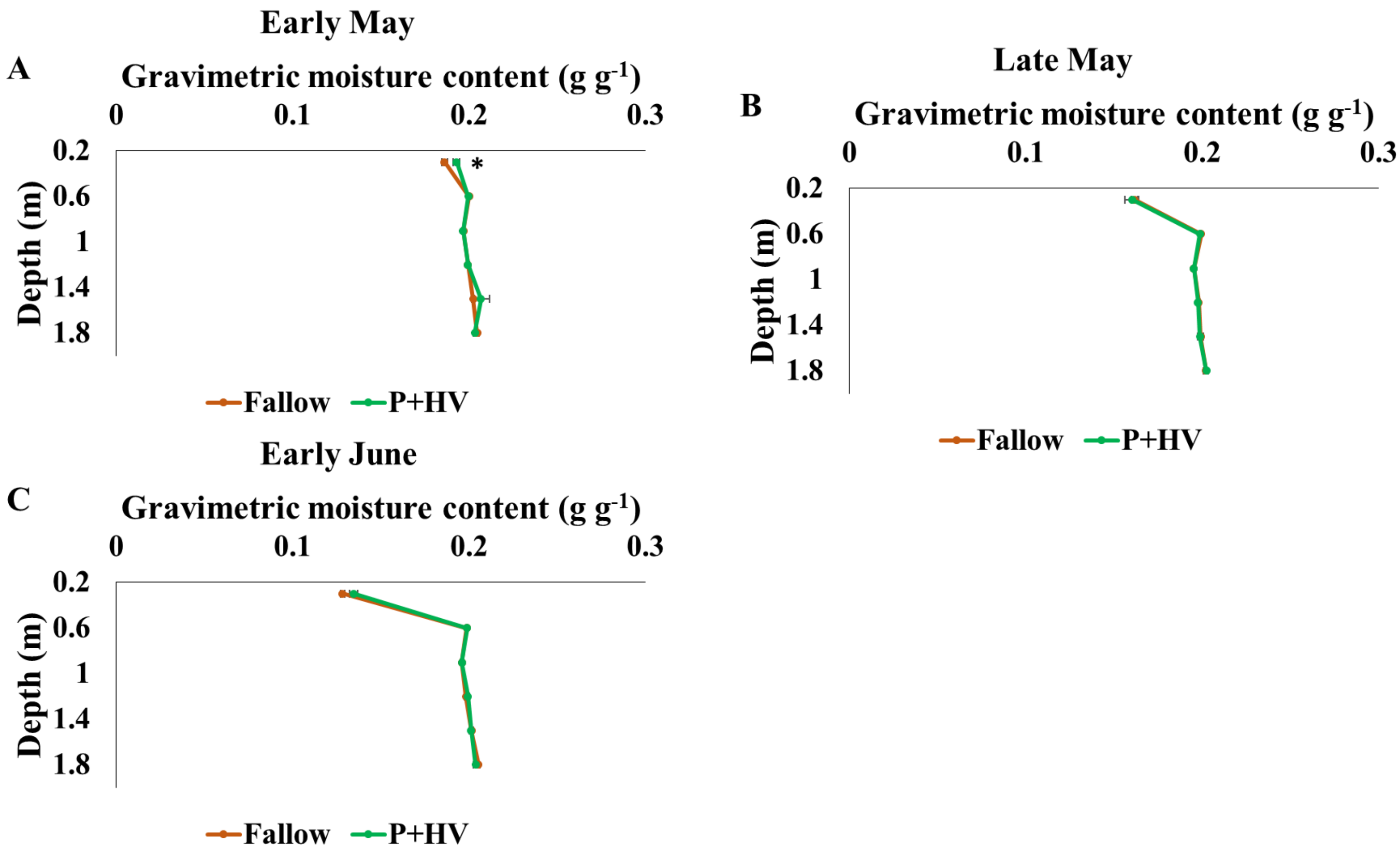


Figure A15: Main effects of cover crops 3 years (wheat rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

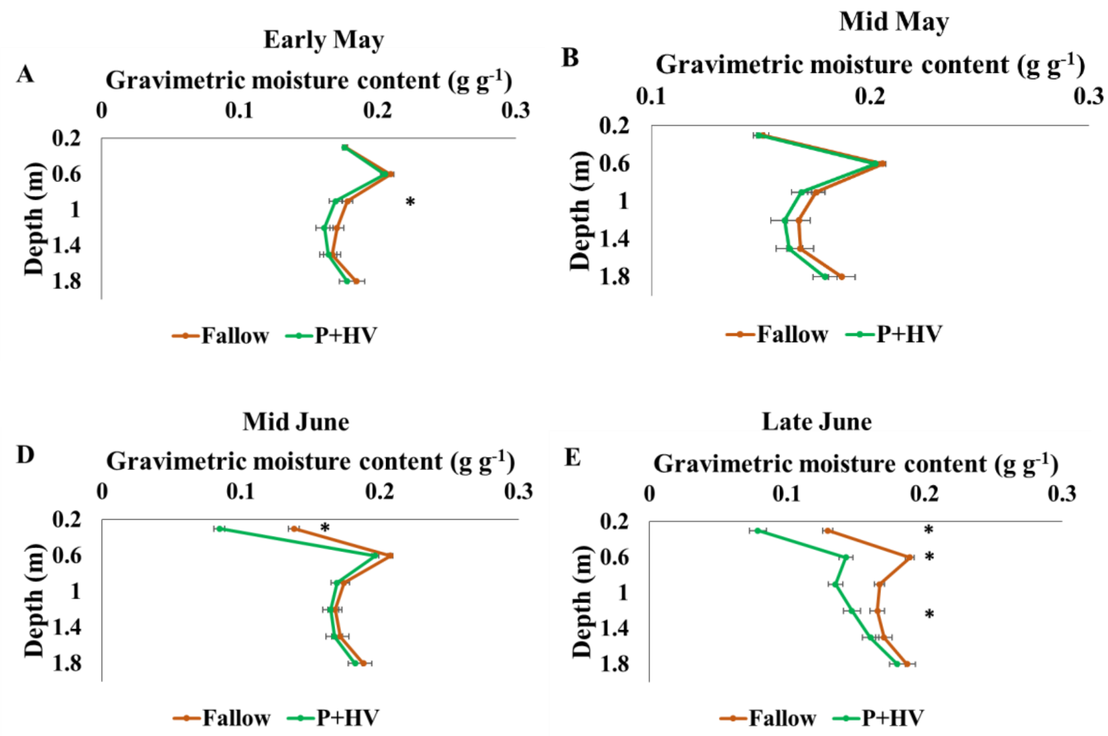


Figure A16: Main effects of cover crops 4 years (fallow rotation) after compost application on soil water at Blue Creek.

* Indicates significant differences using Tukey (0.05).

APPENDIX B

SMALL MACROAGGREGATES MEDIATES THE LONG-TERM RESIDUAL EFFECTS OF A ONE-TIME COMPOST APPLICATION ON PHOSPHORUS AVAILABILITY IN ORGANIC DRYLAND WHEAT

ABSTRACT

Compost application could alter phosphorus (P) storage and cycling in the soil; however, it is unclear how a one-time application of compost affects the effects of aggregate associated P on legacy plant-available P in organic dryland agroecosystems. The objective of this study was to assess P levels within soil aggregates following a one-time compost application and its relationship with legacy plant-available P in organic dryland winter wheat-fallow (WW-F) systems. Compost 0, 25, and 50 Mg DW ha^{-1} were applied once to three organic dryland winter wheat-fallow sites, Snowville (SN), Blue Creek (BC), and Historical (HT) in northern Utah. Aggregate associated P, C, and N were determined 1 and 3 years (SN and BC) and 24 years (HT) after a one-time compost application. Surface soil (0-10 cm) was separated into aggregate sizes (4.00-2.00, 2.00-1.00, 1.00–0.25, and <0.25 mm). Compost addition had similar effects on the P levels within the aggregates across the sites with the highest P increase observed in the 1-0.25 mm small macroaggregate fraction at SN, BC, and HT sites. Additionally, the results showed significant positive linear relationship between bulk soil Olsen-P and macroaggregate associated-P, 1-0.25 mm small macroaggregates at SN ($r=0.6$, $p=0.001$), 2-1 mm large macroaggregates at both BC ($r=0.69$, 0.0002) and HT ($r=0.95$, $p=0.0037$). This indicates that macroaggregates play a vital role in legacy P retention. Thus, P

protection in macroaggregates mediates both the short- and long-term effects of P following compost application in organic dryland WW-F.

MATERIALS AND METHODS

The soils used for this study were collected from three organic dryland winter wheat sites in northern Utah. Two of the sites, Historical (HT) and Snowville (SN), are located at a cooperator farmer's field near Snowille, Utah (41°53' N, 112°46' W) with an elevation of 1,387 m and the third site, Blue Creek (BC), is located at the Utah State Agricultural Experimental Station in Blue Creek, Utah (41°56' N, 112°25' W) with an elevation of 1,433 m.

The experiment at HT was established in 1994 as a randomized complete block split-plot design with three replicates. Dairy manure compost, 0, and 50 Mg DW ha^{-1} were applied once in August 1994 at the whole plot level (6.86 by 8.53 m) and variety was the split-plot Stukenholtz et al. (2002). The soil type is calcareous Thiokol silt loam (fine-silty, mixed, active, mesic Sodic Calcixerepts) based on the USDA soil classification with an average pH of 8.5 and calcium carbonate equivalent between16 and 36 %. Detailed information on the characteristics of the soil and compost can be found in Stukenholtz et al. (2002) and Reeve et al. (2012).

The experiment at SN was established in 2016 as a randomized complete block split-plot design, with cover crop (winter pea *plus* hairy vetch and fallow) as the whole plot, and compost (0, 12.5, 25, and 50 Mg DW ha^{-1}) as the split-plot applied once in 2016 and incorporated immediately. The soil classification at SN is the same as in HT. The

experiment at BC was established in 2011 as a randomized complete block split-plot design, with compost rate (0, 12.5, 25, and 50 Mg DW ha^{-1}) as the whole plot, and cover crop (winter pea *plus* hairy vetch and fallow control) as the split-plot. In August 2016, steer manure compost, 0, 12.5, 25, and 50 Mg DW ha^{-1}, was applied to unamended plots at BC. The soil at BC is classified as a Parleys silt loam (fine-silty, mixed, superactive, mesic Calcic Argixerolls) based on USDA soil classification with an average pH of 7.2 and calcium carbonate equivalent between 0 and 20 %. Detailed properties of the soil at the sites- SN and BC, and compost are presented in tables 1 and 2, respectively.

At SN and BC, the subplot size was 7.3 x 24.3 m and Juniper WW cultivar was planted in August (HT and SN) at 67 kg/ha and November (BC) at 78 kg/ha to a depth of 5 cm and harvested in either July (HT and SN) or September (BC) of the following year. The land was fallowed for the next 13-14 months before the planting of the next wheat crop. The wheat-fallow plots where tilled three times with a Flexicoil chisel plow with 0.45 m sweeps. The first tillage pass in mid-March was 10 cm deep, the second tillage pass in late May was to a depth of 7.62 cm, and the third pass was to a depth of 5 cm in early July.

Soil sampling and aggregate fractionation

Soil for this study was collected from SN and BC in 2017 and 2019 from plots that received compost (0, 25, and 50 Mg/ha DW) in 2016, while soils were collected from HT (0 and 50 Mg/ha DW) in 2018. Soil samples at 0-10 cm depth were collected using a soil auger (i.d. 6.5 cm). Five soil cores were collected, transferred into clear bags, and transported on ice to the laboratory and cold-dried at 4 °C to 10 g g^{-1} to ensure the soils

are at maximum friability and aggregates are separated by fragmentation and not abrasion (Kristiansen et al., 2006; Tiemann and Grandy, 2015). Thereafter, approximately, 100 g of soil was weighed and passed through 8 mm and four aggregates size classes, large macroaggregates (4-2 mm), medium macroaggregates (2-1 mm), small macroaggregates (1-0.25 mm) and microaggregates (<0.25 mm) were obtained as described by Nichols and Toro (2011) using stacked sieves placed in an RX-24 portable sieve shaker (W. S. Tyler Inc, OH) and air-dried at 25 °C.

Chemical analyses

The inorganic $NaHCO_3$ (Olsen-P), inorganic NaOH-EDTA extractable P (oxide-P), and total OC and N were measured in aggregates as well as in bulk soils. Also, organic $NaHCO_3$-P was determined on bulk soils. Although it is not considered to be directly available to plants, the inorganic NaOH-EDTA P pool was assessed because it can significantly contribute to the plant-available pool over time (Garland et al., 2018). Available P in soil aggregates and bulk soil were extracted using 0.5 M $NaHCO_3$ (pH 8.5) (1:20) by shaking on an end-to-end horizontal shaker for 30 mins and filtered with a Whatman filter paper (No.40). Total P in $NaHCO_3$ extract was determined by digesting aliquots with potassium persulfate and H_2SO_4 at 150 ˚C (Nelson, 1987). Oxide-P was extracted with 0.25 M NaOH-0.5M EDTA solution (1:10) by shaking on an end-to-end horizontal shaker for 16 h and filtered with a Whatman filter paper (No. 40). The P concentration in the extracts was measured on diluted subsamples (1:20) colorimetrically at 630 nm using malachite green (D’Angelo et al., 2001). Organic $NaHCO_3$-P was calculated as the difference between the total P and inorganic P of the $NaHCO_3$-P

extracts. The total OC and total nitrogen in the aggregates and bulk soil were measured on air-dried samples (<250 µm) using Primacs SNC total C and N analyzers (Skalar Inc., Buford, GA).

STATISTICAL ANALYSIS

The data obtained from the sites were analyzed separately. The assumptions of normality and equal variance were assessed and log-transformed if necessary. The data were analyzed as a randomized complete block design with repeated measures using the generalized linear mixed model (GLIMMIX). Compost was the fixed effect, year after compost application was the repeated measure, and the block was the random effect. Means were separated using Tukey test (0.05). Relationships between aggregate associated nutrient and bulk soil nutrients were performed using Pearson's correlation (0.05) R (version 4.0.1). Statistical analysis was performed in SAS Studio University Edition (version 9.4, SAS Institute, Cary, NC, USA) while plots were made in Origin Pro (version 8.5, Origin Lab, Northampton, MA, USA) and R (version 4.0.1).

Table B1: Oxide-P concentration (mg/kg) at Snowville, Blue Creek and Historical in different aggregate size classes.

Compost Mg DW ha^{-1}	Snowville				Blue Creek				Historical			
	mm											
	4-2	2-1	1-0.25	<0.25	4-2	2-1	1-0.25	<0.25	4-2	2-1	1-0.25	<0.25
0	74.9Bb[§†]	75.9Bb	80Bab	84.1Ba	112Ab	112Ab	118Aab	103Aa	67.8Bb	71.5Bb	77.7Ba	72.8Bab
25	146Aa	152Aa	147Aa	154Aa	114Aa	111Aa	116Aa	109Aa				
50	149Aa	155Aa	144Aa	152Aa	119Aa	110Aa	115Aa	117Aa	88.7Ab	90.1Ab	96.9Aa	90.7Aab

[§]Means within the same aggregate size class across the treatment with the same upper-case letters are not significantly different at Tukey (0.05).

[†]Means across the four aggregate size classes within a treatment with the same lower-case letter are not significantly different at Tukey (0.05).

Table B2: Compost effect on Olsen-P, oxide-P, total organic carbon and total nitrogen at Snowville, Blue Creek and Historical.

Compost	Snowville				Blue Creek				Historical			
Mg DW ha^{-1}	Olsen-P	$NaHCO_3$-P_o	TOC	TN	Olsen-P	$NaHCO_3$-P_o	TOC	TN	Olsen-P	$NaHCO_3$-P_o	TOC	TN
	mg/kg		g/kg		mg/kg		g/kg		mg/kg		g/kg	
0	8.74b[§]	11.9a	9.45b	1.76a	31.6b	10.7a	11.2b	1.17b	10.6b	25.8b	12.4a	1.49
25	25.8a	11.3a	16.1a	2.21a	49.9a	14.1a	16.3a	1.88ab				
50	28.6a	12.1a	17.8a	2.39a	58.1a	12.9a	19.5a	1.96a	16.1a	35.7a	13.7a	1.80a

[§]Means with the same lower-case letters are not significantly different at Tukey (0.05).

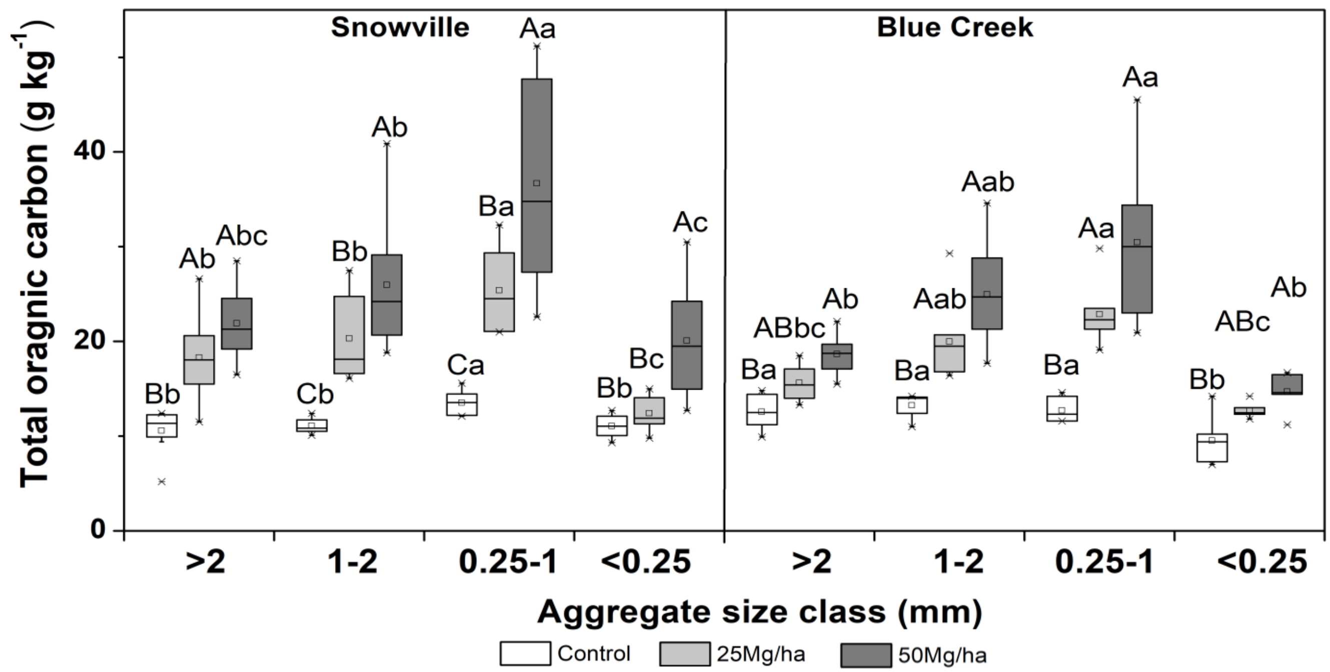


Figure B1: Main effects of compost on soil organic carbon in aggregate size classes averaged over 1- and 3-years following compost application at Snowville and Blue Creek.

Treatments within the same aggregate size class with the same upper-case letters are not significantly different at Tukey (0.05).

Treatments across the four aggregate size classes with the same lower-case letter are not significantly different at Tukey (0.05).

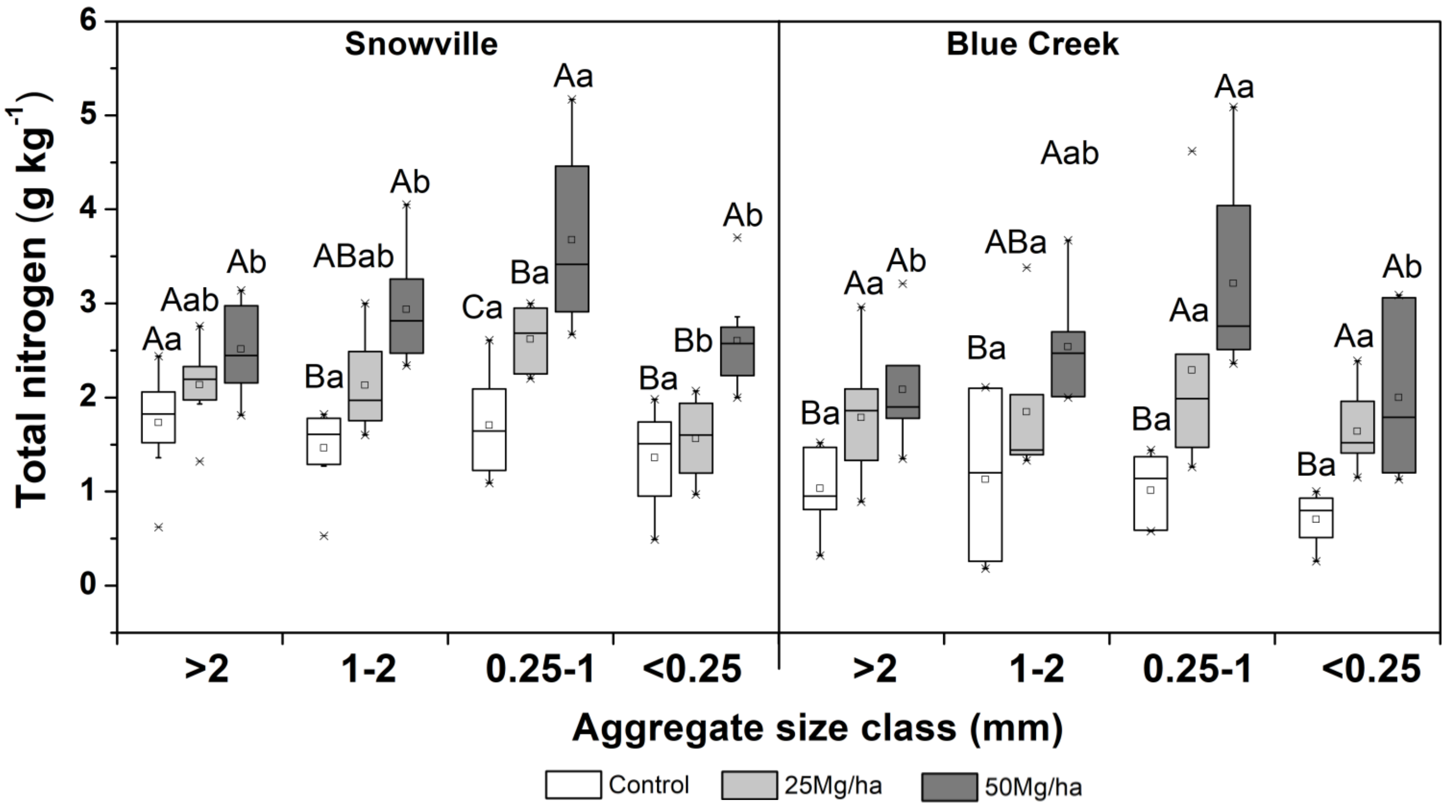


Figure B2: Main effects of compost on total nitrogen in aggregate size classes averaged over 1- and 3-years following compost application at Snowville and Blue Creek.

Treatments within the same aggregate size class with the same upper-case letters are not significantly different at Tukey (0.05).

Treatments across the four aggregate size classes with the same lower-case letter are not significantly different at Tukey (0.05).

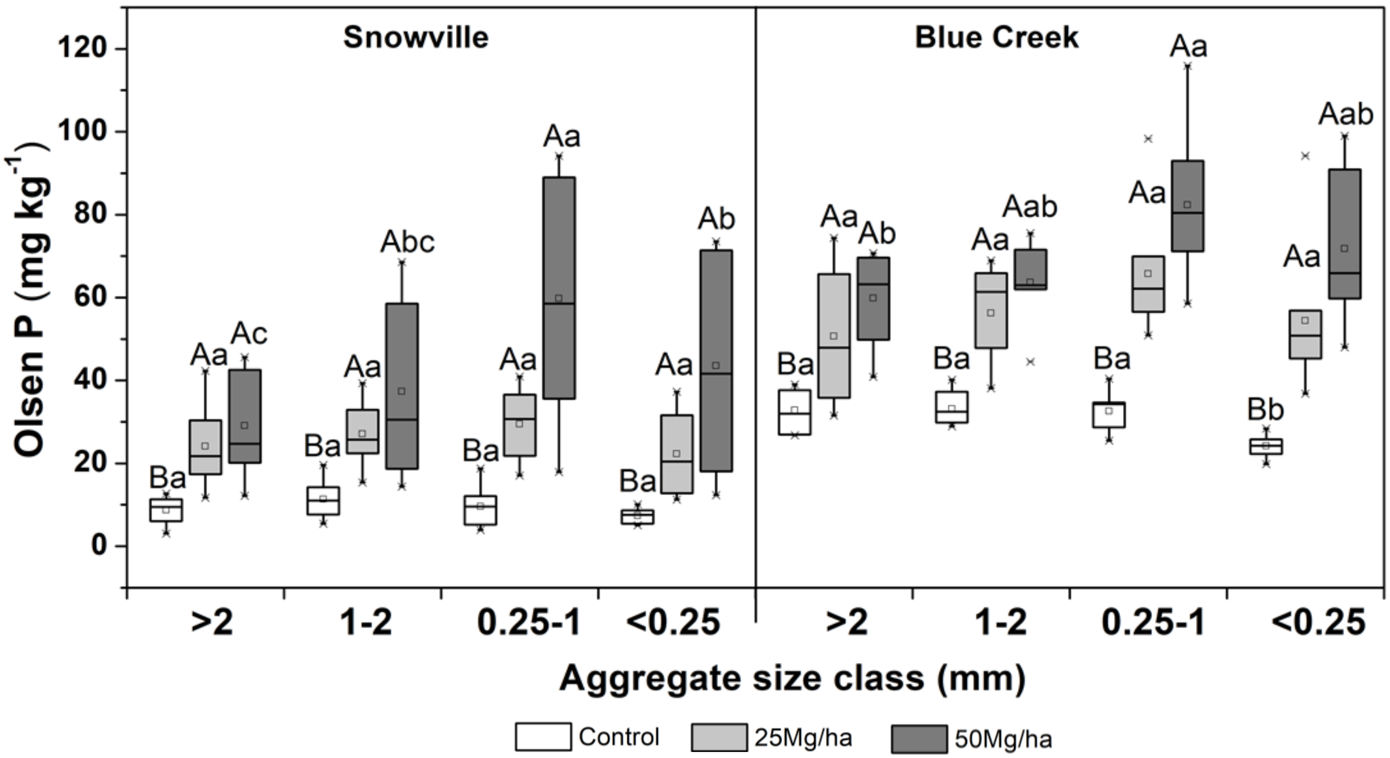


Figure B3: Main effects of compost on available soil phosphorus in aggregate size classes averaged over 1- and 3-years following compost application at Snowville and Blue Creek.

Treatments within the same aggregate size class with the same upper-case letters are not significantly different at Tukey (0.05).

Treatments across the four aggregate size classes with the same lower-case letter are not significantly different at Tukey (0.05).

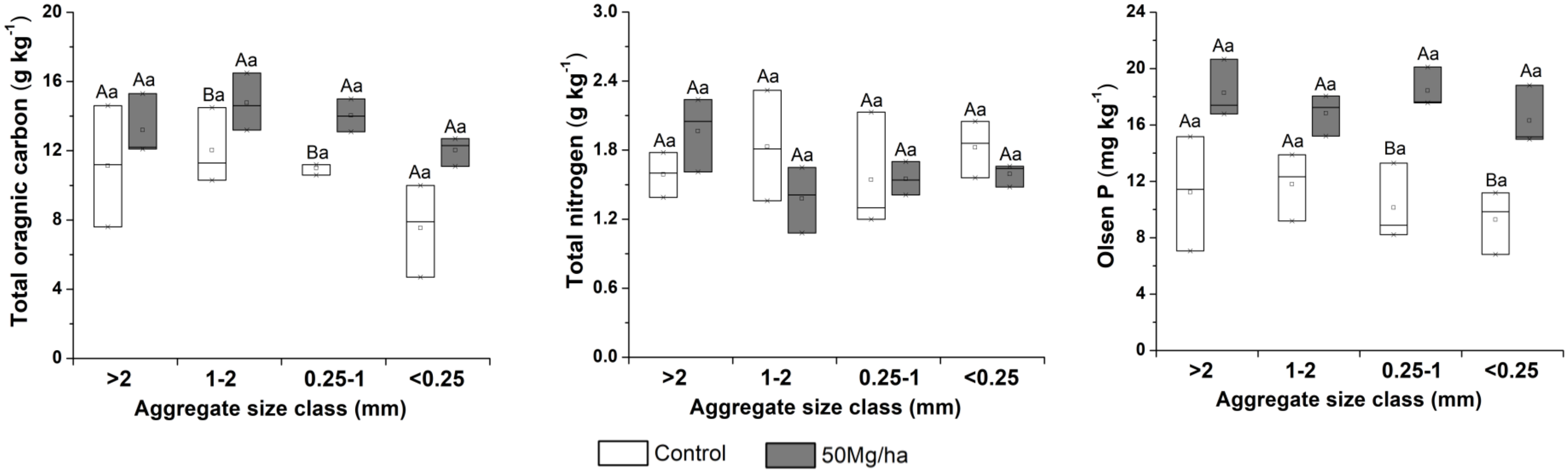


Figure B4: Main effects of compost on total organic carbon, total nitrogen and available soil phosphorus in aggregate size classes, 24 years following compost application at Snowville.

Treatments within the same aggregate size class with the same upper-case letters are not significantly different at Tukey (0.05).

Treatments across the four aggregate size classes with the same lower-case letter are not significantly different at Tukey (0.05).

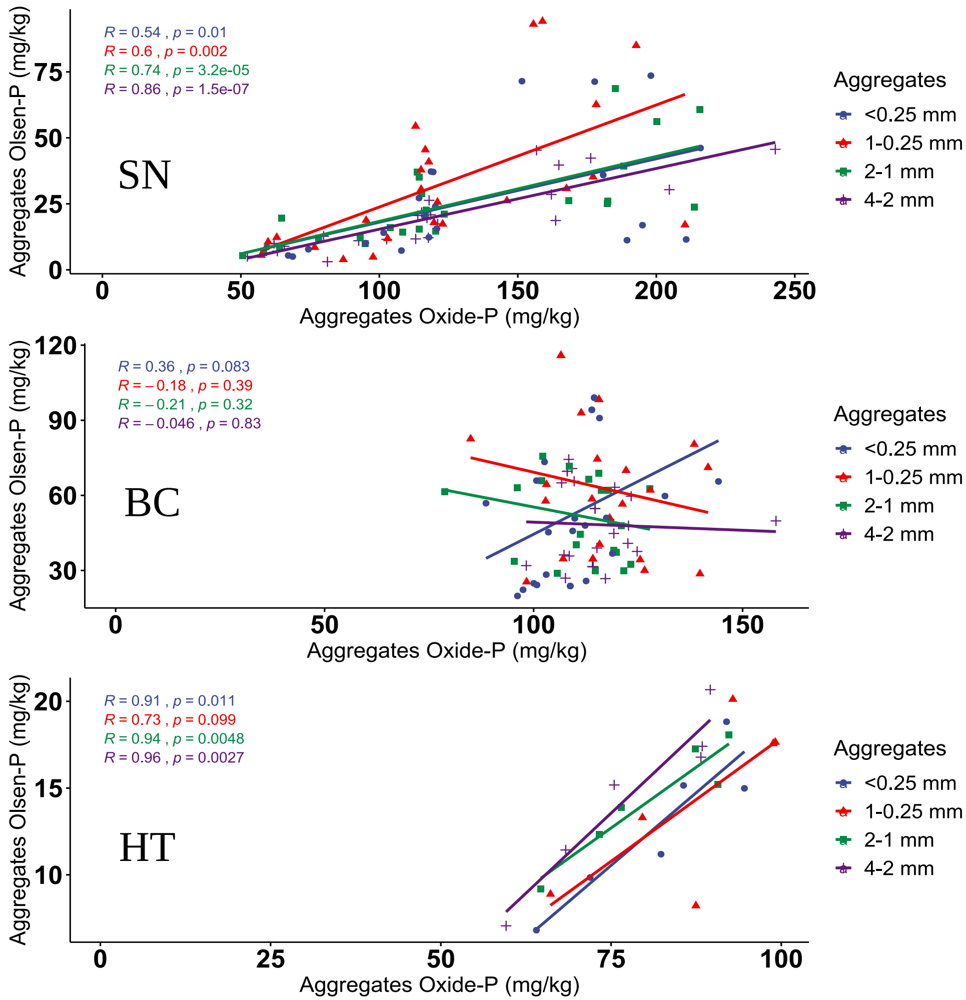


Figure B5: Correlation analysis between aggregate associated Olsen-P and aggregate associated oxide-P Snowville (SN), Blue Creek (BC) and Historical (HT).

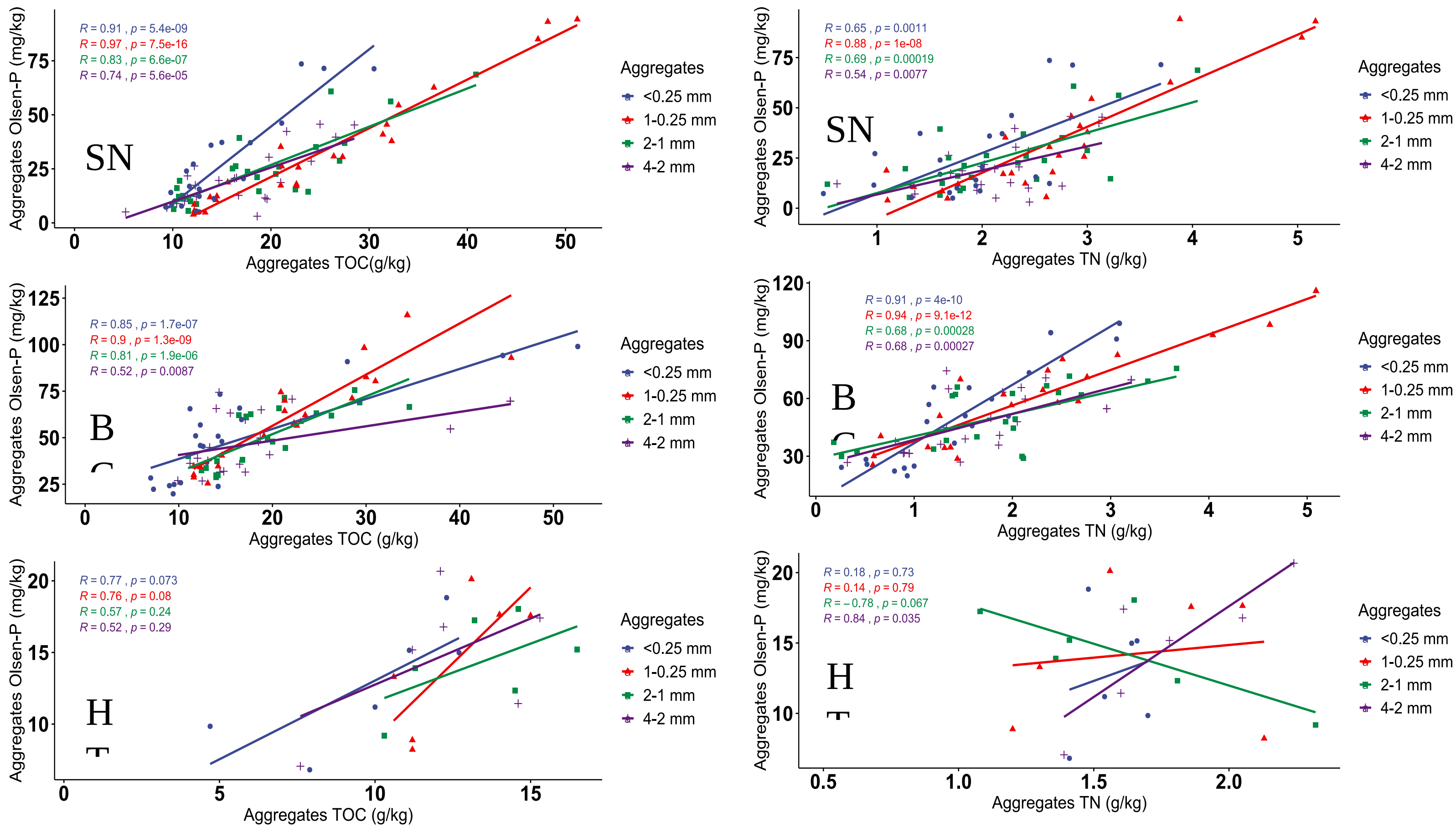


Figure B6: Correlation analysis between aggregate associated Olsen-P and aggregate associated TOC and TN at Snowville (SN), Blue Creek (BC) and Historical (HT).

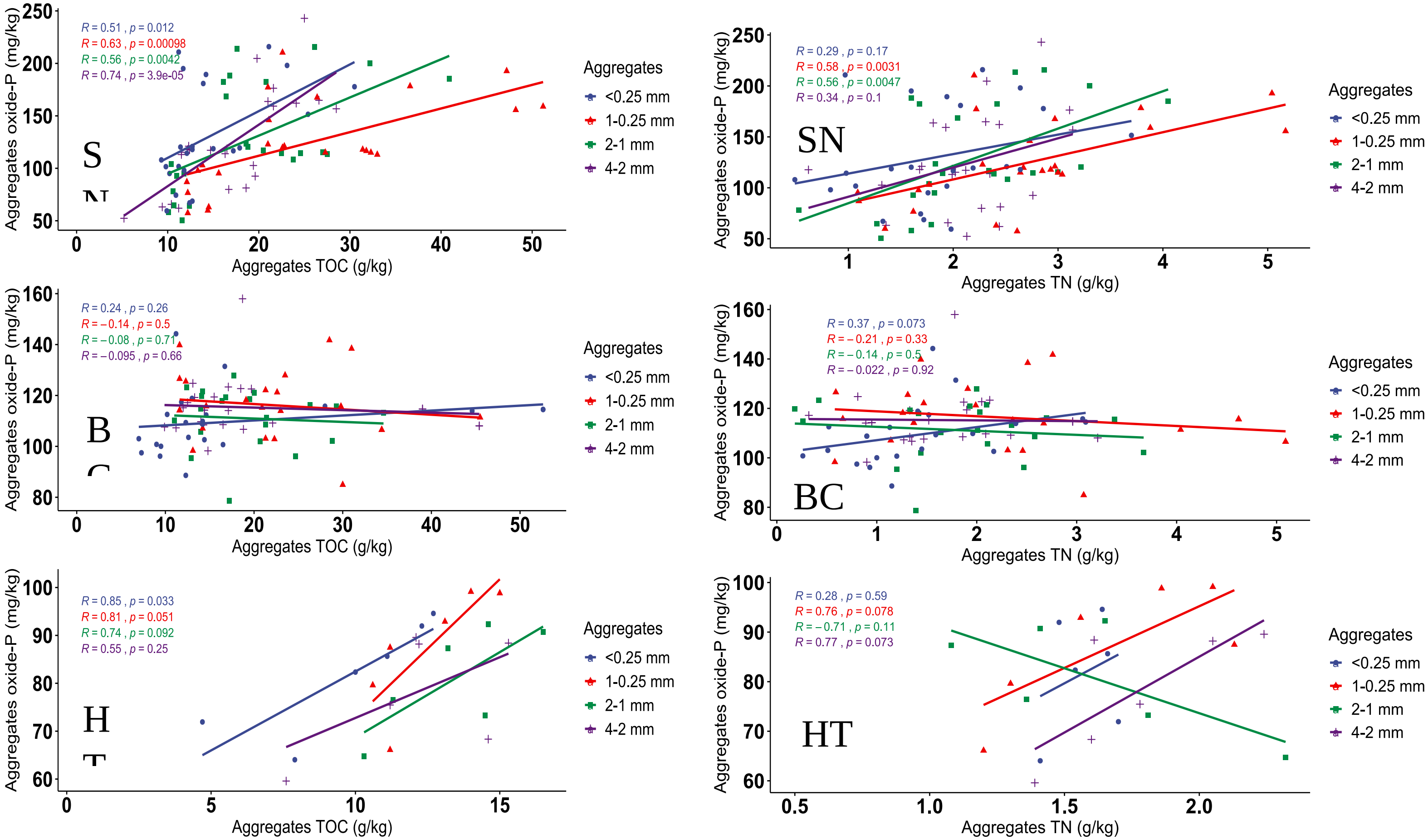


Figure B7: Correlation analysis between aggregate associated oxide-P and aggregate associated TOC and TN at Snowville (SN), Blue Creek (BC) and Historical (HT).

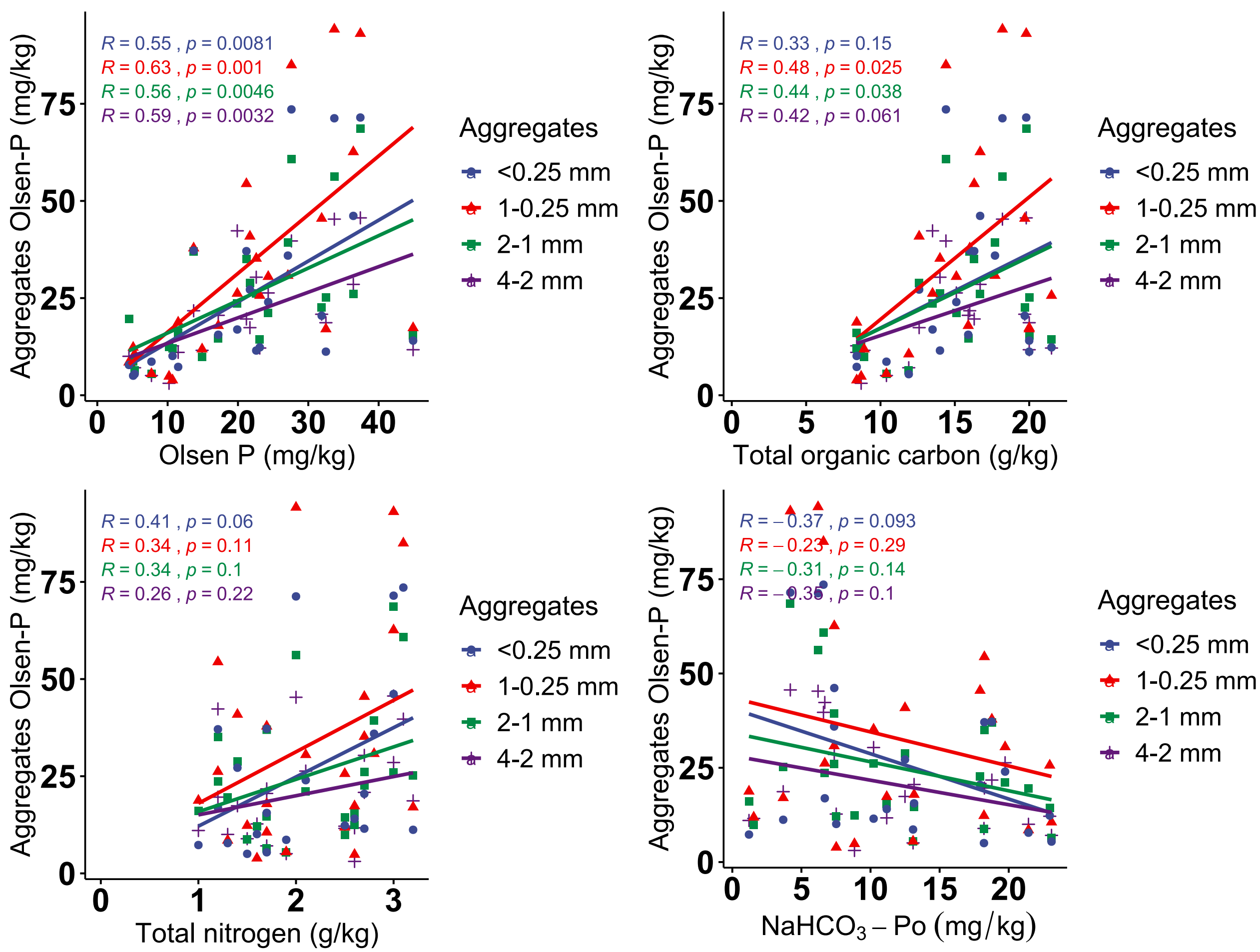


Figure B8: Correlation analysis between aggregate associated Olsen-P and Olsen-P, total organic carbon, total nitrogen, and labile organic P ($NaHCO_3$-Po) 3 years after compost application at Snowville.

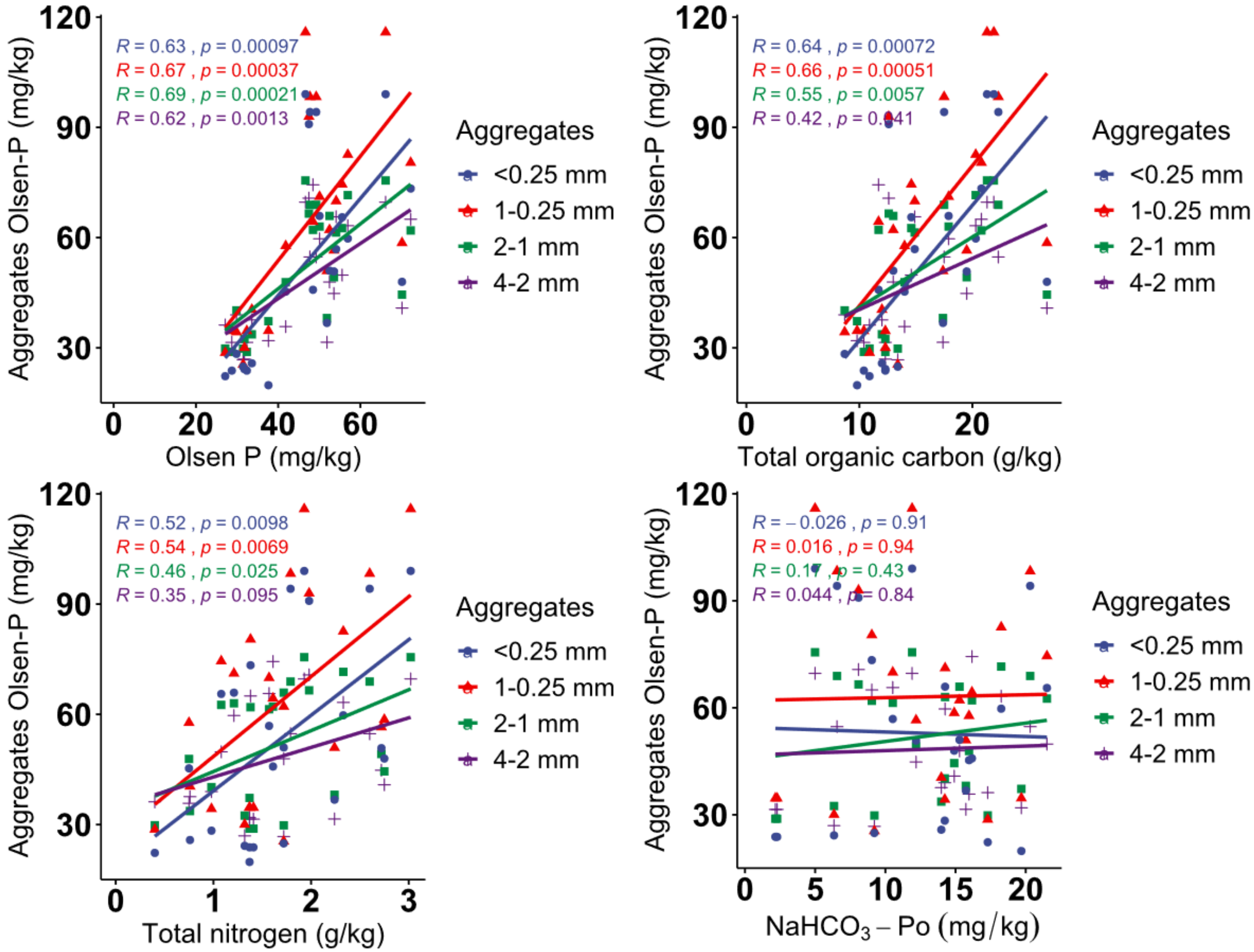


Figure B9: Correlation analysis between aggregate associated Olsen-P and Olsen-P, total organic carbon, total nitrogen, and labile organic P ($NaHCO_3$-Po) 3 years after compost application at Blue Creek.

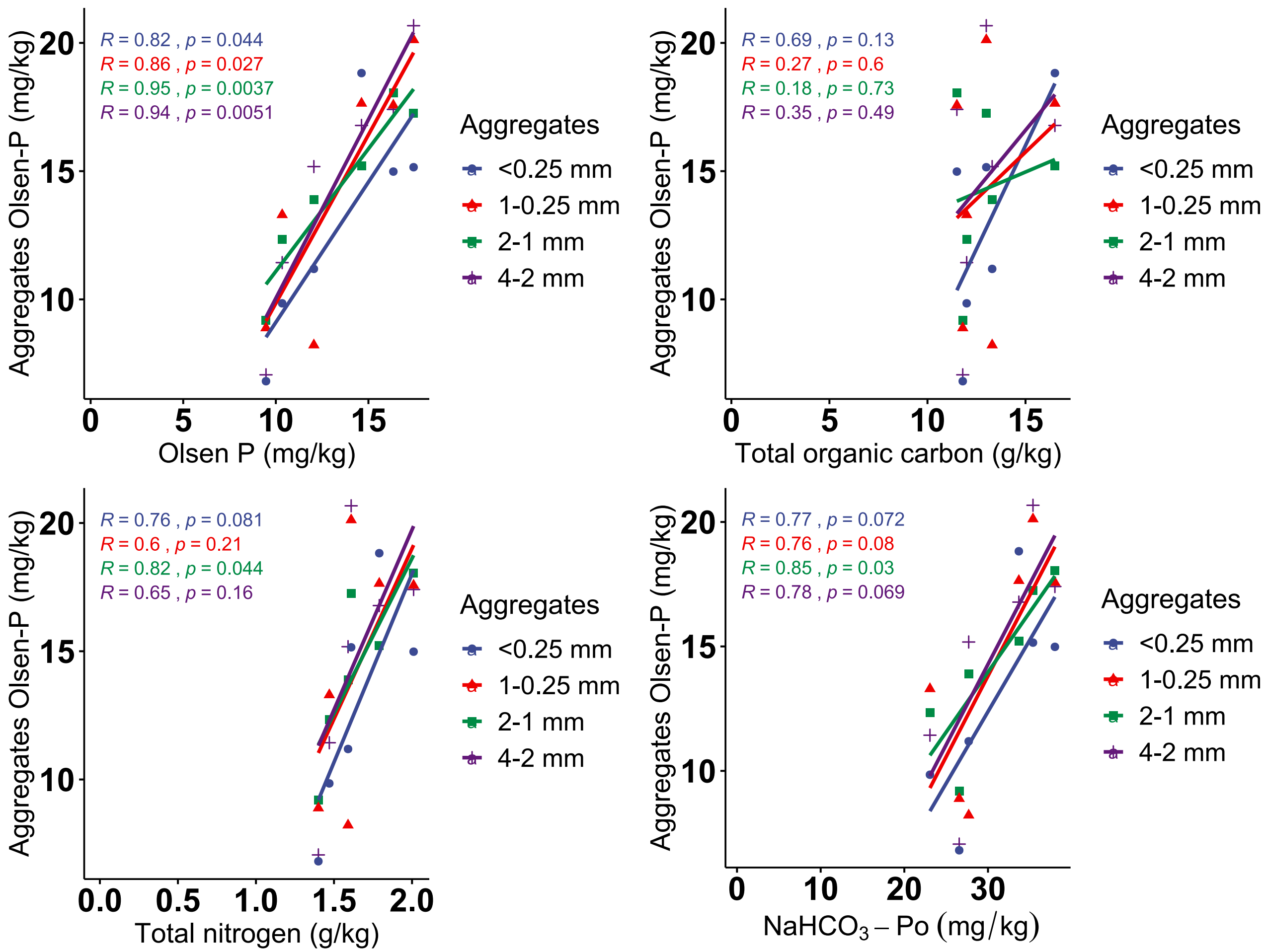


Figure B10: Correlation analysis between aggregate associated Olsen-P and Olsen-P, total organic carbon, total nitrogen, and labile organic P ($NaHCO_3$-Po) 3 years after compost application at Historical.

APPENDIX C

RESIDUAL EFFECTS OF A ONE-TIME COMPOST APPLICATION ON SOIL HEALTH 24 YEARS AFTER

Details of the experiment initiated in 1994 (henceforth referred to as “historical”) are described in Stukenholtz et al. (2002) and Reeve et al. (2012). Briefly, the design was a split-plot design with compost as the whole-plot factor (0 and 50 Mg DW ha^{-1}) and wheat variety as the split-plot factor arranged in randomized complete block designs with three replicates. Twenty-four years after compost application, acid phosphatase ($p=0.0353$, 0-10 cm) and Olsen P ($p=0.0241$, 0-30 cm) were significantly higher in compost treat plots while there were no significant differences ($p>0.05$) in other measured soil variables (Tables C1 and C2).

Table C1: Main efect of compost on gravimetric soil moisture, dehydrogense activity (DHA), acid and alklaine phosphatase, readily minearlizable carbon (RMC), basal respiration (BR), microbial biomass carbon (C_{mic}), total organic carbon (TOC), total nitrogen (TN) and permanganate oxidizable carbon (POXC) 24 years after a one-time application in 0-10 cm depth.

Compost	Gravimetric soil moisture	DHA	Phosphatase		RMC	BR	C_{mic}	TOC	TN	POXC
			Acid	Alkaline						
Mg DW ha^{-1}	g g^{-1}	µg TPF g^{-1} soil hr^{-1}	µg *p*-nitrophenol g^{-1} soil		µg CO2-C g $^{-1}$ soil	µg CO2-C g^{-1} soil hr^{-1}	µg CO2-C g $^{-1}$ soil	g kg^{-1}		mg kg^{-1}
0	0.13a	5.04a	26.9a	178a	123a	0.20a	1845a	12.4a	1.49	361a
50	0.13a	5.96a	45.0b	189a	119a	0.32a	1924a	13.7a	1.8	290b
p-value	0.8167	0.1917	0.0353	0.8282	0.8057	0.4016	0.1823	0.4909	0.5348	0.043

Table C2: Main effects of compost on gravimetric soil moisture, pH, electrical conductivity (EC), total organic carbon (TOC), total nitrogen (TN), Olsen P, zinc (Zn), iron (Fe), manganese (Mn) and copper (Cu) 24 years after a one-time application in 0-30 cm depth.

Compost Mg DW ha^{-1}	Gravimetric soil moisture $g\ g^{-1}$	pH	EC dSm-1	TOC	TN	Olsen P	Zn	Fe	Mn	Cu
				g kg-1				mg kg-1		
0	0.20a	9.08a	0.23a	7.63a	1.69a	6.73a	0.25a	3.77a	4.35a	1.25a
50	0.19a	8.86a	0.20a	8.10a	1.77a	22.6b	0.47a	3.88a	5.35a	1.30a
p-value	0.5301	0.1977	0.3470	0.8074	0.8763	0.0241	0.2374	0.7634	0.3413	0.5603

APPENDIX D

PATH ANALYSES CODES FOR CHAPTER THREE

Blue Creek Path Analysis

```
library(lavaan)
library(semPlot)
library(ggpubr)
getwd()
setwd("C:/Users/idowu/OneDrive/Documents/R")
pathdataL<-read.table("BlueCreekPath.csv",header=TRUE,sep=",")
pathdataL
#This code is to check for normality of the manifest/measured variables
ggdensity(pathdataL$RP,
    main = "P Pool",
    xlab = "P Pool")
ggqqplot(pathdataL$RP)
shapiro.test(pathdataL$RP)
#This is the model specification with dependent variable on LHS and independent on
RHS
model='
LPi~SP+MPi+CompostP
MPi~LPo+SP+RP
LPo~RP+CompostP+SP
```

```
'

#This code is to run the model

model

path = sem(model,data=pathdataL)

summary(path, standardized = T, fit.measures=T, rsquare=T, modindices=T)

semPaths(path, whatLabels ="std", layout = "spring", color = "green", edge.label.cex =

0.9,)

fitmeasures(path)

#This code is to specify the indirect and indirect effects

model2='

LPi~a*SP+b*MPi+c*CompostP

MPi~d*LPo+e*SP+f*RP

LPo~g*RP+h*CompostP+i*SP

indirect RPLPoMPiLPi:=g*d*b

indirect RPMPiLPi:=g*b

indirect CmPLPoMPiLPi:=h*d*b

indirect SPLPoMPi:= i*d

indirect SPLPoMPiLPi:= i*d*b

indirect SPMPiLPi:= e*b

'

model2

path2 = sem(model2,data=pathdataL)
```

```
summary(path2, standardized = T, fit.measures=T, rsquare=T, modindices=T)

fit2 <-sem(modell2, data= pathdataLl)

#This line is to assess the model fitness

fitmeasures(path2)

#This code is to check if any path should be specified in the model

modificationindices(path, sort. = TRUE)
```

Snowville Path Analysis

```
library(lavaan)

library(semPlot)

library(ggpubr)

getwd()

setwd("C:/Users/idowu/OneDrive/Documents/R")

pathdataLl<-read.table("SnowvillePath.csv",header=TRUE,sep=",")

pathdataLl

#LPi     MPi     LPo     SP     RP

ggdensity(pathdataLl$RP,

        main = "P Pool",

        xlab = "P Pool")

ggqqplot(pathdataLl$RP)

shapiro.test(pathdataLl$RP)

modell='

LPi~Compost2+MPi
```

```
LPo~SP+LPi+Compost2

SP~LPi+Compost2+MPi

RP~SP+LPo+MPi

MPi~~0*Compost2

'

modell

pathl = sem(modell,data=pathdataLl)

summary(pathl, standardized = T, fit.measures=T, rsquare=T, modindices=T)

semPaths(pathl, whatLabels ="std", layout = "tree")

fitmeasures(pathl)
```

CURRICULUM VITAE

Idowu Ademola ATOLOYE
Plants, Soils & Climate Department
Utah State University
4820 Old Main Hill
Logan, UT 84322-4820
(435) 799-6571 (cell)
idowu.atoloye@aggiemail.usu.edu

EDUCATION

Ph.D. Soil Science 2020
Utah State University, Logan, UT
Dissertation proposal: *Soil health, Soil Carbon, and Phosphorous Dynamics in Organic Dryland Wheat Systems* (3.81/4.00)

M. Phil. Soil Science 2014
Obafemi Awolowo University, Ile-Ife, Nigeria
Thesis: *Effect of method of application of compost and inorganic N on microbial activities, nitrogen and phosphorus mineralization* (72A)

B. Agric. Soil Science 2007
Obafemi Awolowo University, Ile-Ife, Nigeria
Undergraduate Research Thesis*: Forms of phosphorus distributed along a toposequence underlain by mica schists in Ile-Ife area, southwestern Nigeria* (4.08/5.00)

FELLOWSHIPS AND AWARDS

Fellowships:

Nelson Yield-Limiting Factors Scholarship 2019
- Agronomy Society of America

DeVere McAllister Scholarship, Utah State University (USU) 2019–2020
Apogee Instruments-Campbell Scientific Graduate Fellowship, USU 2017–2019
Elva Acklam & Arvil L. Stark Scholarship, USU 2016–2019
Robert N. Love Scholarship, USU 2016–2017
Presidential Doctoral Research Fellowship, USU 2015–2020
International Humic Substance Society (IHSS) Training Grant 2013
International Plant Nutrition Institute (IPNI) Scholar Awards 2013
Ogun State Undergraduate Scholarship 2004–2007
Egbe Omo Oduduwa Scholarship 2004–2006

Award:

Awardee, Jeffrey L. Smith Graduate Travel Award 2019
Soil Biology and Biochemistry Division, SSSA
Awardee, 5th Annual Graduate Student Leadership Conference 2019
ASA, CSSA, SSSA Leadership Conference
Graduate Enhancement Award, Utah State University 2019
2019-2020 Doctoral Student Researcher of the Year 2019
College of Agriculture and Applied Sciences, Utah State University
2018 Doctoral Student Researcher of the Year 2019
Plants, Soils and Climate Department, Utah State University
Best Graduate Student Poster Presentation-Life Science 2019
Student Research Symposium, Utah State University 2019
2nd Place, Graduate Student Poster Contest at the Western Nutrient Management Conference, Reno, NV
1st Place, Student Poster Contest at the Western Nutrient Management Conference, Reno, NV 2017

PROFESSIONAL EXPERIENCE

Graduate Teaching Assistant — Spring 2019
PSC 5050/6050 Principles of Environmental Soil Chemistry

Guest Lecturer, Soil phosphorus forms and transformations — March 2019
PSC 5530 Soils and Plant Nutrient Bioavailability

Guest Lecturer, Composting — February 2019
PSC 6900 Fundamentals of Organic Agriculture

Guest Lecturer, Lessons from Romans and Greeks — March 2018
PSC 3100 Soils and Civilization

Graduate Teaching Assistant, Obafemi Awolowo University — Sept 2014–Aug 2015

Laboratory Teaching Assistant, Obafemi Awolowo University — Aug 2011–Sept 2014
Courses Taught: Agricultural Chemistry I, Principles of Soil Science, Introductory Pedology and Soil Physics, Introductory Soil Chemistry, Fertility and Microbiology, Agricultural Waste Management and Organic Fertilizers, Soil Microbiology and Biochemistry, Soil Chemical Analytical Techniques

Director of Administration I — Excel Private Home Tutors, Abuja — June 2010 – July 2011

Research Officer II — Jigawa Research Institute — Aug 2008 – May 2010

PEER REVIEWED PUBLICATIONS

Journal Articles:

Erhunmwunse, A. S., Olayinka, A. and **Atoloye, I. A.** (2018) Nutrient mineralization from nitrogen and phosphorus-enriched poultry manure compost in an Ultisol.

Communications in Soil Science and Plant Analysis 50(2): 185-197. http://doi.org/10.1080/00103624.2018.1556290

Mendes, L. A., Barione, P. P., **Atoloye, I. A.**, Landgraf, M. D. and M. O. O. Rezende. (2017) From agricultural residues to biofertilizers: preparation and characterization for use in hydroponics. *American Open Chemistry Journal* 3 (1): 1-14.

Favoretto, L. B., **Atoloye, I. A**., Obikoya, O. A., Borsato, A. V. and M. O. O. Rezende. (2016) Chemical characterization of co-vermicomposted industrial filter cake and orange peel with cattle manure for agricultural use. *International Journal of Recycling of Organic Waste* 5(1): 55-63. *http://doi.org/10.1007/s40093-016-0117-7*.

Atoloye I. A. and A. Olayinka. (2015) Separate and combined applications of organic and inorganic fertilizers influence growth and nutrient uptake by *Zea mays* (L.). *Nigerian Journal of Soil Science* 25 (special): 247-257.

Refereed Conference Proceedings:

Pigatin, L. B. F., Rodrigues R. N., **Atoloye, I. A**, Borsato, A. V. and M. O. O. Rezende. (2017). Influence of agroindustrial vermicomposts on soil organic matter and basil production. *Humic Substances and Natural Organic Matter*: 201-213.

Atoloye, I. A., Ekundayo, R. A., Erhunmwunse, A. S. and A. Olayinka. (2014). Effect of Methods of Application of Compost and Inorganic N on Carbon Dioxide Evolution, N and P Mineralization. *Soil Science Society of Nigeria Conference Proceedings* 38: 339-334.

SUBMITTED

Atoloye, I. A., Olayinka, A. and Erhunmwunse, A. S. Method of compost and inorganic nitrogen application and the mineralization of carbon, nitrogen and phosphorus. (Under review) *Soil Use and Management*.

PAPERS IN PREPARATION

Atoloye, I. A., Reeve, and J. R., Jacobson. Differential effects of a one-time compost application on phosphorus cycling in organic dryland winter wheat systems.

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. Effects of cover crops and a one-time compost application on soil health in organic dryland winter wheat-fallow systems

Atoloye, I. A., Reeve, and J. R., Jacobson. Increase in subsoil organic carbon fractions concentration following compost application in dryland wheat-fallow systems

PRESENTATIONS AT PROFESSIONAL MEETINGS

Oral Presentations:

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. (2019) Variable Impact of Compost on Phosphorus Pool Dynamics in Dryland Organic Wheat. Soils Across Latitudes. Soil Science Society of America international meeting, San Diego, California, January 6-9, 2019.

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. (2018) Soil aggregation and phosphorus availability following a one-time compost addition in semi-arid organic wheat systems. Student Research Symposium, USU, Logan, UT, April 12, 2018

Atoloye, I. A., Reeve, J. R and Jacobson, A. R. (2016) Short-term assessment of compost effects on soil carbon dynamics in dryland soils of UT. PSC Graduate Seminar, USU, Logan, UT.

Atoloye, I. A. and Olayinka, A. (2014) Effects of combined and separate application of compost and inorganic N on microbial activities, N and P mineralization. MPhil. defense seminar. Obafemi Awolowo University, Ile-Ife, Nigeria.

Atoloye, I. A. and Olayinka, A. (2014) Effect of methods of application of compost and inorganic N on carbon dioxide evolution, N and P Mineralization. 38th Annual Conference of the Soil Science Society of Nigeria, Uyo, Nigeria, March 10-14, 2014.

Poster Presentations:

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. A one-time compost application affects carbon dynamics in dryland organic wheat systems in the Intermountain West, USA. Embracing the Digital Environment. ASA-CSSA-SSSA Annual Meeting, San Antonio, Texas, November 10-13, 2019.

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. Aggregate-Associated Phosphorus Dynamics in Different Dryland Organic Wheat Soils. Plants, Soil and Climate Research Event, USU, Logan, UT, March 25, 2019.

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. Aggregate Size, C and P Dynamics in Different Dryland Organic Wheat Soils. Western Nutrient Management Conference, Reno, NV, March 7-8, 2019.

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. Aggregate Size, C, N and P Dynamics in Different Dryland Organic Wheat Soils. Soils Across Latitudes. Soil Science Society of America international meeting, San Diego, California, January 6-9, 2019.

Idowu Atoloye, Jennifer Reeve, Astrid Jacobson and Earl Creech. Effects of a one-time compost application on soil moisture variability in dryland organic wheat. Spring Runoff Conference USU, March 27, 2018.

Idowu Atoloye, Jennifer Reeve, Astrid Jacobson and Earl Creech. Response of phosphorus forms in semi-arid organic wheat following a one-time compost addition. Plants, Soil and Climate Research Event, USU, March 19, 2018.

Atoloye, I. A., Reeve, J. R., Jacobson, A. R. and Creech, E. (2017) Effects of a one-time compost addition on soil health in a rainfed dryland organic wheat system. (presented at three meetings).

Western Nutrient Management Conference, Reno NV, March 1-3, 2017
Plants, Soil and Climate Research Event, USU, Logan, UT, March 20, 2017

Student Research Symposium, USU, Logan, UT, April 13, 2017

Pigatin, L. B. F., Rodrigues R. N., **Atoloye, I. A**, Borsato, A. V. and Rezende, M. O. O. (2015) Influence of agroindustrial vermicomposts on soil organic matter and basil production. The 11th Brazilian Meeting of Humic Substances (XI EBSH), University of São Paulo, São Carlos, Brazil, October 19-23, 2015.

GRANTS AND PROPOSALS

Submitted:

Atoloye, I. A. (2019). Soil quality management for continuous sustainable production of underutilized indigenous vegetable in Nigeria. International Foundation for Science ($14,994, pending). I was the primary author of the proposal.

Awarded Funding:

Adesanwo, O. (PI), Rezende, M. O. O., and Atoloye, I. (Co-PIs) (2013) Comparative assessment of spectroscopic analysis of humic substances and urease activity in compost and vermicompost of various sources. Funded by International Humic Substance Society ($5,500 Funded). I was the primary author of the proposal.

Submitted but not selected for funding:

Jacobson, A. and Reeve, J. (PIs), Creech, E. (Co-PI) and **Atoloye, I. A.** (Graduate students) (2019) Evaluating the multi-year effects of a one-time compost addition on phosphorus bioavailability and root growth in a rainfed dryland organic wheat system. Western Sustainable Agriculture Research & Education - Graduate Student Grant Program ($24,978.99). I was the primary author of the proposal.

Jacobson, A. and Reeve, J. (PIs), Creech, E. (Co-PI) **Atoloye, I**. and Dugova, T. (Graduate students) (2018) Evaluating the multi-year effects of a one-time compost addition on phosphorus bioavailability and root growth in a rainfed dryland organic wheat system. Western Sustainable Agriculture Research & Education - Graduate Student Grant Program ($24,978.99). I was the primary author of the proposal.

Atoloye, I. Understanding how compost addition affects soil water flux and availability in dryland, organic wheat systems. Submitted to METER Group ($9,778). I was the primary author of the proposal.

Jacobson, A. and Reeve, J. (PIs) **Atoloye, I.** (Graduate student) (2017) Evaluating the multi-seasonal effects of a one-time compost addition on phosphorus bioavailability and root growth in a rainfed dryland organic wheat system. Submitted to Western Sustainable Agriculture Research & Education - Graduate Student Grant Program ($24,958.40). I was the primary author of the proposal.

Jacobson, A. and Reeve, J. (PIs) **Atoloye, I.** (Graduate student) (2016) Improving Soil Health and Yield in Organic Dryland Wheat Systems with One-Time Application of Compost. Submitted to the Organic Farming Research Foundation – Graduate Student Grant Program ($14,997.00). I was the primary author of the proposal.

CERTIFICATE

Leadership Certificate, Graduate Student Leadership Conference 2019
ASA, CSSA, SSSA Leadership Conference
Certificate in Desktop GIS, Pace University 2017

SERVICE

University:

Session Moderator, Utah Conference on Undergraduate Research Feb. 2020
Panel Member, How to Mentor and be Mentored Sept. 2019

- Graduate Training Series, USU

Co-Chair, USU Ecology Center Seminar Committee 2017-2018
Presenter, Research Source Management Workshop, USU 2017, 2018
Reviewer, Undergraduate Research & Creative) 2016, 2019, 2020
Opportunity Grants (URCO
Member, USU Ecology Center Seminar Committee 2016-2017
President, Soil Science Society of Nigeria 2006-2007

- Obafemi Awolowo University, Students' Chapter

Welfare Secretary, National Association of Agricultural Students 2003-2004

- Obafemi Awolowo University

Community:

Member, Subcommittee, Soil Biology and Biochemistry division 2020

- Soil Science Society of America

President, Cache Valley Toastmasters International 2019-2020
Secretary, Parent Committee Meeting 2018-2019

- Bear River Head Start

Member, Policy Council Representative 2018-2019

- Bear River Head Start

Vice-President (Educational), Cache Valley Toastmasters International 2018-2019
Volunteer, USU Student Access Nutrition Center (SNAC) 2018
Vice-President (Membership), Cache Valley Toastmasters International 2017-2018

PROFESSIONAL AFFILIATIONS since

International Biochar Initiative 2020
The Agriculture, Nutrition & Health (ANH) Academy 2020
Soil Science Society of America 2014
African Network for Soil Biology and Fertility 2013
Soil Science Society of Nigeria 2012
International Union of Soil Science 2012
International Humic Substance Society 2012