THE INFLUENCE OF CLIMATE AND MANAGEMENT ON SURFACE SOIL HEALTH WITHIN THE INLAND PACIFIC NORTHWEST

By

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ABSTRACT

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Surface soils influence ecosystem health through their role in nutrient cycling and decomposition, gas exchange, water infiltration, and erosion. Soil organic matter (SOM) is critical to soil functioning and subsequently to soil and ecosystem health. Across four dryland sites and one irrigated site within the inland Pacific Northwest (PNW), the objectives were to assess the influence of climate, tillage, and cropping intensity on surface soil health by measuring soil C and N properties related to SOM as well as nutrient availability (NO_3^-, NH_4^+, Ca, Mg, P, K, S, Mn, Fe, Zn, B, Cu) quantified by PRS^{TM} probes (Western Ag Innovations, Saskatoon, Canada).

A multivariate regression of mean annual temperature (MAT) and precipitation (MAP), tillage, and cropping intensity revealed that MAP explained 57% of soil organic carbon (SOC) variability and 69% of total soil N variability. When MAP was removed from the model, MAT explained 42% and 49%, respectively, of SOC and total N variability. Both the hydrolyzable and non-hydrolyzable fractions of SOC were equally sensitive to climate, indicating no relationship between chemical recalcitrance and climate sensitivity. Permanganate oxidizable carbon (POXC) was representative of SOM stabilization, while one-day carbon mineralization was

representative of microbial activity and SOM mineralization. Both POXC and mineralization potential may be increased by cropping diversification, and stabilized inputs, such as compost, along with no-till, may increase POXC.

An increase in MAT across the region was associated with a decrease in potential nitrogen mineralization (PNM) (r = -0.73), potential denitrification (PDR) (r = -0.66), and basal denitrification (BDR) (r = -0.34). An increase in MAP was associated with an increase in PNM (r = 0.60) and PDR (r = 0.55), but was not related to BDR. Tillage intensity was correlated with PNM (r = -0.32), PDR (r = 0.32), and BDR (r = 0.32), whereas cropping intensity was correlated only with PNM (r = 0.40). Plant available nutrients displayed varying correlations with soil C and N properties, management, and climate factors. Overall, POXC and carbon mineralization were the most important indicators of surface soil health.

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DEDICATION

For all my family and friends who have helped to keep me smiling and provided endless support and encouragement throughout this project

CHAPTER 1
GENERAL INTRODUCTION

The Columbia Plateau of the dryland Inland Pacific Northwest is comprised of 62,000 km^2 of which 60% is in dryland crop production (Schillinger & Papendick, 2008). Prior to the introduction of agriculture to this region, the landscape was dominated by expanses of bluebunch wheatgrass [*Pseudoroegneria spicata*] and big sagebrush [*Artemisia tridentata*]. Dryland wheat farming now dominates the landscape, and in the higher rainfall zones located in the eastern parts of this region, world record wheat yields have been reported (Kok et al., 2009).

While the introduction of agriculture to this landscape was the basis for its settlement, it did not come without a price. This region has also been historically associated with some of the highest erosion rates in the United States, ranging from 3 to 67 Mg ha^{-1} yr^{-1} (1.3 to 30 T ac^{-1} yr^{-1}), far exceeding the 2.2 to 11.2 Mg ha^{-1} yr^{-1} (1.0 to 5.0 T ac^{-1} yr^{-1}) that is considered acceptable for sustained productivity (Williams et al., 2009; Kok et al., 2009) and representing a significant environmental threat to downstream water bodies.

To combat these high erosion rates, management practices that result in decreased surface disturbance and increased soil-surface crop residue cover are recommended and include increased cropping intensity and conservation tillage or no-tillage. Through RUSLE2 simulations, Kok et al. (2009) demonstrated the efficacy of these management practices in mitigating soil erosion; erosion rates in high and intermediate precipitation zones have been reduced by as much as 75% and in low rainfall zones by as much as 50%. This is an example of a quantifiable and visible threat to soil productivity and environmental health that has been mitigated through the introduction of appropriate management practices.

There are less visible yet still significant consequences that have resulted from the transition of native landscapes to agricultural landscapes. For example, in a Palouse silt loam in Eastern Washington, Purakayastha et al. (2008) revealed that 100 years of cultivation with a moldboard plow resulted in a 64% reduction in soil organic carbon (SOC) compared to native prairie and 28 years of no-till contained SOC levels 19% below that of native prairie. However, disturbance from agriculture need not be associated with an inevitable decline in SOC, as many have demonstrated with appropriate management SOC of various managed systems located in other regions can surpass that of native systems (Barrow, 1969; Ridley et al., 1990; Ismail et al., 1994).

SOC is an important component of soil organic matter (SOM), which contributes to soil productivity and many of the important ecosystem functions provided by soil in the context of terrestrial ecosystems, including 1) promotion of plant growth; 2) biogeochemical cycling of nutrients; 3) provision of habitat for soil organisms; and 4) partitioning, storage, translocation, and decontamination of water (Brady & Weil, 2010; Campbell, 1999). These vital services provide the context for the somewhat abstract concept of soil health, which has various definitions presented by many authors and can be distilled down to the ability of a soil to function effectively at present and into the future (Doran & Parkin, 1994). Evaluating crop rotations and management practices through the lens of soil health can help assure sustained soil productivity and minimize environmental impacts.

Several studies have shown that changes in the active fraction of soil carbon and nitrogen can serve as an early assessment of the impacts of management practices on soil health (Franzluebbers and Arshad, 1996; Dou et al., 2008; Culman et al., 2013). Particularly,

POXC (Weil, 2003), soil microbial biomass carbon and nitrogen (Powlson and Brookes, 1987), carbon mineralization (Franzluebbers et al., 2000), acid hydrolysis (Rovira and Vallejo, 2002), and water extractable carbon and nitrogen (Haney et al., 2012) have been identified as meaningful and sensitive portions of the active carbon and nitrogen pool that effectively differentiate among management impacts on SOM.

A range of climatic conditions span the inland PNW, where mean annual precipitation ranges from a low of 150 mm in south-central Washington and increases along a west-to-east gradient to a high of 600 mm in eastern Washington and into Idaho (Schillinger et al., 2006). A mean annual temperature gradient also exists in the region and runs inversely to the precipitation gradient, ranging from 8.4^{o}C in the wetter regions in eastern Washington and into Idaho to 10.9^{o}C in the drier regions of south-central Washington. This climatic gradient is also an important consideration in assessing soil health, as precipitation and temperature represent important drivers of soil C and N dynamics. In water-limited regions such the Inland Pacific Northwest, rainfall drives biomass production, and in-turn, C inputs to the soil (Wynn et al. 2006), while decomposition rates, particularly of the labile SOM pool, are influenced by temperature and other soil factors (Davidson and Janssens, 2006). It follows that SOC is positively correlated with annual rainfall in water-limited regions, while negatively correlated with annual temperature (Post et al., 1982).

Furthermore, in the face of climate change, it becomes increasingly important to understand how climatic factors influence soil health. In natural ecosystems, a steady state in soil carbon dynamics with regard to climate is reached after centuries, or even millennia (Mann,

1986). In this state of equilibrium, abiotic factors, along with biological activity, dictate SOC levels through influence on biomass production and decomposition rates.

However, there is uncertainty as to how microbial decomposers will respond to increasing temperatures (Craine et al., 2012). Moreover, research has shown the importance of considering the interaction of management factors, climate factors, and SOM dynamics. For example, while temperature and precipitation represent important controls on C and N input and output, a priming effect (PE), resulting from the addition of fresh organic matter, has also been observed (Bingeman et al., 1953). This PE has been shown to be both negative (decrease in SOM decomposition) (Guenet et al., 2010; Zimmerman et al., 2011) and positive (increase in SOM decomposition) (Nottingham et al., 2009; Guenet et al., 2012). Thiessen et al., (2013) demonstrated a net positive PE with the addition of fresh organic matter, but observed that the rate of change of PE varied with temperature, representing both the complexity and importance of understanding how management and climate can interact to influence SOM dynamics and subsequently soil health.

Chapter 2 of this thesis explores the relationship between different fractions of the soil C and N pools and quantifies the influence of management practices, particularly tillage practices and cropping intensification, on soil C and N properties across five sites within the inland Pacific Northwest. Additionally, this chapter elucidates the influence of climate factors, namely mean annual temperature and precipitation, on soil C and N properties within the context of management factors. Last, this chapter provides an evaluation of a soil health index that has recently been discussed among local farmers and government entities and has shown promise by some in distinguishing between management impacts on soil health.

Ultimately, certain soil biochemical processes are the great integrator of soil properties, management, and climate and are a central component of soil health. Specifically, nitrogen mineralization, denitrification, and nutrient availability are three important features of soils that are critical to soil productivity and are environmentally significant. A major component of the nitrogen cycle, nitrogen mineralization represents the ability of the microbial population to decompose plant residue and SOM and to provide an important source of plant-available nutrients, two functions which are an important component of soil health (Doran & Parkin, 1994). Furthermore, nitrogen mineralization is a process dependent on a diverse microbial community of bacteria, fungi, and actinomycetes that are influenced by soil temperature, water content, and aeration while they feed on SOM and fresh crop residues to convert organic N to inorganic N (Schepers and Meisinger, 1994).

Also nested within the nitrogen cycle, denitrification is the antithesis of N mineralization and represents both a loss of nitrogen from the soil N pool as well as a source of nitrous oxide (N_2O) in the atmosphere, a major greenhouse gas with global warming potential 298 times that of CO_2 (Pittelkow, 2013). Several factors have potential to influence soil denitrification, including soil aeration, pH, soil temperature, the presence of denitrifiers, and NO_3^- and C availability (Sylvia et al., 2005).

Nutrient availability is also an important consideration with regard to soil health due to its role in soil productivity. Plant macro- and micronutrient availability is dependent on a number of factors, including SOM, texture, CEC, as well as management factors such as tillage (Havlin et al., 1999). Ion exchange resins (IER) have a long history in agricultural research (Schlenker, 1942), and are one method of measuring plant-available nutrients and the rates

they are released (Qian and Schoenau, 2001) and measurements using IERs have been shown to correlate well with plant nutrient uptake (Lajtha, 1988; Qian and Schoenau, 1995). Additionally, IER measurements have displayed sensitivity to soil temperature and moisture content, as well as to microbial competition for nutrients (Huang and Schoenau, 1997).

Chapter 3 of this thesis presents the relationship between soil C and N data and these three important soil processes – nitrogen mineralization, denitrification, and nutrient availability using IERs. Additionally, this chapter relates these processes to tillage practices and cropping intensification, as well as to mean annual temperature and precipitation in order to identify the role of these first-order factors in regional soil health.

The fact that the concept of soil health has been around for decades is a testament to its value. However, contrary to water quality and air quality, no set of accepted standards have yet been universally recognized for soil health (Karlen and Stott, 1994). However, whereas air and water resources have a relatively direct and immediate impact on human health, the impact of soil health on society can be less immediate, more circuitous, yet just as important. To be sure, soil is a finite resource and the vision of a future with an uncertain climate coupled with increasing pressure from an ever-increasing world population provides a backdrop for both broader awareness of soil health issues as well as an opportunity for increased understanding in the scientific community of the multiplicity of factors influencing this precious resource and its fundamental effects on society.

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CHAPTER 2
IMPACTS OF CLIMATE, TILLAGE, AND CROPPING INTENSITY ON CARBON AND NITROGEN IN SURFACE SOILS: A SOIL HEALTH PERSPECTIVE

ABSTRACT

Surface soils comprise a critical interface and influence soil health through their role in nutrient cycling and decomposition, gas exchange, water infiltration, and erosion. In this study, we tested multiple surface soil C and N properties across five agricultural sites within the inland Pacific Northwest (PNW) to assess the influence of climate, tillage, and cropping intensity on surface soil health (0-10 cm). Tillage systems ranged from no-till to tillage with a moldboard plow, and cropping intensification systems ranged from winter wheat (WW)/fallow to perennial cropping systems. Mean annual precipitation (MAP) across the study sites ranged from 200 mm to 663 mm, and mean annual temperature (MAT) ranged from 8.4^{o}C to 10.9^{o}C. MAP was positively correlated with SOC and total N, and MAT negatively correlated with SOC and total N. In a multivariate regression of MAP, MAT, tillage and cropping intensity versus soil health measures, MAP was the dominant variable, explaining 57% of SOC variability and 69% of total soil N variability. When MAP was removed from the model, MAT became the dominant variable, explaining 42% and 49%, respectively, of SOC and total N variability. Both hydrolyzable and non-hydrolyzable fractions of SOC were equally sensitive to climate, indicating no relationship between chemical recalcitrance and climate sensitivity. Permanganate oxidizable carbon (POXC) was significantly correlated with non-hydrolyzable carbon (NHC) ($r = 0.84$), non-hydrolyzable nitrogen (NHN) ($r = 0.80$), hydrolyzable carbon ($r = 0.90$), and hydrolyzable nitrogen ($r = 0.90$) and considered representative of stabilized soil organic matter (SOM).

POXC, however, was not strongly correlated with one-day carbon mineralization (Cmin) (r = 0.42). These two soil properties, POXC and one-day Cmin, were used to provide complementary information regarding the influence of tillage and cropping intensity on surface soil health. The sensitivity of SOM stabilization, represented by POXC, to tillage varied across the five study sites, ranging from not significant to a strong negative correlation (r = -0.84), and sensitivity of SOM stabilization to cropping intensity varied as well, ranging from negative (r = -0.46) to positive (r = 0.46). One-day Cmin sensitivity to tillage intensity ranged from not significant to a strong negative correlation (r = -0.87), and sensitivity to cropping intensity ranged from not significant to a positive correlation (r = 0.61).

Interpretation of results in this study along with the literature suggests that both values may be enhanced by cropping diversification; stabilized inputs along with low disturbance may particularly enhance POXC. Both the hydrolyzable soil C (HC) and non-hydrolyzable soil C (NHC) were sensitive to tillage intensity. However NHC/SOC, which is considered to reflect SOM quality, was not sensitive to tillage intensity. These results support that resistance to acid hydrolysis is not equivalent to resistance to biodegradation under changes in land use.

Last, review of a soil health index utilizing water extractable C (WEOC) and N (WEON) along with one-day Cmin revealed the sensitivity of this index to both climate and management; however, the inherent variability of these measurements indicates that the number of field replications must be considered beforehand to aid in a meaningful interpretation of results. While a scale of 0 to 50 has previously been associated with the index, a more moderate scale of 0 to 14 is more appropriate for the inland PNW.

INTRODUCTION

Soil health has been discussed among scientists in analytical terms at least as far back as the 1940s (Jenny, 1941) and most assuredly by farmers in descriptive terms since the advent of agriculture. A uniting theme of modern definitions of soil health is its capacity to function effectively at present and in the future (Doran & Parkin, 1994). Essential soil functions in the context of terrestrial ecosystems, including agriculture, are listed by Brady and Weil (2010): 1) promotion of plant growth; 2) biogeochemical cycling of nutrients; 3) provision of habitat for soil organisms; and 4) partitioning, storage, translocation, and decontamination of water. Soil organic matter (SOM) is crucial to these functions and therefore an important attribute of soil health and integral to soil productivity and the overall physical well-being of soils (Campbell, 1999). Furthermore, surface soils, the focus of this study (0-10-cm), greatly influence erosion potential, water infiltration, exchange of gases such as nitrous oxide, and nutrient cycling, all factors which are crucial to soil conservation and influence soil and environmental health (Franzluebbers, 2002).

Climate variables, such as mean annual temperature and precipitation, are important factors, which influence SOM levels and dynamics (Jenny, 1941). The inland Pacific Northwest (PNW), the focus area of this study, is a water-limited region. In water-limited regions, rainfall drives biomass production and in-turn, residue inputs to the soil (Wynn et al., 2006), while decomposition rates are influenced by temperature and other soil factors (Davidson and Janssens, 2006). It follows that SOM is positively correlated with annual rainfall in drier regions, while negatively correlated with annual temperature (Post et al., 1982). In the inland PNW, climate change models predict warmer and wetter springs in the future, translating to an

increase in annual average temperature and precipitation (Littell, 2009). In natural ecosystems, a state of equilibrium in SOM dynamics with regard to climate is reached after centuries, or even millennia (Mann, 1986), and considering both the increase in biomass production and decomposition that may result from this shift in climate, implications of climate change on SOM dynamics and soil health within the inland PNW are unclear.

Tillage and cropping intensity are also two variables which numerous researchers have identified as impacting SOM and soil health (Schomberg & Jones, 1999; Deen and Katkai, 2003; Liebig et al., 2004). Increasing soil disturbance alters SOM dynamics by altering substrate availability and decomposition rates. Tillage facilitates microbial degradation of SOM by promoting crop-residue-soil contact and placing residues into a moister sub-surface environment as compared to surface placemen under NT (Halverson et al., 2002) and by creating a more oxidative environment and reduced soil aggregation (Denef et al., 2004). Therefore, operations that reduce soil disturbance have the potential to increase SOM.

Accordingly, in a review of SOC data across the PNW, Brown and Huggins (2012) found that conversion from conventional till (CT) to NT resulted in net SOC accumulation in the surface 30 cm during the initial years of NT adoption. In a Palouse silt loam in Eastern Washington, Purakayastha et al., (2008) revealed that 100 years of cultivation with a moldboard plow resulted in a 64% reduction in SOC compared to native prairie; the greatest gains in SOC in the surface 10-cm was achieved through 28 years of NT with a diverse crop rotation including two cereal grains and a grain legume that resulted in SOC levels 19% below that of native prairie. Similarly, in this same study, Purakayastha and co-workers reported that soil microbial biomass, an important measure of the active portion of soil carbon, was 34%

greater in the surface 10 cm after 28 years of NT than after only four years of NT. Likewise, multiple studies have documented the detrimental impact of tillage on total N of surface soils (Martel and Paul, 1974; Wienhold and Halvorson, 1998).

Other studies have emphasized that cropping intensification, or reduction of fallow, along with the adoption of NT, are necessary to mitigate a decline in SOM. For example, Halvorson et al. (2002) evaluated the impacts of tillage on SOC sequestration in dryland cropping systems in the Great Plains and found that a spring wheat-winter wheat-sunflower rotation under NT was effective at building SOC and total N in the surface 15.2 cm while spring wheat-fallow under both NT and CT was not. Even further emphasizing the nuances and important considerations associated with cropping intensification, Huggins et al. (2007) found that along with reduced tillage intensity, annual cropping systems that enhanced biomass input, represented by continuous corn or corn-soybean, were more effective than annual cropping with less biomass input, represented by continuous soybean, at mitigating SOC losses.

Soil erosion, also highly influenced by tillage and cropping intensity, represents another major threat to soil health, and studies show that a reduction in tillage along with an increase in cropping intensity are important considerations in combating erosion's destructive forces (Williams and Wuest, 2011). In the inland PNW, soil erosion rates on the order of 3 to 50 Mg soil ha^{-1} are not uncommon and can far exceed USDA's established threshold for sustained productivity of 2.2 to 11.2 Mg soil ha^{-1} (Williams et al., 2009). NT or reduced tillage and increased cropping intensity work together to increase surface residue cover and promote improved macroaggregate formation, two factors that increase surface infiltration and result in less runoff and less soil movement (Williams et al., 2009).

The active fraction of SOC and total N has been shown to be a key indicator for an early assessment of management practice impacts on soil health (Franzluebbers and Arshad, 1996a; Dou et al., 2008; Culman et al., 2013), and an early assessment is critical to reversing or slowing this decline in SOM resulting from management practices. Particularly, permanganate oxidizable carbon (POXC) (Weil, 2003), soil microbial biomass carbon and nitrogen (Powlson and Brookes, 1987), carbon mineralization (Franzluebbers et al., 2000), acid hydrolysis (Rovira and Vallejo, 2002), and water extractable carbon and nitrogen (Haney et al., 2012) have been identified as measureable SOM constituents that are sensitive to management impacts on SOM.

In this study, we focus on the impact of climate, tillage, and cropping intensity on these SOM constituents. Specifically, the objectives of this study were to 1) explore the relationship between the soil C and N properties measured; 2) assess the influence of mean annual temperature and precipitation on soil C and N properties; 3) quantify the influence of tillage and cropping intensification on soil health and SOM quality; and 4) apply values obtained in this study to a recently developed soil health index and assess its application to the inland PNW. In addition, published literature values from other regions are presented to provide context for values reported in this study and to give a comparative sense of soil health within the region.

METHODS AND MATERIALS

Site Descriptions

Research plots located in five long-term agricultural research centers within the dryland and irrigated cropping regions of the inland PNW comprise the basis of this study. These research plots are located at the following research centers: Kambitsch Farm near Genesee, ID

operated by the University of Idaho; Palouse Conservation Field Station near Pullman, WA; Pendleton Research Station near Pendleton, OR, and Sherman Research Station near Moro, OR, both associated with the Columbia Basin Agricultural Research Center near Pendleton, OR; and Irrigated Agricultural Research Center near Prosser, WA. These five sites were selected based on the cropping systems present as well as the range of climactic conditions collectively represented by the sites. Together, the five sites span four agroecological classes (AECs), or land use classifications that represent unique biophysical and socioeconomic conditions that result in distinct cropping systems (Huggins et al., 2011): (1) annual cropping (limited annual fallow); (2) annual crop-fallow transition (e.g. 3-yr rotations with fallow every third year); (3) grain-fallow (e.g. 2-yr wheat-fallow rotation); and (4) irrigated. Following is a description of these sites. For the purposes of this study, unless otherwise noted, the winter wheat portion of rotations represents the crop present during sampling.

Kambitsch Farm, University of Idaho – Genesee, ID (AEC 1)

The Kambitsch experimental plots selected for this research originated in 2000 to study the effects of tillage on soil properties and crop growth. The experimental design is a split-plot randomized complete block design and sub-plots are 6.1 m by 80.5 m; however, as winter wheat was the only crop sampled, in the context of this study, the experimental design simplifies to a randomized complete block design. Prior to 2000, the site was managed strictly with conventional tillage. The predominant soil type is a Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxeroll). The crop rotation present since 2010 includes winter wheat (WW) (*Triticum aestivum)* -spring cereal (SC) (barley - *Hordeum vulgare* or spring wheat) - spring legume (SL) (garbanzo – *Cicer arietinum* or spring pea - *Pisum sativum*) with

tillage as the management variable (Table 1.1). Prior to 2010, crop sequences were not randomized and additional management details can be found in Johnson-Maynard et al. (2007). In 2010, whole plots were subdivided into three equal subplots with the present crop rotation randomized across these subplots. The whole plot tillage treatments that were present prior to 2010 remained the same after subdividing to allow for crop randomization within a given tillage treatment. CT plots are tilled a few days prior to planting for both fall and spring planted crops using a Glenco Soil Saver followed by a Will-Rich 2500 field cultivator. NT and CT plots are planted with a Flexi-Coil No-Till drill at 25.4-cm row spacing.

Palouse Conservation Field Station – Pullman, WA (AEC 1)

Soils at this site consist predominately of Palouse (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxeroll) and Thatuna (fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls) silt loam. Plots range in size from a minimum of 11 m wide to accommodate field-scale equipment up to 30 m in width and from 100- to 350-m in length as needed to capture significant portions of soil and landscape variability. The plots selected for study include five cropping systems established in 2001 and arranged in a randomized complete block design with three replications. The five cropping systems include two perennial systems, two, 3-year annual cropping systems that are continuous NT and one organic system that is a combination of perennial and annual crops (Table 1.1). The perennial systems include a native prairie system and a perennial tall wheatgrass system. The native perennial system was established in accordance with Conservation Reserve Program (CRP) guidelines and planted with Idaho Fescue (*Festuca idahoensis*) and Bluebunch Wheatgrass (*Agropyron spicatum*). The perennial wheatgrass plots were planted with a tall wheatgrass, developed from a hybrid of annual wheat

and *Thinopyrum*, a cool-season perennial grass known to produce large quantities of aboveground biomass. The annual, NT cropping systems include two rotations: WW-SB-SW and WW-SL-SW. These plots are seeded with a Cross Slot® inverted-T opener no-till drill at 25.4-cm row spacing. The organic cropping system is a reduced tillage alfalfa (*Medicago sativa*)-cereal-SL rotation managed according to organic agriculture protocols. The organic system was planted to a spring pea green manure crop during collection of the soil samples analyzed for this study.

Pendleton Station, Columbia Agriculture Research Center – Pendleton, OR (AEC 2)

The management variables studied at this site are tillage and cropping intensity. Three different rotations were selected for study and consist of WW-NT fallow rotation under NT initiated in 1982, a WW-fallow rotation with CT initiated in 1997, and a WW-winter pea (WP) (*Pisum sativum)* rotation under NT initiated in 1997 (WP was inserted in the rotation in 2012; prior to 2012 the rotation was WW-NT fallow). Prior to 1997, these latter two rotations were under CT that used a mold-board plow. Soils in these plots are predominately a Walla-Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls). Plots are 2.0 m by 33.5 m and the experimental design is a factorial design using tillage and fertilizer rate (0 and 120 kg ha^{-1} banded) as the treatments with four reps for each factorial combination Only fertilized plots in WW were selected for this study, and the plots were subsequently modeled as randomized complete block design (Table 1.1). For all plots, WW is planted in mid-October and harvested in mid to late July. A moldboard plow is used on CT plots for primary tillage in spring of the fallow year. These plots are also rod-weeded as necessary through the summer fallow season until

fall planting of WW. All plots are seeded with a Noble No-Till modified deep furrow drill at 25.4-cm row spacing.

Sherman Station, Columbia Agriculture Research Center – Moro, OR (AEC 3)

Experimental plots located in Moro, Oregon, were initiated in 2003 to compare NT and CT for annual cropping, as well as two- and three-year rotations with and without a fallow period. The predominate soil type at the site is a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll). The following four rotation and tillage treatments were selected for this study: WW – fallow under CT, and WW-WP, WW-fallow, WW-SB-fallow all under NT management (Table 1.1). Plots are 15 m by 105 m, and the experimental design is a randomized complete block design with three blocks. CT plots are tilled in the spring using a chisel plow and rod weeded as necessary from May to August. Winter wheat is seeded in September or early October at 40 cm row spacing. NT plots are direct seeded using a Fabro drill at 30-cm row spacing.

***Prosser Irrigated Agricultural Research Station – Prosser, WA* (AEC 4)**

This experiment was established in the fall of 2011 to study winter cover crop and NT management effects on crop productivity, water use efficiency, and N and C cycling. Due to the short history of this site, only plots not under a winter cover crop were selected for the purposes of this study and tillage was selected as the management variable. The crop rotation is WW-Sweet Corn (*Zea mays)*-potato (*Solanum tuberosum*); all crops are irrigated throughout the growing season as needed. The predominate soil type is a Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids). All plots, NT and CT, are disced prior to potato

planting and after harvest of potatoes prior to planting WW. Otherwise, NT pots receive minimum disturbance. WW is planted using a Fabro drill at 16.5 cm row spacing. Plots are 4.9 m by 14.6 m and the experimental design is randomized complete block design (Table 1.1).

Tillage and Cropping Intensity

These five study sites represent a range of tillage and cropping intensities. The Natural Resources Conservation Service (NRCS) has developed a system of quantifying soil disturbing activities known as the soil tillage intensity rating (STIR) (USDA-NRCS, 2006). The STIR was developed by the NRCS for use in calculating potential soil erosion utilizing the revised universal soil loss equation (RUSLE2) (USDA-NRCS, 2006). The rating captures the range and severity of operations for an entire rotation, from spraying herbicide to plowing, planting and harvesting. The final STIR value is annualized based on the set of operations required for the entire rotation (Table 1.1). More on this rating and how it was derived for each site can be found in Appendix A.

The NRCS establishes a STIR of 30 as the maximum value for NT operations (USDA-NRCS, 2011). In the previous site descriptions and in subsequent tables, all treatments with a STIR exceeding 30 are referred to as CT, while those under 30 are referred to as NT. The primary tillage implement for CT plots are listed in Table 1.1. Prosser is the deviation from this dichotomy, as plots managed primarily under NT are subject to greater disturbance due to the presence of potatoes in rotation, and consequently plots at Prosser managed as NT have a STIR greater than 30 (Table 1.1).

Cropping intensity was captured by assigning a value to each crop in a rotation based on the duration of growing plant cover (months) in a 12-month period. The following values were

used for this study: perennial crops – 0.83 (10 months divided by 12 months), fall planted crops – 0.75 (9 months divided by 12 months), spring planted crops – 0.33 (4 months divided by 12 months). The intensity rating for a rotation was derived by summing this value for each crop in the rotation and averaging across the length of the rotation (Table 1.1). More details on calculating cropping intensity values for each cropping system are available in Appendix A.

Table 1.1 Five study locations with management and site information.

Location	Experimental Design	Soil Type	MAP† (mm)	MAT† (°C)	Crop Rotation‡	Cropping Intensity	Year Established	Tillage	STIR‡ Rating	Equipment
Kambitsch Farm - Genesee, ID (N 46.58°, W 116.95°)	Rondomized Complete Block Design - (4 reps)	Palouse Silt Loam	663	8.6	WW - SC - SL	0.47	2000	No Till	14.4	Double Opener
								Conventional	88.3	Chisel Plow
Palouse Conservation Field Station - Pullman, WA (N 46.73°, W 117.18°)	Randomized Complete Block Design (3 reps)	Palouse/Thatuna Silt Loam	530	8.4	Native (CRP) Grasses	0.83	2001	N/A	0.15	N/A
					Perennial Tall Wheat Grass	0.83		N/A	0.45	
					Alfalfa - cereals - SL (organic)	0.49		No Till	22.8	Sweep/ Single Opener
					WW - SB - SW	0.47		No Till	6.3	Single Opener
					WW- SL - SW	0.47			5.2	
Columbia Basin Agriculture Reseach Center - Pendleton, OR (N 45.44°, W 118.37°)	Randomized Complete Block Design (4 reps)	Walla Walla Silt Loam	417	10.3	WW - Fallow	0.38	1982	No Till	12.9	Modified Deep Furrow
					WW - WP	0.75	1997		25.2	
					WW - Fallow	0.38	1997	Conventional	88.2	Mold-board
Columbia Basin Agriculture Agriculture Reseach Center - Moro, OR (N 45.48°, W 120.69°)	Randomized Complete Block Design (3 reps)	Walla Walla Silt Loam	288	9.4	WW - chem fallow	0.38	2003	No Till	7.4	Double Opener
					WW - WP	0.75			14.4	
					WW - SB - Fallow	0.36			9.7	
					WW - Fallow	0.38		Conventional	70.9	Chisel Plow
WSU Irrigated Agricultural Research Center - Prosser, WA (N 46.29°, W 119.74°)	Rondomized Complete Block Design (4 reps)	Warden Silt Loam	200	10.9	WW - Sweet Corn - Potato	0.54	2011	No Till	68.6	Double Opener / Disc§
					WW - Sweet Corn - Potato			Conventional	78.1	Ripped/Disc

† MAP = mean annual precipitation; MAT = mean annual temperature (Climate data from NOAA from 1955 to 2012; Appendix B).

‡ WW = winter wheat; SC = spring cereal; SL = spring legume; SB = spring barley; SW = spring wheat; WP = winter pea.

‡ STIR = Soil Tillage Intensity Rating.

§ No-till disced during potato sequence.

Soil Sampling

Each site was sampled in June and July of 2013 prior to harvest from 0- to 10-cm, collecting 50 to 60 samples across each plot using a hand-operated soil probe (2.0 cm inside diameter). Four bulk density cores (3.0 cm inside diameter) were also collected from 0 to 10 cm from each subject plot using a hand operated soil probe; these samples were also used to determine field water content. All samples were immediately placed on ice in the field and transferred to cold storage at 4°C until further processing.

Laboratory Analysis

Physical Characterization & Soil pH

Bulk density and water content represent the physical indicators comprising this study. Gravimetric soil water content was determined from the bulk density cores after drying at 104°C for 24 hours. Bulk density was determined from the oven-dried weight of samples and the volume of the core sampler following the method of Veihmeyer and Hendrickson (1948). In addition to these physical properties, soil pH was also measured using a 1:1 soil-water mixture (Eckert, 1991).

Soil Carbon Fractionation

Total soil C (SOC) and N were determined by dry combustion using a CHN autoanalyzer (LECO CHN-1000, Leco Corp., St Joseph, MI, USA) (Tabatabai and Bremner, 1970). Acid hydrolysis was performed with a modified version of the method described by Paul et al. (1997). In short, air dry soil was ground to a fine powder and 1.0 g of soil refluxed at 115°C for 16 hours with 6.0-M HCl. This suspension was then washed with deionized water through a glass-fiber filter and the recovered sample dried at 40°C for 72 hours. Samples were then

analyzed for total C and N as mentioned previously, representing NHC and NHN, and the hydrolyzability of samples calculated based on mass balance.

Microbial biomass C and N (MBC/MBN) was performed on 10-g oven-dry weight soil using the chloroform fumigation-extraction method as outlined by Voroney et al. (2008). Soils were brought to field capacity (estimated at 25% water content for Kambitsch, PCFS, Pendleton, and Moro and 20% for Prosser) and incubated at 20°C for 48 hours prior to fumigation with ethanol-free chloroform. Instead of a 0.5-M K_2SO_4 extraction, fumigated and non-fumigated soils were extracted using 30 ml of deionized water, shaken for 30 minutes using an oscillating shaker then filtered through 0.2-µm nylon filter after centrifuging for 5 minutes at 3200 rpm (1500g). The filtrate was frozen until analyzing for C and N on a high-temperature combustion Shimadzu total organic carbon (TOC) analyzer.

Water extractable organic C and N (WEOC, WEON) analyses were performed according to established laboratory protocol at the USDA/ARS Soil Biogeochemistry lab at Washington State University. Soils were dried at 40°C for 24 hours and sieved to 2.0 mm prior to adding 12.5 ml of 18-MΩ water (purified to remove C) to 5.0-g oven-dry weight equivalent soil. This soil- water mixture was shaken for one minute on an oscillating shaker, centrifuged for five minutes at 5000 rpm, then filtered through 0.2-µm nylon filter paper. The collected filtrate was frozen until analyzing for C and N on a high-temperature combustion Shimadzu TOC machine. Samples were also analyzed for inorganic N and WEON determined from subtracting out this inorganic fraction. Carbonates were assessed using the same high-temperature combustion Shimadzu TOC machine with a 1.0-M HCl solution; however no carbonates were detected and all C values presented can be considered representative of organic C.

Permanganate oxidizable carbon (POXC) was performed according to the method of Weil et al. (2003) in which 0.02-M $KMnO_4$ is used. This methodology was developed by Weil et al. (2003) as a sensitive analysis to capture a representative portion of active soil carbon that is most influenced by management, as opposed to the method developed by Blair et al. (1995), which attempts to capture and define the entire active carbon pool using a more concentrated permanganate solution. Additionaly, the method developed by Weil et al., (2003) is available in a field kit version, making this a low cost and highly accessible soil property to meaasure. This procedure was performed in triplicate on 2.5-g oven-dry weight equivalent soil that was air dried for 24 hours and sieved to 2.0 mm. Absorbance was measured on a Spectra Max M2 single cuvette reader set at 550 nm as recommended by Weil et al. (2003).

Mineralizable Carbon Potential

Measurement of carbon mineralization (Cmin) from re-wetted soils was performed on laboratory-incubated soil in triplicate as a measure of active carbon and soil microbial activity. Soils were oven dried at 40°C for 24 hours then sieved to 2.0 mm (Haney et al., 2008). Processed soils were then packed to a dry bulk density of 1.0 g cm^{-3} in 40-ml glass vials with rubber top septa through which gas samples were collected using a syringe and needle at the designated times. Prior to bringing samples to field capacity, they were covered with a breathable film which allows oxygen exchange while preventing moisture loss and incubated at 20°C for 24 hours. After this incubation time, water was added to bring samples to field capacity (estimated at 25% water content for Kambitsch, PCFS, Pendleton, and Moro and 20% for Prosser), which was designated as time zero. Gas samples were collected at 24 hours, and 3, 7, 10, 17, and 24 days. At these sampling times, vials with soils at field capacity were flushed

with a breathing-air mixture containing approximately 200-ppm CO_2, and gas samples were collected immediately after flushing on every tenth sample and two hours after flushing from every sample. The CO_2 evolution rate was calculated as the difference between average time zero CO_2 and CO_2 measured at two hours (McLauchlan and Hobbie, 2004). Samples were run on a Shimadzu gas chromatograph equipped with an automated valve system for routing gas samples to the electron capture (ECD) and flame ionization (FID) detectors.

Statistical Analysis

Treatment effects on soil properties were analyzed using General Linear Model in SAS System for Windows Version 9.3 (SAS Institute, 2012) and means were separated using Fisher's protected Least Significant Difference (LSD) test at the $p = 0.10$ level. Within a site, sources of variation in the statistical model were field (block) and agroecosystem treatment. Tukey's mean separation procedure was used to identify significant differences when the global F-test was non-significant ($p > 0.10$). Cumulative Cmin values were analyzed using mixed models with repeated measures (SAS Institute, 2012). Unless specifically stated otherwise, all statistical differences represent $p < 0.10$. In performing multivariate analysis, model entry was also set at $p < 0.10$. A less rigorous alpha was selected for this study due to both the short management histories associated with some of the sites (Table 1.1) and the inherent spatial variability of many of the soil C and N properties measured. In consideration of these two factors, an alpha of 0.10 was considered a judicious step towards minimizing type II errors (failing to reject a false null hypothesis).

RESULTS AND DISCUSSION

Soil C and N Relationships

A high degree of correlation exists between many of the measured soil C and N properties (Table 1.2). One-day Cmin was significantly correlated with 24-day Cmin (r = 0.70), suggesting that short-term Cmin can be extrapolated to gauge the active organic carbon pool and associated processes, particularly nutrient cycling and decomposition capacity (Franzluebbers et al., 2000). Similarly, Franzluebbers et al. (2000) dound that 3-day Cmin was as effective as Cmin after 24 days, MBC, and SOC at identifying significant changes resulting from management practices. Other researchers have found a strong correlation across a range of conditions between Cmin data and other measures of active C, particularly MBC (r = 0.93) (Franzluebbers et al., 2000); the correlation in our study was significant, albeit weaker (r = 0.31) (Table 1.5).

A less pronounced correlation of Cmin with MBC than was cited in the literature could be due to differences in methodology. In Franzluebbers et al. (2000), soil microbial biomass was determined by chloroform fumigation followed by ten days of incubation, which is more similar to Cmin measurements than the chloroform-fumigation-extraction method employed in this study, in which microbial biomass was measured separately from Cmin. Haney et al. (2008) noted a significant relationship between one-day Cmin and WEOC (r^2 = 0.76) and WEON (r^2 = 0.86); this relationship between one-day Cmin and the water extractable fraction of soil C and N, however, was not significant in the present study (Table 1.2). This finding indicates that Cmin may have been fueled by additional sources of C and N than just the water extractable

fraction of soil C and N, or vice-versa, that WEOC and WEON contained constituents in addition to that which fueled one-day Cmin.

Across all study sites, POXC was strongly correlated with multiple soil properties, including SOC and total N, as well as with the hydrolyzable and non-hydrolyzable fractions of SOC and total N (Table 1.2, Figure 1.1). Others have demonstrated a comparable relationship between POXC and SOC (Culman et al., 2012; Lucas and Weil, 2012; Culman et al., 2013); to the authors' knowledge, however, nowhere in the literature has this relationship between POXC and results of acid hydrolysis been noted.

The relationship between POXC and the more highly active pools of C and N, as represented by Cmin, microbial biomass, and WEOC and WEON, was not as strongly correlated (Table 1.2, Figure 1.1). In corn, soybean and wheat rotations in Michigan Culman et al. (2013) found poor correlations between POXC and one-day Cmin, and concluded that the two measurements responded differently to management. POXC was more influenced by stabilized C inputs, while Cmin was more influenced by substrate diversity.

The slope for the C/N regression line for the most labile soil C and N pools, the water extractable and microbial biomass fractions, was similar. This relationship is representative of the active nature of these constituents of SOM, which is also indicated by the significant correlation between these properties (Figure 1.2, Table 1.2). The slope of the regression line for the non-hydrolyzable fraction of SOC exceeded the fraction of total N that was non-hydrolyzable N (Figure 1.3).

Olson and Lowe (1990) found similar results in cultivated soils and concluded that nitrogenous organic compounds were more susceptible to hydrolysis than SOM as a whole,

partially due to the hydrolysability of amino acids and amino sugars. Martens and Loeffelmann (2003) demonstrated this through methanesulfonic acid hydrolysis and ion chromatography, identifying as much as 85% of total N as amino acids/amino sugars and NH_4^+ across a range of unsaturated soils (0-5 cm). Plante et al. (2006) further explains that organic compounds which are easily protonated, including nitrogenous compounds, are more easily hydrolyzed than C compounds. This fact underlies the relationship between NHC/NHN and HC/HN, whereby the non-hydrolyzable C/N ratio exceeded that of the hydrolyzable C/N ratio (Figure 1.2).

These results are in accordance with studies across a range of terrestrial ecosystems and climates for surface soils, including pine plantation soils in Australia (He et al., 2009), as well as cultivated and uncultivated soils in British Columbia (Olson and Lowe, 1990). These results are, however, also contrary to the observation that more decomposed SOM generally has a lower C/N ratio (Brady and Weil, 2010). This hydrolyzable fraction of total N represents N available for potential mineralization (Pare et al., 1998), as well as loss through various gaseous forms. However, hydrolyzable N can also become stabilized with linkages to humus-like material, a fact which has been demonstrated during the composting process (Pare et al., 1998). Therefore, susceptibility of N to hydrolysis does not equate to active N, as some of this N can become incorporated into more stabile C-based compounds. This fact is also evidenced by the significant correlation of NHN and HN with NHC (Table 1.2). This non-hydrolyzable fraction of SOC is thought to represent a more processed fraction, evidenced by carbon dating where NHC has been shown to be older than the HC fraction (Paul et al., 2006; Rovira and Vallejo, 2007).

Table 1.2. Pearson correlation between various soil properties across five study sites*.

Property†	$Cmin_{0-1d}$	$Cmin_{0-3d}$	$Cmin_{0-10d}$	$Cmin_{0-17d}$	$Cmin_{0-24d}$	qCO_2	POXC	SOC	Total N	NHC	NHN	HC	HN	MBC	MBN	WEOC	WEON
$Cmin_{0-3d}$	0.98																
$Cmin_{0-10d}$	0.81	0.91															
$Cmin_{0-17d}$	0.75	0.85	0.98														
$Cmin_{0-24d}$	0.70	0.80	0.94	0.98													
qCO_2	ns	ns	ns	ns	ns												
POXC	0.42	0.45	0.50	0.46	0.39	-0.31											
SOC	0.28	0.31	0.39	0.35	0.29	-0.36	0.93										
Total N	0.31	0.33	0.39	0.33	0.25	-0.44	0.93	0.97									
NHC	0.28	0.32	0.39	0.37	0.33	-0.31	0.84	0.88	0.86								
NHN	0.27	0.30	0.34	0.30	0.27	-0.35	0.80	0.82	0.82	0.93							
HC	0.32	0.35	0.41	0.35	0.28	-0.36	0.90	0.92	0.93	0.74	0.68						
HN	0.26	0.29	0.36	0.31	0.23	-0.41	0.90	0.95	0.98	0.77	0.70	0.94					
MBC	0.31	0.37	0.43	0.38	0.33	-0.72	0.50	0.49	0.52	0.51	0.57	0.43	0.45				
MBN	0.29	0.34	0.35	0.33	0.34	-0.44	ns	ns	ns	ns	0.26	0.24	ns	0.72			
WEOC	ns	0.25	0.35	0.35	0.31	-0.26	0.53	0.64	0.58	0.67	0.58	0.43	0.53	0.53	0.29		
WEON	ns	ns	0.25	ns	ns	-0.33	0.53	0.63	0.60	0.62	0.62	0.45	0.56	0.50	0.29	0.83	
pH	ns	ns	ns	ns	ns	0.44	-0.7	-0.74	-0.78	-0.65	-0.63	-0.67	-0.76	-0.49	ns	-0.45	-0.48

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† Cmin = Cumulative carbon mineralized at 1, 3, 10, 17 and 24 days; qCO_2 = Microbial metabolic quotient, calculated from daily carbon mineralized between day 10 and 24 per unit of microbial biomass carbon; POXC = permanganate oxidizable carbon; SOC = soil organic carbon; NHC = non-hydrolyzable carbon; HC = hydrolyzable carbon; MBC = microbial biomass carbon; WEOC = water extractable organic carbon; NHN = non-hydrolyzable nitrogen; HN = hydrolyzable nitrogen; MBN = microbial biomass nitrogen; WEON = water extractable organic nitrogen; pH = soil pH from 1:1 water extract.

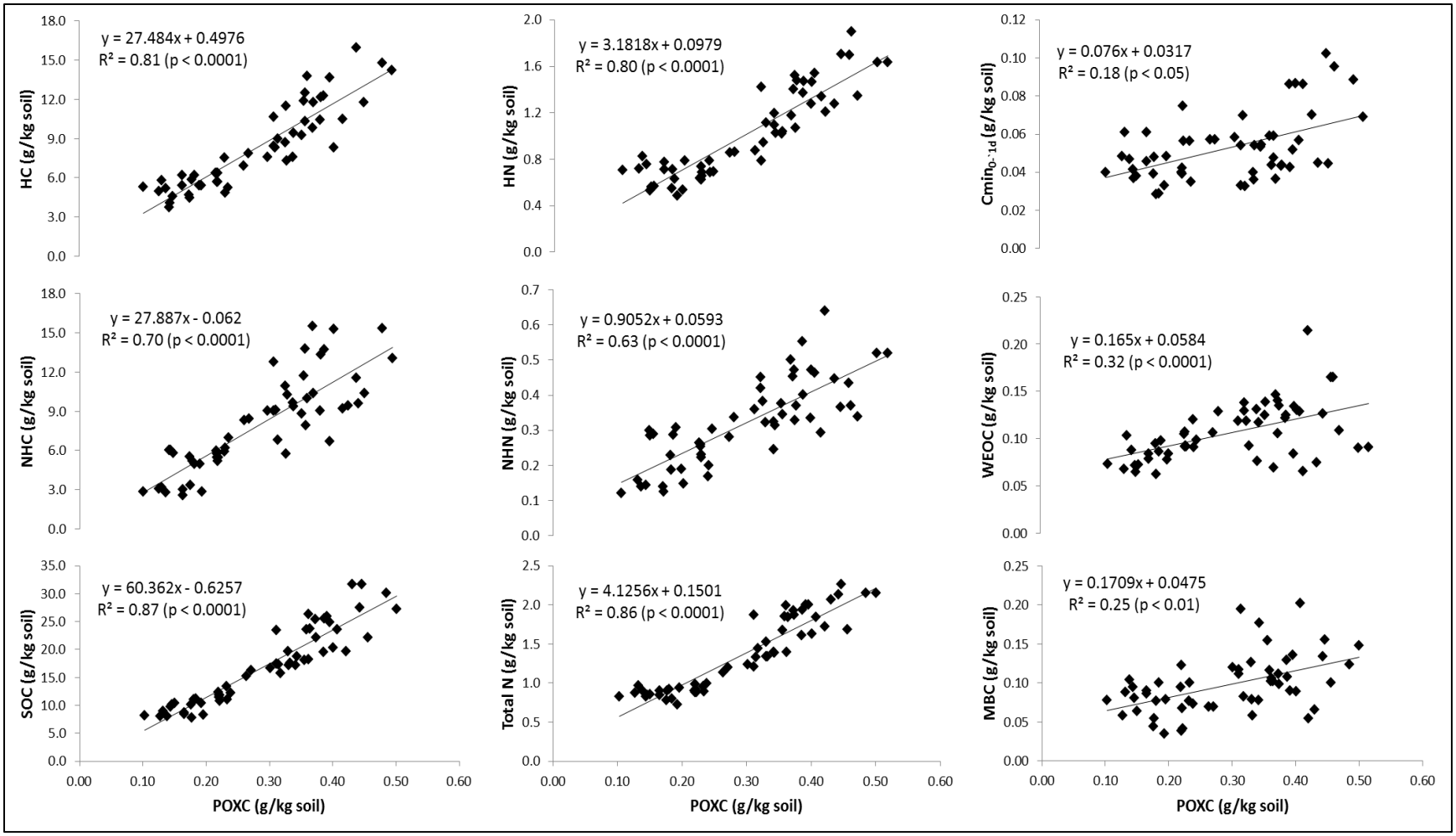

Figure 1.1 Relationship between POXC and various soil C and N properties across five study sites. (POXC = permanganate oxidizable carbon; HC = hydrolyzable carbon; NHC = non-hydrolyzable carbon; SOC = soil organic carbon; HN = hydrolyzable nitrogen; NHN = non-hydrolyzable nitrogen; $Cmin_{0\text{-}1d}$ = one-day C mineralization; WEOC = water extractable organic carbon; MBC = microbial biomass carbon.

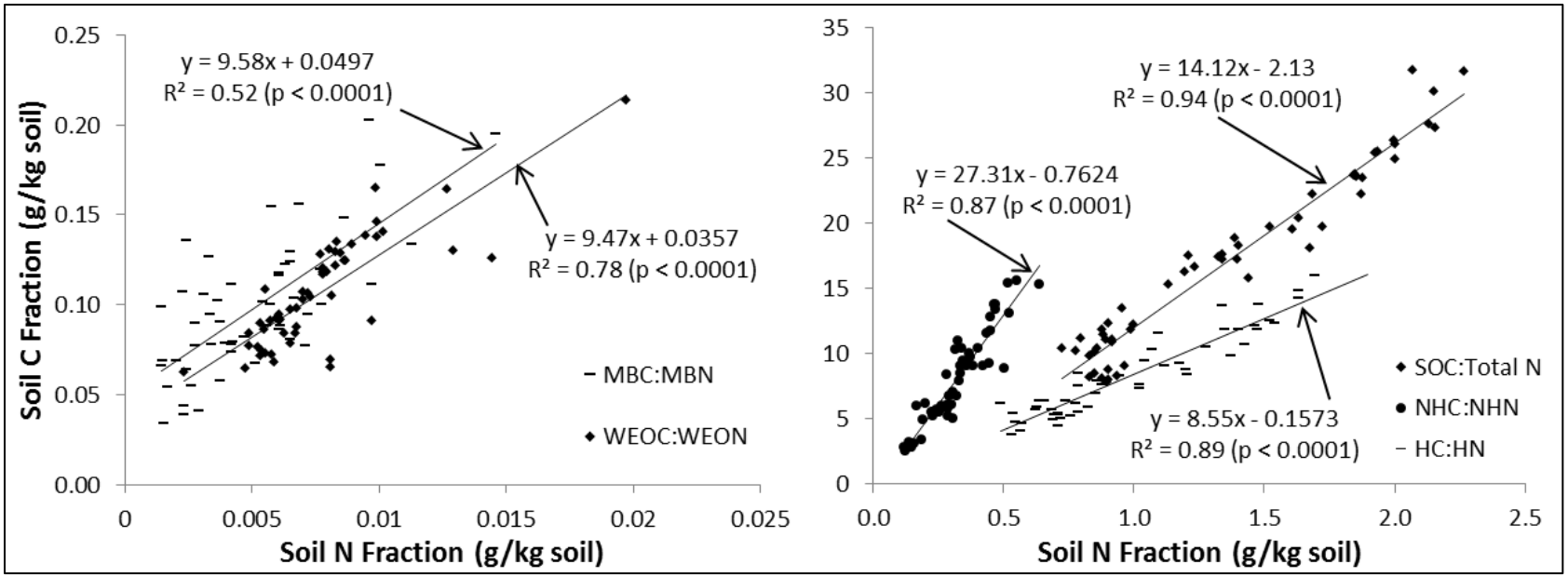

Figure 1.2 C:N relationship of various soil C and N properties across five study sites. (MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen; SOC = soil organic carbon; NHC = non-hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HC = hydrolyzable carbon; HN = hydrolyzable nitrogen).

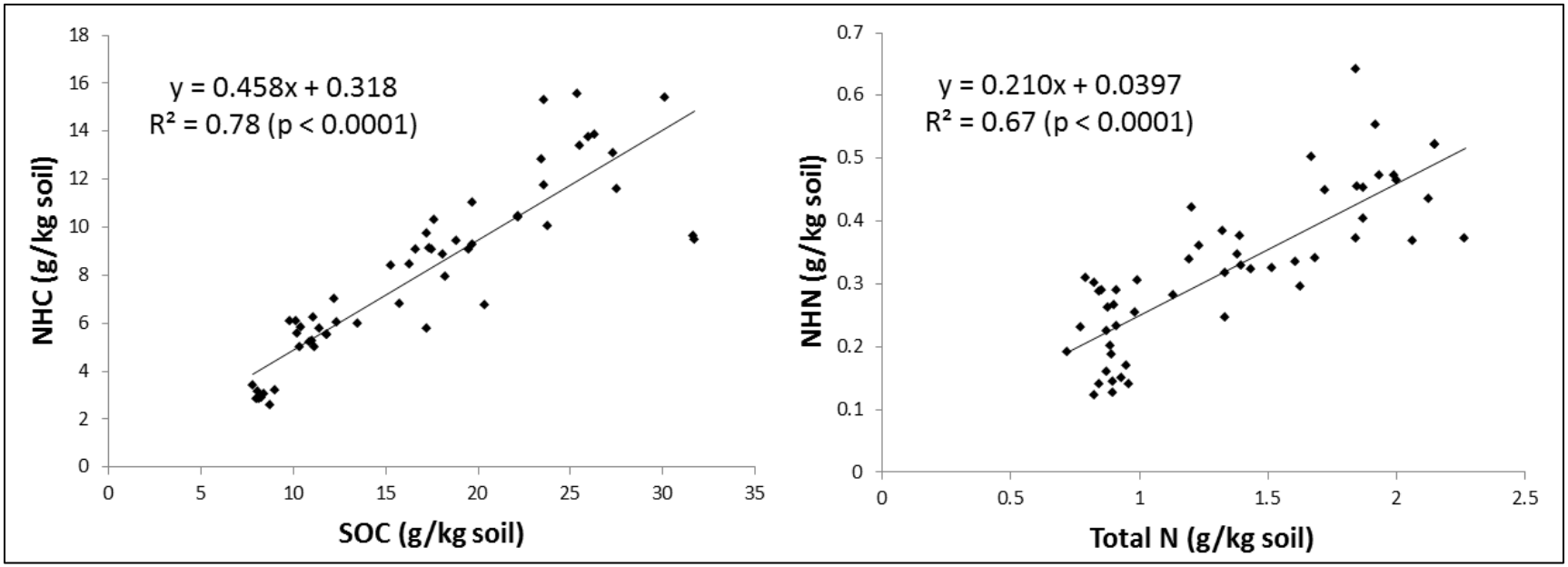

Figure 1.3 Relationship between non-hydrolyzable C and N and SOC and Total N across five study sites. (SOC = soil organic carbon; NHC = non-hydrolyzable carbon; NHN = non-hydrolyzable nitrogen).

Mean Annual Temperature and Precipitation Influence on Soil C and N

The four non-irrigated sites selected for this study span a mean annual precipitation (MAP) gradient that increases by 130% from Moro (288 mm) to Kambitsch (663 mm), and a mean annual temperature (MAT) gradient that increases by 23% from PCFS (8.4^{o}C) to Pendleton (10.3^{o}C). The Prosser site was excluded from this analysis because it is an irrigated site. The MAT and MAP gradients across the site locations considered collectively were used to assess the impact of these climate variables on soil C and N properties.

Across the four dryland cropping sites, POXC, SOC, total N, HC, NHC, HN, and NHN were positively correlated with MAP and negatively correlated with MAT (Table 1.3). In a multivariate analysis of climate along with management variables, MAP explained 57% and 69% respectively of the variation in SOC and total N. If MAP is removed from the model, MAT becomes the dominant significant variable, explaining 42% of SOC variation and 49% of total N variation (Table 1.4).

The hydrolyzable and non-hydrolyzable fractions of soil C and N are subject to a similar influence by MAP and MAT as SOC and total N (Table 1.4). MAP explains 50% of NHC variation, 55% of NHN variation, and a slightly greater percent of variation in the hydrolyzable fraction, explaining 57% of HC variation and 63% of HN variation (Table 1.4). As with SOC and total N, if MAP is removed from the model, MAT becomes the significant factor in explaining the variation in the hydrolyzable and non-hydrolyzable fractions of SOC and total N. As already presented, POXC is strongly correlated with SOC, total N, as well as the hydrolyzable and non-hydrolyzable fractions, and it follows that POXC is similarly influenced by climate variables (Tables 1.3 and 1.4).

The more active soil properties measured in this study, including WEON, MBC, and one-day Cmin, were positively correlated with MAP, while only WEON along with WEOC displayed a significant correlation with MAT (Table 1.3). The microbial metabolic quotient (qCO_2) is an indicator of microbial efficiency, whereby an increase in qCO_2 indicates a decrease in microbial efficiency (Smith et al., 2002). In the present study, qCO_2 displayed a negative relationship with MAP (Table 1.3), indicating a decrease in MAP was associated with a decrease in microbial efficiency. MAP was also an important factor, more so than management factors, in explaining the variation in MBC ($r^2 = 0.22$), one-day Cmin ($r^2 = 0.12$), qCO_2 ($r^2 = 0.26$), and WEON ($r^2 = 0.14$). Variation in MBN was not explained by management or climate factors (Table 1.4). When MAP was removed from the model, MAT was not a signficant variable in explaining variation in these more active soil properties (Table 1.4).

This multivariate analysis of climate along with management indicates that soil C and N of surface soils within the scale covered by this study were influenced by MAP and MAT more so than STIR and cropping intensity. Similar results were found by Colman and Schimel (2013), who found that on a continental scale across 84 different soils, mean annual precipitation and temperature could explain 60% of the observed variation in SOC.

In the inland Pacific Northwest, future climate scenarios predict rising mean annual temperatures and precipitation (Littell et al., 2009). MAT tends to influence decomposition more so than productivity where growing degree days are sufficient, while MAP in drier regions increases productivity, and thus inputs of SOM to the soil, more than it increases decomposition (Weil and Magdoff, 2004). Similarly, Kirschbaum (2000) demonstrated that net

primary productivity was more sensitive to water availability and decomposition more sensitive to temperature.

This interplay of temperature and precipitation on SOM dynamics is also supported by studies showing that the ratio of MAT (^{o}C) to MAP (mm x 0.01) (climate ratio) displays a strong correlation with SOC; SOC levels are highest when this ratio is near one and drops as this value increases (Weil and Magdoff, 2004). This relationship holds true for the current study as well, where SOC and total N along with the hydrolyzable and non-hydrolyzable fractions are greatest at PCFS and Kambitsch, which have a climate ratio nearest 1.0, and these soil properties decrease as this ratio increases (Figure 1.4).

These figures indicate that a disproportionate rise in MAT uncoupled from a rise in MAP would result in slow degradation of surface SOM across the region. For the inland PNW, climate models predict a 1.7^{o}C to 2.2^{o}C rise in MAT by 2050 and a 2.2^{o}C to 3.6^{o}C rise in MAT by 2100, and correspondingly 5 to 15% rise in MAP by the middle and latter part of the 21st century (REACCH, 2014). Applying the extremes of these climate predictions to present day climate ratios results in an increase in climate ratios across the study sites, and subsequently a decline in average SOC and total N across the region for 2050 and 2100 (Figure 1.5); for example, SOC for 2050 and 2100 at Pendleton, based on forecasted shifts in MAT and MAP, is 8.4% and 10.1% respectively below the present day average for Pendleton across treatments (Figure 1.5).

While this prediction demonstrates the susceptibility of SOM to climate change, understanding how SOM pools of different turnover times are impacted by climate variables is an important part of predicting SOM dynamics under future climate scenarios. Plante et al.

(2010) demonstrated temperature sensitivity of SOM resistant to acid hydrolysis as well as the particulate organic matter fraction, typically considered labile C, to decomposition under elevated temperatures. This is supported by results from the present study, where the hydrolyzable and non-hydrolyzable fractions of SOM were sensitive to MAT (Tables 1.3 and 1.4), and further supports that chemical recalcitrance alone does not explain residence times of SOC (Conant et al., 2011). Lefevre et al. (2014) demonstrated in an analysis of long-term bare-fallow soils that SOM pools with longer turnover times exhibited greater temperature sensitivity than SOM pools with shorter turnover times, as would be indicated by enzyme kinetic theory which dictates greater temperature sensitivity of more recalcitrant compounds (Davidson and Janssens, 2006).

Drawing similar conclusions from the present study is complicated by the fact that MAP and MAT are confounded across the four dryland sites. Enzyme kinetic theory (Davidson and Janssens, 2006) and results from Lefevre et al. (2013), however, support results in the present study wherein pools with the shortest turnover times, namely MBC, MBN, and one-day Cmin did not display sensitivity to the MAT gradient, while pools known for a longer turnover time, namely SOC, total N, and the hydrolyzable and non-hydrolyzable fractions, did display a temperature sensitivity (Table 1.3 and 1.4). However, this can also be explained by the achievement of a steady state prior to performing MBC, MBN, and Cmin incubations, as soils were incubated for at least 24 hours at room temperature prior to analyses, thus minimizing the influence of MAT. Likewise, incubating soils over short periods under different temperatures has shown greater sensitivity to temperature than soils under steady state (Conant et al., 2011).

Due to the confounded nature of MAT and MAP in the present study, utilizing the climate ratio can provide insight regarding climate sensitivity and soil C and N turnover time. A comparison of the hydrolyzable and non-hydrolyzable fractions of SOC with the climate ratio reveals that the NHC fraction, which is understood to have a longer turnover time than the HC fraction (Paul et. al, 2006, Rovira and Vallejo, 2007), did not display a greater sensitivity to the climate ratio than the HC fraction. This is indicated similarity ($p > 0.10$) between the slopes of the regression line of NHC and HC with the climate ratio (Figure 1.4). The HN fraction, composed primarily of amino acids and amino sugars (Martens and Loeffelmann, 2003), however did display greater sensitivity to the climate ratio than the NHN fraction (Figure 1.4). This is consistent with the previous discussion of HN, in which it was established that a portion of HN may be stabilized by the presence of more processed material, such as NHC, and therefore a decline in NHC leads to a decline in HN (Figure 1.4), and is also the result of soil C/N ratios established through microbial activity.

Conant et al. (2011) reviewed multiple cross-site studies spanning a temperature gradient and found three different categories of relationship between SOM, turnover time, and temperature sensitivity: 1) three studies reported temperature sensitivity increased with a decrease in SOM turnover time; 2) eight studies reported no apparent relationship between temperature and SOM turnover time; and 3) one study reported temperature sensitivity increased with an increase in SOM turnover time. These varying results in published studies demonstrate the complexity of factors involved in understanding how SOM pools with varying turnover times will respond to a changing climate. The present study incorporates both MAT

and MAP and indicates based on NHC and HC results, no apparent relationship between turnover time and the climate ratio, MAT/MAP x 0.01.

Studies utilizing carbon isotope measurements and radiocarbon dating can also prove insightful for understanding the fate of SOM under conditions that promote increased decomposition. Balesdent et al. (1990) evaluated C_4 abundance of SOC under no-till maize 18 years after conversion from grassland and found that 83% of the SOC within the upper 400 kg m^{-2} soil was derived from the original grassland, suggesting that annual inputs from agriculture to the slower SOM pool compared to that from the native grassland were minimal. Similarly, in an analysis of the source of SOC in a forest soil that had been cleared and cultivated for 35 years under fertilized, continuous maize with biomass returned to the soil, Poirier (2006) found that the NHC of the cultivated soil within the tilled layer not only decreased with cultivation by 65%, but 92% of NHC was inherited from forest C prior to cultivation. The results from these two studies are likely the outcome of a reduction in quantity of SOM input, a decrease in recalcitrant inputs, and/or an increase in disturbance or erosion resulting from a switch from native conditions to agricultural conditions (Hassink, 1997; Huggins et al., 1998; Krull et al., 2003). These studies also demonstrate that a loss of SOM, particularly the fraction with a longer turnover time, resulting from an increase in decomposition may not be easily replaced under traditional cropping systems. Subsequently, an increase in C and N inputs, as may result from an increase in precipitation, is only a component in countering loss of biochemically recalcitrant SOM that can result from an increase in decomposition.

Constraints other than intrinsic chemical recalcitrance are also an important consideration in SOM turnover, most notably physico-chemical and physical stabilization (Krull

et al., 2003). In interpretation of continental SOC and microbial respiration, Colman and Schimel (2013) theorized that as SOM pools increase, microbes are less capable of decomposing a constant proportion of the increasing total SOM. This is at least partly due to spatial separation of microbes from increasingly protected SOM, which diminishes microbial capacity to degrade SOM. The inverse of this statement indicates that regions with lower SOM will be inherently more susceptible to SOM degradation under an increase in temperature. Physical protection of SOM through promotion of management strategies conducive to micro- and macroaggregate formation is crucial to protecting and/or building SOM under climate change.

Table 1.3 Pearson correlations between climate and soil properties across four study sites*.

Variable†	pH	SOC	Total N	POXC	NHC	NHN	HC	HN	$Cmin_{0-1d}$	qCO_2	MBC	MBN	WEOC	WEON
MAP	-0.77	0.76	0.83	0.84	0.70	0.74	0.75	0.80	0.51	-0.51	0.47	ns	ns	0.37
MAT	0.60	-0.64	-0.70	-0.61	-0.50	-0.47	-0.63	-0.70	ns	ns	ns	ns	-0.28	-0.35
Temp/Precip *0.01	0.84	-0.82	-0.88	-0.84	-0.75	-0.75	-0.8	-0.86	-0.42	0.56	-0.46	ns	-0.31	-0.42

* All variables significant at $p < 0.10$. ns = not significant($p < 0.10$) (Prosser excluded from analysis).

† MAP = mean annual precipitation (mm); MAT = mean annual temperature (^{o}C); Temp/Precip * 0.01 = MAT/MAP*0.01; pH = soil pH with 1:1 water extract; SOC = soil organic carbon; POXC = permanganate oxidizable carbon; NHC = non-hydrolyzable carbon; HC = hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HN = hydrolyzable nitrogen; $Cmin_{0-1d}$ = 1 day C mineralization; qCO_2 = microbial metabolic quotient; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen.

Table 1.4 Stepwise multivariate regression of climate and management variables for soil C and N properties across four study sites*.

Variable†	SOC	Total N	POXC	NHC	HC	NHN	HN	$Cmin_{0-1d}$	qCO_2	MBC	MBN	WEOC	WEON
MAP	0.57	0.69	0.7	0.5	0.57	0.55	0.63	0.12	0.26	0.22	ns	0.06	0.14
MAT	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
STIR	0.16	0.12	0.13	0.13	ns	0.03	ns	ns	ns	ns	ns	0.18	ns
Cropping Intensity	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
S*I	ns	ns	ns	ns	0.12	ns	0.14	ns	ns	ns	ns	ns	ns
Model R^2	0.73	0.81	0.83	0.63	0.69	0.58	0.77	0.12	0.26	0.22	0	0.24	0.14

Variable	SOC	Total N	POXC	NHC	HC	NHN	HN	$Cmin_{0-1d}$	qCO_2	MBC	MBN	WEOC	WEON
MAP	Excluded												
MAT	0.42	0.49	0.38	0.25	0.40	0.22	0.49	ns	ns	ns	ns	ns	0.13
STIR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.18	ns
Cropping Intensity	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
S*I	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Model R^2	0.42	0.49	0.38	0.25	0.4	0.22	0.49	0	0	0	0	0.18	0.13

* All variables significant at $p < 0.10$. ns = not significant($p < 0.10$) (Prosser excluded from analysis).

† MAP = mean annual precipitation (mm); MAT = mean annual temperature (^{o}C); STIR = soil tillage intensity rating; S*I = STIR/cropping intensity interaction; SOC = soil organic carbon; POXC = particulate organic carbon; NHC = non-hydrolyzable carbon; HC = hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HN = hydrolyzable nitrogen; $Cmin_{0-1d}$ = 1 day C mineralization; qCO_2 = microbial metabolic quotient; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen.

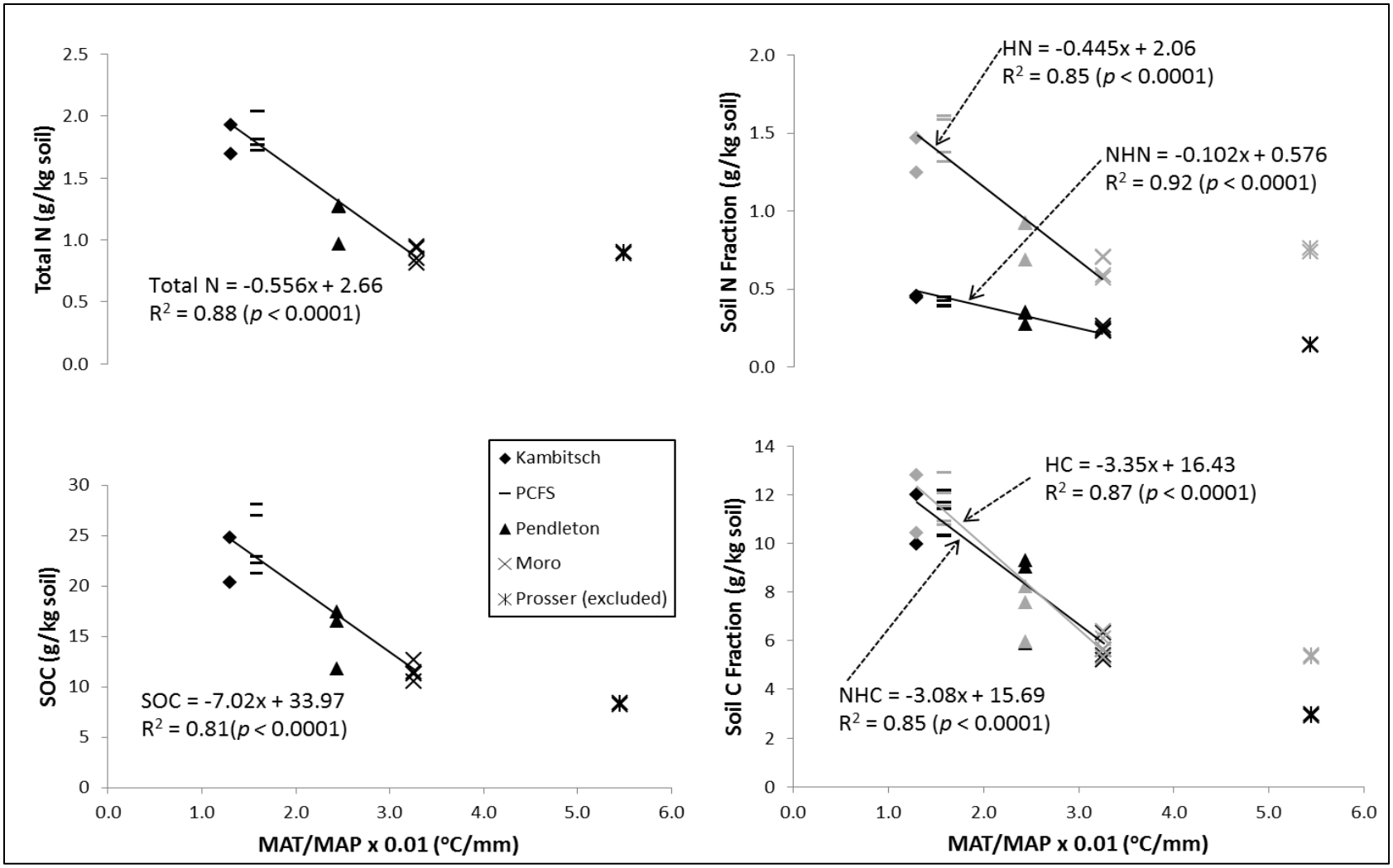

Figure 1.4 Relationship of SOC, total N, NHC, NHN, HC, and HN with temperature and precipitation ratio for four dryland study sites; Prosser shown but excluded from regression analysis (MAT = mean annual temperature (^{o}C); MAP = mean annual precipitation (mm); SOC = soil organic carbon; NHC = non-hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HC = hydrolyzable carbon; HN = hydrolyzable nitrogen).

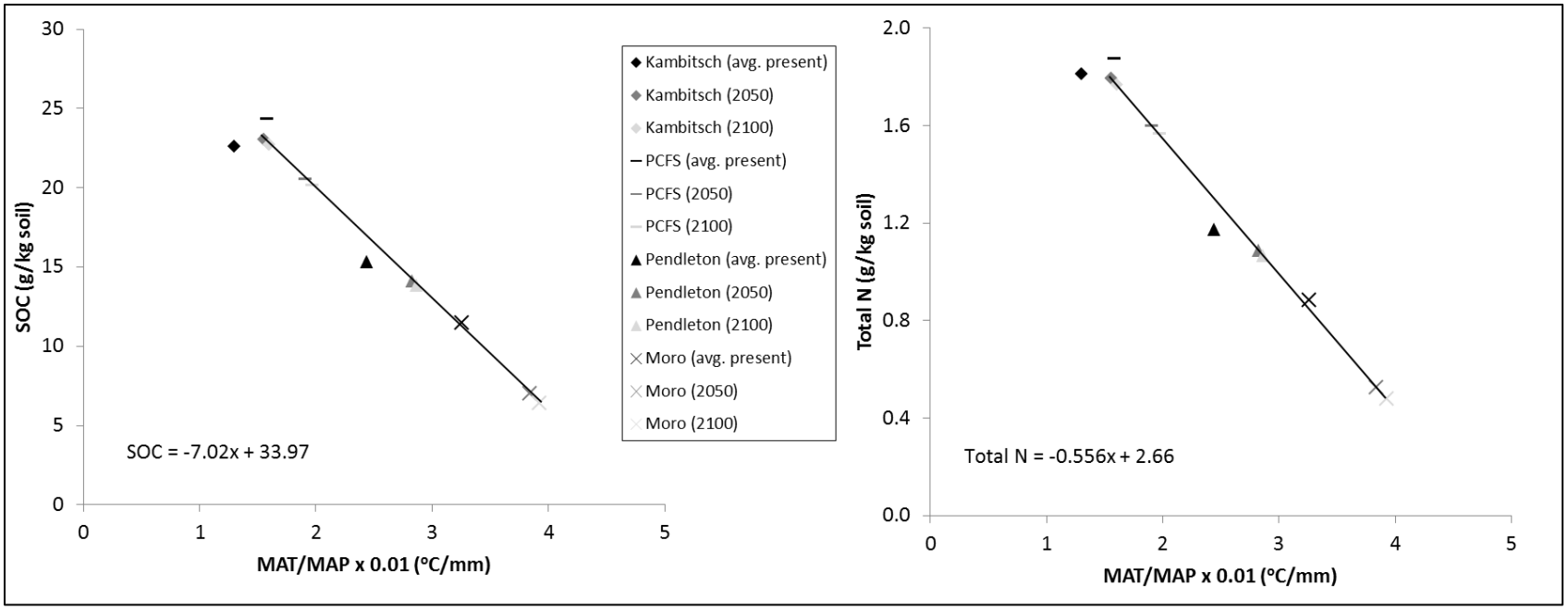

Figure 1.5 Future climate scenarios and SOC and total N across four dryland study sites (SOC = soil organic carbon; MAT = mean annual temperature, MAP = mean annual precipitation) (Notes: Present average for each site represents average across all treatments. MAT/MAP ratio for 2050 based on 2.2^{o}C rise in MAT and 5% increase in MAP based on current MAP, and for 2100 based on 3.6^{o}C rise in MAT and 15% rise in MAP based on current MAP. Regression equations shown from Figure 1.4 and represent present day relationship between SOC and total N with MAT/MAP*0.01).

Management and Soil C and N Properties

While climate may be a critical driver of C and N properties of surface soils, management practices also have a significant influence as indicated by significant differences within sites between treatments for the soil C and N properties measured (Tables 1.5, 1.6, and 1.7). These significant differences are representative of surface soils (0-10 cm) and potential differences at greater depths were not examined by this study. Significant differences in SOC were observed at all sites but Prosser; the reason for the lack of significant differences at Prosser may be due to the relatively recent history under current management combined with the high STIR associated with the NT treatment (Table 1.1).

On all accounts other than Prosser, comparisons of tillage treatments in which cropping intensification was not a variable indicated a reduction in tillage resulted in an increase in SOC; for example WW/fallow-NT at Pendleton had 47% greater SOC in surface soils than WW/fallow-CT (Table 1.5). The results of cropping intensification in SOC were apparent at Moro, where WW/WP-NT had 10.5% greater SOC than WW/fallow-NT. The NHC and HC fractions were less affected by treatment than SOC, as did the smaller pools, specifically the POXC, MBC and WEOC fractions (Table 1.5). Where significant differences were observed, a reduction in tillage and an increase in cropping intensity proved beneficial for increasing the pool sizes of these SOC fractions measured in surface soils.

Significant treatment differences in total N were less apparent than for SOC, and detected only at Pendleton (Table 1.6). This is likely the result of the greater CV for total N compared to SOC (Tables 1.5 and 1.6) and is indicative of the multiple dynamics influencing total N, including denitrification and leaching losses which are influenced by nitrification,

denitrification, and immobilization (Luxhoi et al., 2006). At Pendleton, the NHN and HN fractions were 26% and 34%, respectively, greater under NT than for CT, while cropping intensification under NT did not significantly influenced these fractions. At Moro, however, cropping intensification under NT, represented by WW/WP-NT, did have 20% greater HN than WW/fallow NT, while tillage without cropping intensification did not significantly influence HN (Table 1.6). Significant differences in MBN were detected only at Moro, where an increase in cropping intensity with WP under NT resulted in 123% greater MBN than WW/fallow-CT cropping. WEON varied significantly by treatment at both Moro and Pendleton, where CVs were also lower than at other sites (Table 1.5). At Moro, NT without cropping intensification resulted in 16% greater WEON than CT, and at Pendleton, 60% greater WEON under NT than CT. At Moro, cropping intensification with WP under NT also resulted in significantly greater WEON than WW/fallow NT cropping (Table 1.5).

Significant differences in cumulative Cmin between treatments increased with increasing incubation time (Table 1.6). At day one, significant differences in Cmin were detected only at Pendleton, whereas at 24 days, significant differences in Cmin were detected at all sites but Prosser. At all sites where significant differences were observed, the greatest values for each site at one-day Cmin persisted so that they also had the greatest values for 24-day Cmin, and similarly for the lowest values, indicating that trends established after one-day readings persist through longer incubation periods, and in some instances result in significant differences.

This trend is also indicated by the significant relationship between one-day Cmin and 24-day Cmin already discussed. Where significant differences were observed at 24 days, NT

consistently had higher Cmin than CT, regardless of cropping intensity (Table 1.5). Cropping intensification under NT also resulted in significantly greater 24-day Cmin than less intensely cropped systems under NT; the exception to this was PCFS where NT annual cropping systems had significantly greater 24-day Cmin than perennial cropping systems. The microbial metabolic quotient varied significantly by treatment only at PCFS and Moro (Table 1.5). At PCFS significant differences in qCO_2 overlapped between perennial and annual cropping systems; however, the perennial cropping systems were lower, indicating greater microbial efficiency. Similarly, at Moro, significantly lower qCO_2 values were observed for more intensely cropped/diversified systems under NT.

Management and SOM Stabilization and Mineralization

As previously demonstrated, POXC captures a range of information about the soil as it is highly correlated with overall SOC and N as well as the hydrolyzable and non-hydrolyzable fractions. Therefore, increasing POXC can be considered indicative of building SOM. Furthermore, Culman et al. (2012) established that across a range of geographic regions, soil types, and depth increments, POXC was representative of the processed fraction of SOC, indicated by its stronger association with the smaller size and higher density fraction of particulate organic carbon (POC) than with the larger and lighter fraction of POC, concluding that POXC is indicative of more stabilized SOM. Culman et al. (2013) further supports this conclusion by showing that POXC was particularly sensitive to compost additions in corn-based rotations.

In the present study, the association of POXC with stabilized SOM is supported by the strong correlation between POXC and the non-hydrolyzable and hydrolyzable fractions of SOM

(Table 1.2), as all components of SOM are essential for its formation and stabilization (Paul et al, 2006). POXC, however, is less strongly correlated with Cmin, most notably one-day Cmin (Table 1.2), an observation which is representative of the highly active fraction of SOM and indicative of soil microbial activity, nutrient cycling, and decomposition (Franzluebbers et al., 2000) and has also been shown to be a sensitive predictor of yields in corn rotations (Culman et al., 2013). A comparison of POXC and one-day Cmin (Figure 1.6) can thus provide important information about surface soils with regard to the impacts of tillage and cropping intensity on SOM stabilization and mineralization, and subsequently on surface soil health. The ease and accessibility of measuring these two soil properties also adds value to this comparison, as commercialized versions are available that have demonstrated a significant correlation with laboratory generated data for POXC (r^2 = 0.98)(Hach™ palm-top calorimeter; Weil et al. 2003) and one-day Cmin (r^2 = 0.82) (Solvita™ gel system; Haney et al., 2008).

Placement of values measured in the present study in the context of published values provides a comparative assessment of soil health within the inland PNW and also helps to elucidate management impacts on SOM stabilization and mineralization. Reported values for POXC in surface soils span an almost threefold range, with the highest values reported in Kansas grasslands and the lowest values reported in cultivated cropland on the East Coast (Table 1.8). Culman et al. (2012) reports an average value of 626 mg POXC kg^{-1} soil (±242) across a range of treatments, depths, and soil types that span the continental United States, whereas in the present study 292 mg POXC kg^{-1} soil (±107) was the average value across treatments for the surface soils tested (Table 1.8). Of course, methodology varies somewhat across these measurements, particularly with sieving. Weil et al. (2003), however, found the

influence of sieving to be minimal in POXC values, noting that crushing aggregates from a maximum diameter of 2.0 mm down to 0.10 mm increased the amount of POXC 7-12%. In the present study, samples were sieved to 2-mm. With this is in mind, this comparison of average POXC values indicates that soils within the dryland PNW are below average in POXC and subsequently SOM stabilization within surface soils, when compared to available data across a broad range of conditions.

Correlation of management variables with POXC on a site-by-site basis emphasizes the importance of reducing tillage intensity in improving SOM stabilization and is demonstrated by the significant negative correlation between STIR and POXC at 3 of 5 study sites (Table 1.9); at the other two sites, either there was not a significant STIR gradient, as is the case with PCFS, or as with Prosser, only two years under tillage treatments was not sufficient time to detect differences. At Pendleton and Moro, which have both a STIR and cropping intensity gradient (Table 1.1), NT without cropping intensification resulted in significantly greater POXC than CT, and at Moro, cropping intensification with a legume further increased POXC significantly within NT treatments (Table 1.5, Figure 1.6). Subsequently, POXC displayed a significant correlation to cropping intensity at Moro as well as PCFS; however, the direction of this relationship was positive at Moro and negative at PCFS.

This negative relationship between POXC and cropping intensity at PCFS is likely the result of the perennial systems, which were assigned a greater cropping intensity value than the annual systems (Table 1.1) but also have apparently not provided sufficient aboveground biomass inputs to exceed the annual systems in POXC or other measures of SOC (Table 1.5). This condition may be due to fertilization of annual crops at PCFS resulting in greater

production of aboveground biomass compared to unfertilized perennial crops. These same differences, where POXC of annual cropping systems exceeds that of perennial systems, would likely not be expressed at deeper depths where biomass inputs from roots of perennial crops generally exceed that of annual crops.

Contrary to these results at PCFS for surface soils, however, published results document greater POXC values associated with perennial based systems. For example, Culman et al. (2010), documented 36% greater POXC (0-10 cm) in native grassland compared to a cultivated wheat-based cropping system and associated this difference with more complex soil food webs in the native system. In Maryland, Spargo et al. (2011) found that an organically managed system with cereal rye and hairy vetch as cover crops in a corn-soybean-wheat rotation had greater POXC than conventionally managed systems, further emphasizing the role of cropping intensification, along with diversity, in increasing POXC. Mirsky et al. (2008) found that annual applications of liquid dairy manure applied to meet crop N requirements enhanced POXC in corn-based rotations and also concluded that crops such as corn and cereal grains with high C/N ratios and phenolic acids are associated with higher POXC. This latter finding cannot be substantiated with the present findings because cereal-only rotations did not contain significantly more POXC than rotations containing a legume, as demonstrated at Moro and PCFS (Table 1.5, Figure 1.6).

These findings along with the present findings collectively indicate that low disturbance systems with a diversity of inputs, whether from cover cropping/green manures or soil amendments applied to meet nutrient requirements, are critical to enhancing POXC and subsequently SOM stabilization. The significant correlation between POXC and the

hydrolyzable and non-hydrolyzable fractions of SOC and total N further supports the need for diversification, represented by soil amendments, perennials, and legumes, as a diverse cropping system in theory is better equipped to supply both the recalcitrant and active SOM needed to increase POXC and enhance SOM stabilization. Due to the dryland cropping nature and commodity-crop orientation of much of the inland PNW cropland, crop rotation options are limited. However, in regions where the climate or access to irrigation can support diversification, inclusion of cover crop/green manures in shoulder seasons or the use of soil amendments such as manures and composts, along with the continued adoption of no-till practices, may prove beneficial in improving POXC readings, and subsequently SOM stabilization.

As with POXC, comparing Cmin values across regions and studies can also provide a perspective on where soils in the inland PNW reside with regard to what this important soil property represents from a soil health perspective. Franzluebbers et al. (1996b) reports a range of one-day Cmin values, summarized from the literature across studies spanning multiple ecosystems and climates that range from 8.9 to 58.8 mg CO_2-C kg^{-1} soil. In evaluating the efficacy of a commercialized version of measuring one-day Cmin, Haney et al. (2008) reported values ranging from less than 10 mg CO_2-C kg^{-1} soil to greater than 100 mg CO_2-C kg^{-1} soil for soils from 16 states spanning multiple regions of the continental United States; details on the types of management systems, however, are not reported with these values. In analyzing the influence of management on Cmin and its ability to predict corn performance in Michigan, Culman et al. (2013) reported values ranging from less than 40 to near 60 mg CO_2-C kg^{-1} soil in continuous corn and from greater than 40 to greater than 80 mg CO_2-C kg^{-1} soil in corn-soy-

wheat rotations. Values obtained in the present study vary from 34 to 81 mg CO_2-C kg^{-1} soil (Table 1.7, Figure 1.6), and fall within this range reported in the literature.

Yet, it is important to understand how management factors influence Cmin in order to prevent its decline and subsequently a decline in SOM mineralization. Many factors have the potential to influence microbial respiration, including management factors that alter the abundance and nature of the active fraction of SOM and in turn impact microbial populations. The present study showed fewer significant differences in one-day Cmin than with POXC and 24-day Cmin (Table 1.7, Figure 1.6), and correlations of one-day Cmin with STIR and cropping intensity were also not as pronounced as for 24-day Cmin and POXC with these management variables (Table 1.9); this phenomenon is likely the result of greater CV values for one-day Cmin than for both POXC and 24-day Cmin (Tables 1.5 and 1.7), indicative of greater spatial variability of one-day Cmin. This lack of differences must be considered in light of the inherent spatial variability of one-day Cmin, which may mask biologically meaningful differences (Kravchenko and Robertson, 2011). If the significance level is reduced to $p < 0.30$, significant differences for one-day Cmin begin to resemble 24-day Cmin (data not shown). Therefore, while the value of one-day Cmin lies partially in its ease of measurement and wide accessibility, 24-day Cmin results in the present study can provide support of interpretation of one-day Cmin results (Table 1.7).

As with POXC, correlations on a site-by-site basis reinforce the role of reducing disturbance in increasing Cmin, as indicated by the negative correlation between STIR and one-day Cmin at two of five sites and three of five sites for 24-day Cmin (Table 1.9). PCFS and Prosser were the two sites that did not show a significant correlation between Cmin and STIR,

and as with POXC, lack of a tillage gradient (PCFS) and short history under tillage treatments (Prosser) (Table 1.1) apply to this lack of a significant correlation as well. Likewise, Bowman et al. (1990) showed a substantial decrease in 21-day Cmin resulting from conversion of native prairie in the Great Plains dominated by four species of grass and patches of cacti to tilled wheat-fallow, documenting a 72% decline in Cmin of the surface 15 cm after 60 years of cultivation, and noted that 87% of this decline occurred in the first 3 years.

The cropping intensity gradient at Pendleton is significantly associated with one-day Cmin, and with 24-day Cmin at Pendleton, Moro, and PCFS. Results at Pendleton and Moro for 24-day Cmin indicate that NT without cropping intensification can significantly increase Cmin, while intensification with a legume further increases Cmin under NT (Table 1.7, Figure 1.6); furthermore, this significant increase in Cmin resulting from intensification occurred at Pendleton after only one year of intensification with WP (Table 1.1).

Results from these sites, though, do not provide sufficient evidence to deduce if this increase in Cmin is the result of intensification with a legume, or merely intensification. Cropping intensification at PCFS was negatively associated with 24-day Cmin, and as with POXC, this implies that the perennial systems, which were assigned a greater cropping intensity value than the annual systems (Table 1.1), did not provide sufficient inputs to fuel greater Cmin than the annual systems. Results for 24-day Cmin for annual cropping systems at PCFS suggest that inclusion of legumes in rotation, compared to an all cereal rotation, do not significantly increase Cmin (Table 1.7), indicating that greater Cmin under more intensely cropped systems at Moro and Pendleton may be the result of intensification rather than diversifying with a legume.

Culman et al. (2013), however, found that diverse rotations had a beneficial impact on one-day Cmin, where crop rotations with a legume in rotation enhanced one-day Cmin compared to continuous corn, thereby supporting the idea that substrate quality resulting from diversification is important in enhancing mineralization. In support of diversification of biomass inputs, Spehn et al. (2000) demonstrated that a log-linear decrease of heterotrophic bacterial abundance, the drivers of mineralization, was associated with a decrease in plant species richness, suggesting that a diversified C substrate pool appeals to a wide range of heterotrophic organisms. In the present study, significant differences in microbial biomass did not prevail across all sites, yet at Moro, the more diverse rotations did have significantly greater MBC than rotations with strictly WW (Table 1.5).

A possible corollary to findings by Spehn et al, (2000) and Culman et al. (2013) is that a diversity of inputs appeals to broader taxa of organisms and a diversity of organisms with niche roles is as important as microbial biomass in mineralization. In a review of microcosm studies, Setala et al. (1998) approached this observation from a different perspective in concluding that declining species diversity can alter carbon mineralization through a reduction in trophic level interactions. These findings all suggest that a diversity of plant species along with intensification is important in maintaining and enhancing Cmin.

Management and SOM Quality

An important measure of the quality of SOM is the distribution between labile and recalcitrant pools (Rovira and Vallejo, 2002), and a current paradigm of SOM dynamics suggests that with increased decomposition, SOM quality decreases as the active fraction critical to soil microbial processes comprises a smaller portion of the total SOM (Plant et al., 2006; Rovira and

Vallejo, 2007). The fraction of SOC in the present study that was resistant to acid hydrolysis did not show sensitivity to STIR (Figure 1.7). Values of the fraction of SOC as NHC were around 50%, except for Prosser where values were 36% for both treatments; no significant differences in NHC/SOC between treatments within sites were observed (data not shown).

These results are contrary to the idea that the NHC pool represents a strictly recalcitrant pool and the HC pool a more active pool (Rovira and Vallejo, 2002); if this were the case, the proportion of SOC as NHC under increased tillage should increase due to enhanced mineralization of HC (Paul et al., 2006). Multiple studies, though, have dated NHC as much older than HC and SOC, supporting that NHC is associated with a more recalcitrant pool (Martel and Paul, 1974; Paul et al., 2001; Paul et al., 2006). This finding is also in light of findings that have shown recent plant residues contribute to NHC through addition of lignin (Collins et al. 2000), which is known to be resistant to acid hydrolysis (Rovira and Vallejo, 2002). Abiven et al. (2011) measured lignin content at the various growth stages for wheat and at maturity documented lignin content ranging from 2.4% in leaves to 13.4% in roots; this contribution to NHC from recent plant residue is thought to be negligible (Paul et al., 2006, Rovira and Vallejo, 2007). Furthermore, while researchers express some uncertainty around findings due to assumptions behind the methodology, several studies utilizing C tracing methods have shown that residue lignin turns over faster than bulk soil C (Abiven et al., 2011), thereby dampening the influence of lignin-C relative to bulk SOC.

The significant correlation between NHC and HC in the present study indicates that both pools are impacted by increased disturbance (Table 1.2), as was also demonstrated for climate. This observation is consistent with other studies, such as Paul et al. (2006), who found that the

ratio of NHC to SOC was greater in low or no disturbance systems and concluded that factors other than biochemical recalcitrance influence the proportion and age of NHC in soils; they also cited Poirier et al. (2005) in stating that resistance to acid hydrolysis is not equivalent to resistance to biodegradation resulting from land-use changes. The corollary is that NHC does not accurately represent the passive SOM pool (Paul et al., 2006), an observation which is supported by results from the present study showing that both NHC and HC were impacted by tillage or erosion.

The complexity of the interaction of chemical recalcitrance and physical protection was evaluated by He et al. (2009), who observed that chemically recalcitrant SOM is associated with physical protection, and that labile C compounds may become stabilized through protection into microaggregates. This observation indicates that a certain degree of biochemical recalcitrance is afforded to physically-protected labile C with time. Biochemical stabilization of labile C has been observed to occur through a series of condensation reactions known as the browning reaction (Krull et al., 2003).

This phenomenon is supported by results from Prosser which has greater sand content than other sites, affording less protection than more fine-textured soils of the other sites with higher silt content (Krull et al., 2003; Plante et al., 2006), and a corresponding lower NHC% than the other sites (Figure 1.7). Furthermore, Plante et al. (2006) established the importance of texture, revealing a greater %NHC associated with the silt-sized fraction than with the clay-sized fraction, and partially explained this by suggesting microaggregate derived silt-sized fractions are made up of a combination of both silt-sized particles and similarly sized clay-based microaggregates.

Therefore, while NHC and HC represent finite pools based on chemical recalcitrance, the reality of in-situ recalcitrance is a continuum where a portion of the HC pool is part of the passive C pool through physical protection, and a portion of the NHC pool is susceptible to biodegradation. The susceptibility of recalcitrant SOM to mineralization has been noted in studies which examine the priming effect (PE), whereby the ability of microorganisms to degrade recalcitrant SOM is impacted by fresh additions of labile C (Thiessen et al. (2013), emphasizing the role of physical protection in preserving NHC as well.

While NHC and HC cannot be clearly connected to a recalcitrant and active pool, the %NHC considered in the context of other findings with regard to management practices can help to elucidate how management practices within the dryland PNW impact SOM quality. In a transect of soils between Minnesota and Pennsylvania, Paul et al. (2001) found the fraction of SOC as NHC ranged from 33% to 65%. They found that %NHC varied both with depth, which has also been related in other studies (Collins et al., 2000), decreasing at lower profiles, and with soil type; however, for agricultural soils that were grassland derived, the NHC of surface soils (0-20 cm) was 49% and 50% for the two sites measured, similar to results from the present study.

Additionally, Collins et al. (2000) noted an increase in the mean residence time with decreasing sand content, suggesting that increasing sand content is associated with decreasing NHC, a theme that has already been discussed with regard to results from Prosser. Across a range of land use types including grassland, forested, and no-till agriculture (depth in soil profile not noted), Paul et al. (2006) observed that NHC comprised approximately 55% of SOC. Thus, present findings are in alignment with NHC% reported across a range of terrestrial ecosystems

as well as in other climates, and help to establish that soil texture exerts a significant influence on %NHC, and subsequently on SOM quality.

Table 1.5. Soil bulk density, pH, and various carbon properties for five study sites*.

Site	Treatment†	Bulk Density g cm^{-3}	pH	SOC‡	NHC	HC	POXC	MBC	WEOC
				g kg^{-1} soil					
Kambitsch	WW/SB/SL - NT	1.06 (21)	5.29 b (2)	24.82 a (19)	12.00 (23)	12.81 (16)	0.466 a (8)	0.107 (37)	0.091 (1)
	WW/SB/SL - Till	1.06 (11)	5.41 a (2)	20.39 b (11)	9.96 (37)	10.43 (22)	0.388 b (6)	0.144 (33)	0.108 (66)
PCFS	WW/SL/SW - NT	1.19 (8)	4.69 b (3)	27.06 ab (15)	11.68 (18)	12.07 (2)	0.399 (11)	0.121 (27)	0.147 (12)
	WW/SB/SW - NT	1.12 (6)	4.71 b (8)	28.20 a (11)	12.17 (25)	12.90 (33)	0.416 (9)	0.104 (33)	0.137 (17)
	Alf/SC/SL (organic) - NT	1.24 (14)	5.34 a (5)	22.33 ab (26)	10.29 (48)	10.75 (23)	0.358 (11)	0.107 (25)	0.120 (21)
	Perrenial Tall Wheat Grass	1.17 (8)	5.09 b (2)	22.99 ab (13)	11.43 (15)	11.55 (22)	0.361 (8)	0.112 (12)	0.133 (2)
	Native/CRP Grass	1.24 (2)	5.41 a (1)	21.28 b (13)	10.35 (24)	10.93 (7)	0.349 (10)	0.105 (6)	0.122 (13)
Pendleton	WW/ NT Fallow - NT	1.30 (5)	5.58 b (1)	17.54 a (6)	9.29 a (8)	8.25 (11)	0.315 a (10)	0.105 (52)	0.128 a (7)
	WW/Pea - NT	1.24 (7)	5.65 b (2)	16.62 a (6)	9.03 a (6)	7.59 (7)	0.305 a (11)	0.115 (50)	0.117 a (7)
	WW/Fallow - Till	1.31 (4)	5.80 a (1)	11.89 b (30)	5.90 b (3)	5.98 (62)	0.193 b (48)	0.079 (16)	0.071 b(7)
Moro	WW/WP - NT	1.24 (9)	5.72 b (2)	12.68 a (5)	6.30 (6)	6.38 (18)	0.230 a (4)	0.081 ab (14)	0.108 a (10)
	WW/NT Fallow - NT	1.18 (3)	5.88 a (2)	11.47 b (3)	5.40 (7)	6.07 (6)	0.209 b (10)	0.060 b (58)	0.099 b (9)
	WW/SB/NT Fallow - NT	1.16 (7)	5.84 a (1)	11.25 bc (5)	5.61 (9)	5.64 (13)	0.225 ab (3)	0.097 a (29)	0.092 bc (1)
	WW/Fallow - Till	1.26 (1)	5.93 a (2)	10.53 c (4)	5.22 (5)	5.31 (11)	0.183 c (5)	0.052 b (43)	0.086 c (10)
Prosser	WW/Sw. Cn./Potato - NT	1.42 (5)	5.78 (4)	8.24 (5)	2.92 (12)	5.32 (13)	0.162 (10)	0.083 (25)	0.078 (14)
	WW/Sw. Cn./Potato - Till	1.39 (4)	5.73 (4)	8.38 (5)	2.98 (6)	5.40 (6)	0.139 (28)	0.076 (17)	0.082 (19)

* Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

‡ SOC = soil organic carbon; NHC = non-hydrolyzable carbon; HC = hydrolyzable carbon; POXC = permanganate oxidizable carbon; MBC = microbial biomass carbon; WEOC = water extractable organic carbon, pH = soil pH from 1:1 water extract

Table 1.6 Soil nitrogen properties for five study sites*.

Site	Treatment†	Total N	NHN‡	HN	MBN	WEON
		g kg^{-1} soil				
Kambitsch	WW/SB/SL - NT	1.93 (13)	0.456 (19)	1.47 (13)	0.0056 (51)	0.0065 (33)
	WW/SB/SL - Till	1.69 (6)	0.442 (36)	1.25 (6)	0.0070 (25)	0.0102 (64)
PCFS	WW/SL/SW - NT	2.04 (10)	0.429 (12)	1.61 (16)	0.0055 (29)	0.0011(16)
	WW/SB/SW - NT	2.04 (5)	0.451 (21)	1.59 (12)	0.0056 (90)	0.0118 (27)
	Alf/SC/SL (organic) - NT	1.81 (18)	0.397 (27)	1.32 (22)	0.0036 (32)	0.0079 (26)
	Perrenial Tall Wheat Grass	1.77 (12)	0.388 (19)	1.38 (11)	0.0037 (44)	0.0084 (5)
	Native/CRP Grass	1.72 (16)	0.394 (16)	1.32 (17)	0.0047 (93)	0.0089 (10)
Pendleton	WW/ NT Fallow - NT	1.28 a (7)	0.354 a (13)	0.928 a (13)	0.0055 (63)	0.0085 a (8)
	WW/Pea - NT	1.27 a (9)	0.349 a (13)	0.924 a (8)	0.0068 (85)	0.0079 a (7)
	WW/Fallow - Till	0.97 b (26)	0.280 b (9)	0.690 b (39)	0.0050 (44)	0.0053 b (8)
Moro	WW/WP - NT	0.952 (5)	0.246 (28)	0.707 a (10)	0.0049 ab (40)	0.0073 a (7)
	WW/NT Fallow - NT	0.852 (6)	0.263 (16)	0.589 b (15)	0.0037 bc (50)	0.0064 b (10)
	WW/SB/NT Fallow - NT	0.932 (6)	0.228 (11)	0.704 a (4)	0.0064 a (20)	0.0061 b (1)
	WW/Fallow - Till	0.806 (12)	0.235 (21)	0.570 b (9)	0.0022 c (28)	0.0055 c (11)
Prosser	WW/Sw. Cn./Potato - NT	0.888 (3)	0.148 (18)	0.739 (5)	0.0043 (57)	0.0056 (39)
	WW/Sw. Cn./Potato - Till	0.902 (7)	0.142 (11)	0.760 (7)	0.0047 (17)	0.0061 (10)

***** Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

‡ NHN = non-hydrolyzable nitrogen; HN = hydrolyzable nitrogen; MBN = microbial biomass nitrogen; WEON = water extractable organic nitrogen.

Table 1.7 Cumulative carbon mineralization and microbial metabolic quotient for five study sites*.

Site	Treatment†	$Cmin_{0-1d}$ ‡	$Cmin_{0-3d}$	$Cmin_{0-10d}$	$Cmin_{0-17d}$	$Cmin_{0-24d}$	qCO_2
		Cumulative CO_2 (g CO_2 -C kg^{-1} soil)					g CO_2 - C hr^{-1} g^{-1} MBC
Kambitsch	WW/SB/SL - NT	0.081 (16)	0.223 (15)	0.620 (15)	0.926 (16)	1.18 a (17)	0.409 (32)
	WW/SB/SL - Till	0.072 (23)	0.196 (25)	0.522 (32)	0.765 (33)	0.950 b (33)	0.230 (45)
PCFS	WW/SL/SW - NT	0.047 (9)	0.138 (4)	0.444 (14)	0.683 ab (16)	0.858 a (17)	0.248 ab (10)
	WW/SB/SW - NT	0.064 (53)	0.162 (48)	0.432 (32)	0.673 ab (22)	0.859 a (19)	0.311 a (27)
	Alf/SC/SL (organic) - NT	0.056 (50)	0.148 (39)	0.425 (22)	0.647 bc (18)	0.790 ab (15)	0.252 ab (20)
	Perrenial Tall Wheat Grass	0.040 (8)	0.120 (7)	0.399 (9)	0.611 bc (9)	0.759 bc (10)	0.231 ab (19)
	Native/CRP Grass	0.045 (29)	0.125 (22)	0.374 (16)	0.559 c (12)	0.670 c (6)	0.201 b (5)
Pendleton	WW/ NT Fallow - NT	0.055 a (3)	0.147 a (7)	0.382 b (9)	0.603 b (7)	0.797 b (6)	0.337 (46)
	WW/Pea - NT	0.060 a (12)	0.166 a (11)	0.458 a (12)	0.713 a (10)	0.944 a (9)	0.344 (35)
	WW/Fallow - Till	0.038 b (7)	0.103 b (3)	0.275 c (7)	0.447 c (9)	0.585 c (8)	0.285 (25)
Moro	WW/WP - NT	0.054 (24)	0.189 (45)	0.509 a (24)	0.791 a (21)	1.02 a (20)	0.457 bc (27)
	WW/NT Fallow - NT	0.041 (34)	0.127 (19)	0.419 ab (3)	0.677 bc (6)	0.892 b (5)	0.679 ab (46)
	WW/SB/NT fallow - NT	0.051 (42)	0.143 (28)	0.434 ab (10)	0.707 ab (8)	0.928 ab (8)	0.379 c (27)
	WW/Fallow - Till	0.034 (16)	0.100 (8)	0.344 b (9)	0.585 c (7)	0.792 c (6)	0.699 a (40)
Prosser	WW/Sw. Cn./Potato - NT	0.050 (14)	0.140 (15)	0.381 (16)	0.578 (15)	0.743 (17)	0.329 (34)
	WW/Sw. Cn./Potato - Till	0.049 (18)	0.137 (24)	0.389 (29)	0.601 (30)	0.761 (33)	0.351 (29)

* Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

‡ Cmin = Cumulative carbon mineralized at 1, 3, 10, 17 and 24 days. qCO_2 = Microbial metabolic quotient.

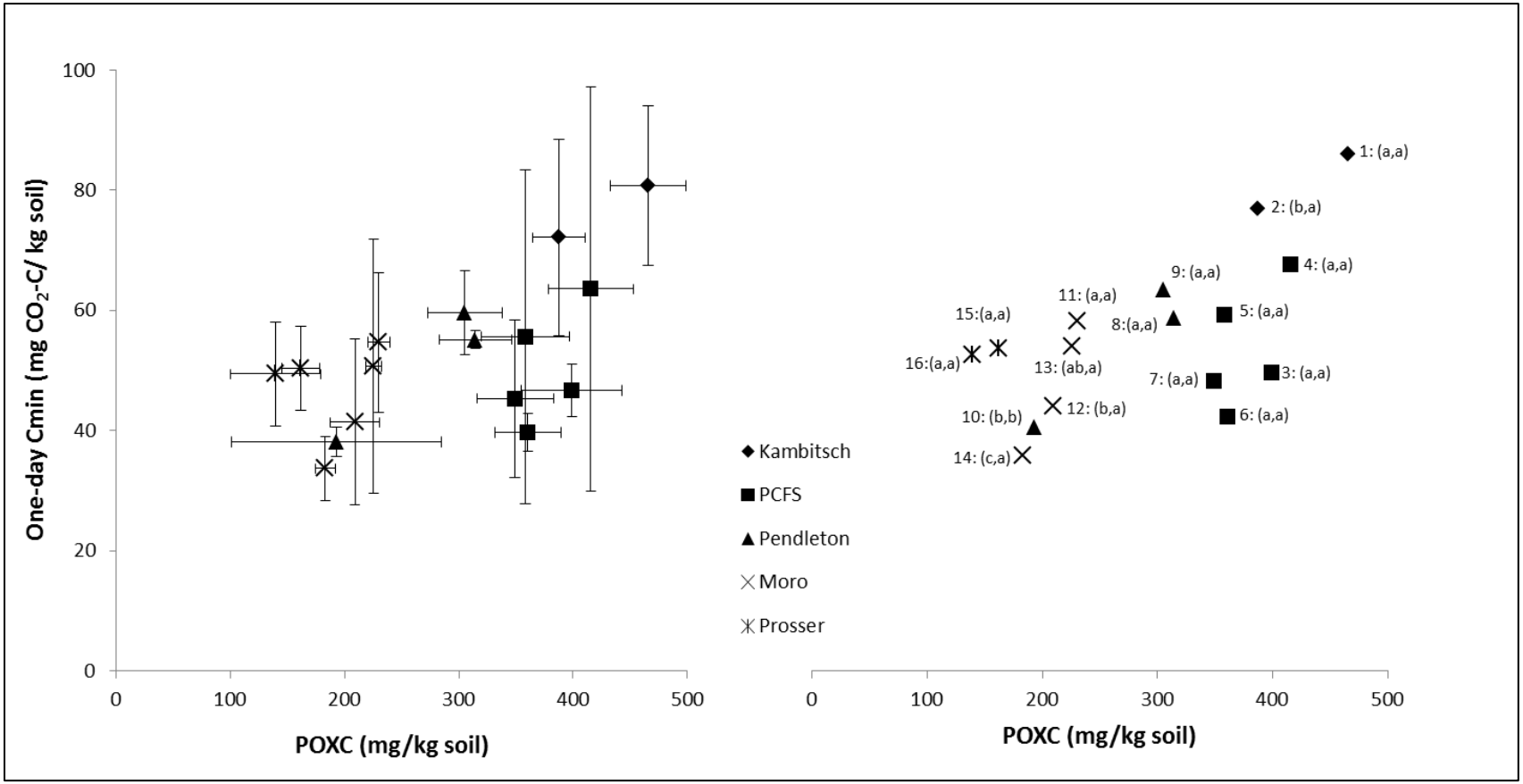

Figure 1.6 Management influence on stabilization and mineralization of SOM. (Error bars display standard deviation. Letters in parenthesis display significant differences (Tables 1.5 and 1.7) between treatments within sites, first letter represents POXC, second letter one-day Cmin. **Kambitsch – 1)** WW/SB/SL – NT **2)** WW/SB/SL – Till; **PCFS – 3)** WW/SL/SW –NT **4)** WW/SB/SW – NT **5)** Alf./SC/SL – RT **6)** Perennial Tall Wheat **7)** Native/CRP; **Pendleton** - **8)** WW/NT fallow – NT **9)** WW/WP – NT **10)** WW/fallow – Till; **Moro – 11)** WW/WP – NT **12)** WW/NT fallow – NT **13)**WW/SB/NT fallow – NT **14)**WW/fallow – Till; **Prosser – 15)** WW/Sw. Corn/Potato – NT **16)** WW/Sw. Corn/Potato – Till).

Table 1.8 Range of POXC values across multiple published studies*.

Location	Description	Particle Size (µm)	Depth (cm)	POXC	Study
Kansas	Cultivated (wheat) Native Grassland	500	0-10	766 (kg/ha) 1040 (kg/ha)	Culman et al. (2010)
Kansas	Native grassland and recent conversion to NT (sorghum, soybean, wheat)	500	0-10	1010 - 1050 (kg/ha)	Dupont et al. (2010)
Pensylvania	Cultivated (corn, soybean, wheat, alfalfa, oat)	2000	0-15	467 - 608 (mg/kg)	Mirsky et al. (2008)
Maryland	Till/NT - Organic (corn,soybean,wheat)	2000	0-20	419 - 483 (mg/kg)	Spargo et al. (2011)
California	Irrigated vegetable/row crops	ground	0-15	597 (mg/kg)	Lee et al. (2009) reported in Culman et al. (2012)
Washington	Till/NT wheat-based rotations	2000	0-10	292 (mg/kg)	Present Study
Multiple	Average across multiple studies	multiple	multiple	626 (mg/kg)	Culman et al. (2012)

* POXC = permanganate oxidizable carbon; NT = no-till.

Table 1.9 Pearson correlations for POXC, one-day Cmin, and 24-day Cmin with management factors across five study sites*.

	POXC		$Cmin_{0-1d}$		$Cmin_{0-24d}$	
Site	STIR	Intensity	STIR	Intensity	STIR	Intensity
Kambitsch	-0.84	NA	-0.32	NA	-0.44	NA
PCFS	ns	-0.46	ns	ns	ns	-0.51
Pendleton	-0.73	ns	-0.87	0.61	-0.79	0.76
Moro	-0.75	0.46	ns	ns	-0.5	0.51
Prosser	ns	NA	ns	NA	ns	NA

* POXC = permanganate oxidizable carbon; Cmin = cumulative carbon mineralized at one and 24 days; STIR = Soil Tillage Intensity Rating.

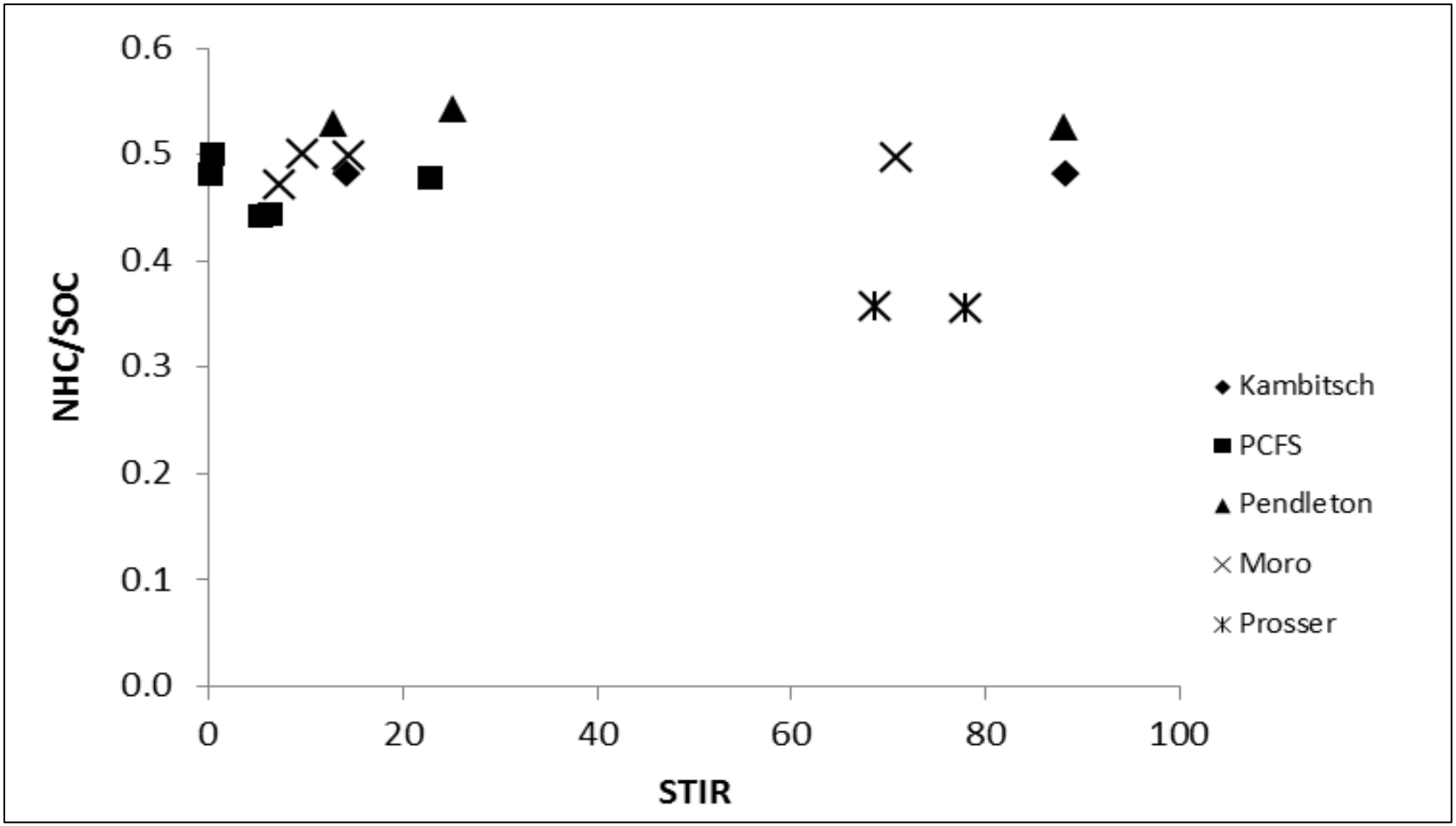

Figure 1.7 STIR does not influence proportion of SOC as NHC (No significant relationship between parameters; $p < 0.10$; STIR = Soil Tillage Intensity Rating; NHC = non-hydrolyzable carbon; SOC = soil organic carbon).

Assessing a Soil Health Index

Given the multiple methods available for measuring soil C and N, several of which comprise the basis of this study, those interested in soil health have found it advantageous to define methods of assessing soil health through development of indices that combine results from multiple tests. Examples include the Cornell Soil Health Tool (CSHT) (Idowu et al., 2009), the Soil Management Assessment Framework (SMAF) (Andrews et al., 2004), the agroecosystems performance assessment tool (AEPAT) (Wienhold et al., 2005), and the NRCS-USDA soil health assessment tool (Haney, 2014). These tools are capable of integrating physical, chemical, and biological soil health indicators and indexing results into a soil health index.

Regardless of the index, a challenge of assessing soil health is the selection of appropriate indicators that reflect management goals and are sensitive to soil type, climate regions, and management practices (Idowu et al., 2009). The NRCS-USDA soil health assessment tool (Haney, 2014) contains a proposed index which utilizes three measurements of the active fractions of soil C and N (Haney, 2014):

$$H_{index} = \frac{Cmin_{0-1d}}{WEOC/WEON} + \frac{WEOC}{100} + \frac{WEON}{10}$$

Unlike the CSHT, SMAF, and AEPAT, this index focuses solely on soil biological indicators. However, as Cmin is also impacted by the physical and chemical characteristics of soils, the index is theoretically sensitive to these factors as well. Additionally, as indicated in the present study and other studies, Cmin is sensitive to management changes (Franzluebbers, 2000; Watts et al., 2010) and has also been shown to be indicative of potential nitrogen mineralization (Franzluebbers, 1996b). WEOC and WEON are measures of the highly labile

fractions of soil C and N and represent what is theoretically available to microbes as microbial metabolism depends on water transport of resources (Bu et al., 2010). These fractions of C and N have been shown to correlate well with one-day Cmin, suggesting they are an important source of energy for heterotrophic microbes (Rees et al., 2005; Haney et al., 2012). Furthermore, soil C/N ratio is often documented as an important variable in net nitrogen mineralization or immobilization; assuming a microbial C/N ratio of 10/1 and a microbial efficiency of 50%, a soil C/N ratio of 20/1 establishes the threshold above which net nitrogen immobilization occurs and below which net mineralization occurs (Sylvia et al., 2005). Therefore, the H_{index} captures the significance of the one-day Cmin as a management-sensitive indicator of soil microbial activity and adjusts this value to account for the importance of the C/N ratio in nutrient dynamics.

As an illustrative example, a soil sample has a relatively high CO_2 respiration rate at one-day, indicating healthy microbial activity and readily available active C; however, if the same soil has a high C/N ratio, the high microbial activity is at the expense of nitrogen immobilization, and this fact will be reflected in the index value. Conversely, if Cmin is high and the WEOC/WEON ratio is low, greater organic N mineralization can be expected. The weighted factors (*WEOC/100 +WEON/10)* capture the importance of building the active fractions of C and N and adjusts them according to an optimal C/N ratio of 10:1, representing a narrower C/N ratio than a typical C/N ratio of bulk soil (SOC/total N) and an ideal ratio reflecting greater microbial use efficiency (Haney, personal communications).

In the present study, WEOC was not significantly correlated with one-day Cmin; however, it was significantly correlated with Cmin for the remaining measurement periods

(Table 1.2), while WEON was significantly correlated only with ten-day Cmin. This finding suggests that WEOC was available for supporting microbial activity but was either not immediately available during the initial re-wetting period, or contained constituents that were not immediately available. Furthermore, across all sites, CV for WEON was 36%, compared to 28% for WEOC; this higher CV for WEON may partly explain the lack of correlation with Cmin readings (Table 1.2). The CV for Cmin across the five sites ranged from 33% at day 1 to 23% at day 24. As a benchmark, soil organic carbon measurements are typically found to have a CV ranging from 15%-35% (Pennock et al., 2008).

Significant differences in H_{index} were identified only at Pendleton, where CVs were also lowest across treatments; Pendleton also had the lowest CVs for index parameters (Tables 1.5 and 1.7). A multivariate stepwise analysis of H_{index} values with management factors and climate variables across all study sites revealed that H_{index} was primarily sensitive to precipitation, which explained 31% of the variation in H_{index}, increasing with an increase in precipitation (Tables 1.11 and 1.12). At Pendleton, STIR and cropping intensity collectively explained 90% of the significant variation detected in H_{index} (Table 1.11). Furthermore, H_{index} displayed a significant correlation with climate variables and multiple soil properties across all sites (Table 1.12). Considering that H_{index} displayed sensitivity to climate variables across the sites and to STIR and cropping intensity at Pendleton, where significant differences were measured, differentiating between moldboard plowing and NT at Pendleton indicates that the index has value for monitoring soil health within the inland PNW.

However, results also show the difficulty of interpretation due to measurement variability, and at sites with significant spatial heterogeneity, an increase in the number of field

replications tested may be needed to increase power and aid in interpretation of results. Based on the CVs in the present study, however, the number of field reps needed may be cumbersomely large in certain instances (Table 1.10). Also, considering that some of the expected relationships between soil properties were not present in this data set that were cited in development of the index, particularly a significant relationship between water extractable C and N and one-day Cmin, it may be informative to further analyze the index at other locations with a new data set.

At other locations, H_{index} values can reportedly range between 0 and 50 (Haney, personal communications). In theory, higher index values are associated with soils having high one-day Cmin readings coupled with a low C/N water extractable ratio and high levels of water extractable C and N. One-day Cmin values have been reported as high as 100 mg CO_2-C kg^{-1} soil (Haney et al., 2008). Assuming a C/N ratio of 10 and solving algebraically, it is clear the equation would require a WEOC soil concentration of 2000 mg C kg^{-1} soil and a WEON concentration of 200 mg C kg^{-1} soil to achieve an H_{index} value of 50 (at a C/N ratio of 8, WEOC would be 1500 and WEON 188 mg C kg^{-1} soil, and at C/N ratio of 15, WEOC would be 3250 and WEON 217 mg C kg^{-1} soil for an H_{index} value of 50). These values are significantly greater than what was measured in the present study, where WEOC ranged from 71 to 147 mg C kg^{-1} soil and WEON from 5.3 to 11.8 mg N kg^{-1} soil (Tables 1.5 and 1.6).

Methodology for determining WEOC and WEON can vary, particularly with regard to soil/solution ratio and shaking time; however values reported in literature are much lower than values required to achieve H_{index} values on the high end of the spectrum. In Quebec, CA, Chantigny et al. (2010) reported values of WEOC ranging from 118 mg C kg^{-1} soil for virgin forest

to 397 mg C kg^{-1} soil for agricultural land, and WEON respectively ranging from 4.7 to 49.0 mg N kg^{-1} soil. Similarly, in Winnipeg, CA, Xu et al. (2013) reported values for WEOC ranging from 20.8 to 34.1 mg C kg^{-1} soil for grassland and an organic wheat-alfalfa-flax rotation, and WEON ranging from 1.3 to 2.3 mg N kg^{-1} soil in the same systems. In Georgia, Zhang et al. (2011) report slightly higher values, with WEOC for a cotton-corn rotation with rye as a cover crop measured at 430 mg C kg^{-1} soil and WEON at 87 mg N kg^{-1} soil.

Consideration of this range of values for natural and agricultural lands indicates that a H_{index} value on the higher end of the spectrum may not be realistic and more modest values should be targeted. Based on the above cited literature, 200 mg C kg^{-1} soil is an average WEOC value across a range of conditions and climates and is slightly higher than the highest value of 147 mg C kg^{-1} soil for WEOC measured in the present study; a one-day Cmin of 100 mg CO_2-C kg^{-1} soil is on the high end reported in the literature and also slightly higher than the highest value of 81.0 mg CO_2-C kg^{-1} soil measured in the present study. Using these values in the index and an idealized C/N ratio of 10 provides a more modest index range of 0 to 14 and a scale for which to evaluate H_{index} values within the inland PNW.

As already reported in the present study, Cmin values are sensitive to disturbance and potentially to cropping diversity, increasing with a decrease in disturbance and an increase in cropping diversity. In studying the influence of management practices on WEOC and WEON, Xu et al. (2013) found that rotations incorporating a perennial legume such as alfalfa had higher WEOC and WEON and attributed this to the rooting mechanisms of perennial crops as well as to an increase in root exudates and improved soil structure. In support of this hypothesis, Marinari et al. (2010) found that WEOC was highest in a diverse 7-year rotation that included

winter wheat (2), soybeans, maize, clover (2), and potatoes with rye as a catch crop grown after wheat and soybeans. In the present study, WEOC and WEON tended to be higher in NT (Tables 1.5 and 1.6), indicating a detrimental impact of increased tillage intensity on WEOC and WEON. These results, considered with literature results, suggest that Cmin along with WEOC and WEON, and subsequently H_{index}, can be simultaneously improved by increasing crop diversity, with the inclusion of legumes, and decreasing tillage intensity.

Table 1.10 H_{index} values for five study sites and required field reps (N) for estimating true mean for two confidence levels and two relative errors*.

				Required Field Reps (N)ǂ			
			Actual Field	90% Confidence		80% Confidence	
Site	Treatment†	H_{index}	Reps	N_{10}	N_{15}	N_{10}	N_{15}
Kambitsch	WW/SB/SL - NT	7.2 (19)	4	10	4	6	3
	WW/SB/SL - Till	8.8 (27)	4	20	9	12	5
PCFS	WW/SL/SW - NT	6.1 (22)	3	13	6	8	4
	WW/SB/SW - NT	7.9 (37)	3	37	16	22	10
	Alf/SC/SL (organic) - NT	5.6 (33)	3	29	13	18	8
	Perrenial Tall Wheat Grass	4.7 (7)	3	1	1	1	1
	Native/CRP Grass	5.4 (16)	3	7	3	4	2
Pendleton	WW/NT Fallow - NT	5.8 a (4)	4	1	1	1	1
	WW/WP - NT	6.0 a (7)	4	1	1	1	1
	WW/Fallow - Till	4.1 b (8)	4	2	1	1	1
Moro	WW/WP - NT	5.4 (15)	3	5	3	4	2
	WW /NT Fallow - NT	4.3 (17)	3	8	3	5	2
	WW/SB/NT Fallow - NT	4.9 (28)	3	21	9	13	6
	WW/Fallow - Till	3.6 (13)	3	4	2	3	1
Prosser	WW/Sw. Cn./Potato - NT	4.8 (32)	4	29	12	17	7
	WW/Sw. Cn./Potato - Till	5.2 (13)	4	4	2	3	1

* Significant differences between treatments within sites indicated by different letters (significant at $p < 0.10$). Coefficient of variation (CV) located within parenthesis.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

ǂ $N_x = (Z^2 \times CV^2)/e^2$ where Z = 1.645 for 90% confidence interval, 1.28 for 80% confidence interval, CV =coefficient of variation and e = 0.10 for 10% relative error and 0.15 for 15% relative error (Gilbert, 1987).

Table 1.11 Stepwise multivariate regression of H_{index} with climate and management variables across all sites and for each of five study sites*.

Site	STIR†	Cropping Intensity	SI	MAT	MAP
All sites	ns	ns	ns	ns	31%
Kambitsch	ns	NA	NA		
PCFS	ns	ns	ns		
Pnedleton	85%	5%	ns		
Moro	28%	ns	ns		
Prosser	ns	NA	NA		

***** All values significant at p < 0.10. ns = not significant (*p* > 0.10).

† STIR = Soil Tillage Intensity Rating; SI = STIR x cropping intensity interaction; MAT = mean annual temperature; MAP = mean annual precipitation; ns = not significant; NA = not applicable (entire blacked out section is NA).

Table 1.12 Pearson correlation of H_{index} with management, climate, and multiple soil properties*.

Variable†	STIR	Intensity	MAP	MAT	BD	pH	$Cmin_{0-1d}$	$Cmin_{0-24d}$	POXC	MBC	MBN	WEOC	WEON
H_{index}	ns	ns	0.55	-0.35	-0.57	-0.42	0.75	0.44	0.60	0.53	0.40	0.46	0.72

* All correlations significant at *p* < 0.10. ns = not significant (*p* > 0.10).

† STIR = Soil Tillage Intensity Rating; Intensity = cropping intensity; MAP = mean annual precipitation (mm); MAT = mean annual temperature (^{o}C); BD = bulk density, pH = soil pH with 1:1 soil water extract; Cmin = carbon mineralization at one and 24 days; POXC = permanganate oxidizable carbon; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen.

SUMMARY AND CONCLUSIONS

Multiple soil C and N properties were measured in this study and a few key soil properties exhibited a significant correlation with other soil properties. Specifically, POXC displayed a significant and strong correlation with SOC, total N, and the hydrolyzable and non-hydrolyzable fractions of SOM; however the correlation of POXC with the more highly active fractions of SOM, including one-day Cmin, and the microbial or water extractable fractions of SOM, was not as strong. One-day Cmin was significantly correlated with cumulative Cmin values throughout the incubation period, up to 24 days, and to a lesser extent with the microbial biomass fraction. These results suggest that POXC is representative of building SOM and SOM stabilization. Conversely, Cmin provides unique information about soil health not captured by POXC, particularly microbial activity, decomposition, and nutrient cycling. This finding that POXC and Cmin each provide unique information about soil health, coupled with the ease of measurement and commercial availability of both tests (one-day Cmin test: Solvita™ gel system; POXC: Hach™ palm top colorimeter), underlies the significance and applicability of a coupling of these two measurements in analyzing soil health.

A multivariate regression of MAP, MAT, and tillage and cropping intensity, revealed that MAP explains 57% of SOC variability and 69% of total N variability. When MAP was removed from the model, MAT became the dominant variable, explaining 42% and 49%, respectively, of SOC and total N variability. This result indicates that MAP is the main variable driving soil C and N dynamics in the inland PNW. Furthermore, both the hydrolyzable and non-hydrolyzable fractions of SOC were equally sensitive to climate, indicating that both chemically recalcitrant and labile SOM is susceptible to a changing climate.

POXC, and subsequently SOM stabilization, showed sensitivity to tillage and, to a lesser extent, cropping intensity. Values reported in the literature for POXC (419 – 1050 mg POXC kg^{-1} soil) indicate that soils within the inland PNW are below average in stabilized SOM (292 mg POXC kg^{-1} soil). Along with the input of stabilized SOM, as has been reported in the literature, other studies coupled with present findings suggest that cropping diversification along with NT are essential to building POXC. Cmin values also showed sensitivity to both tillage and cropping intensity. Cmin is, however, subject to variability from the spatial heterogeneity of factors that influence this important soil property, and this fact must be considered in interpretation of results. Values for one-day Cmin measured in the present study (34.0 – 81.0 mg CO_2-C kg^{-1} soil) were within the range of values reported in the literature across a range of conditions (8.9 to 100-mg CO_2-C kg^{-1} soil), indicating that microbial activity, decomposition and nutrient cycling capacity of soils are within an acceptable range. Results from the present study along with literature findings suggest that cropping intensification/diversification along with NT is also critical to enhancing Cmin.

The present study also revealed sensitivity of both NHC and HC to tillage intensity. This result indicates that while these soil properties represent finite pools based on chemical recalcitrance, resistance to hydrolysis is not equivalent to resistance to biodegradation under land-use changes. Subsequently, NHC cannot be considered representative of only the passive pool and HC representative of only the active pool; the reality of in-situ recalcitrance is a continuum where a portion of the HC pool is part of the passive C pool through physical protection, and a portion of the NHC pool is susceptible to biodegradation. It follows that the

fraction of SOC as NHC, thought to be reflective of SOM quality, is not an accurate indicator for gauging the influence of management on soil health.

Last, evaluation of a soil health index which utilizes one-day Cmin, WEOC, and WEON revealed sensitivity of this index to both climate and management. However, inherent variability of the measurement made detecting significant differences in index values associated with tillage and cropping intensity difficult, indicating the evaluation of soil health using the index may benefit from increased field replication/samples. Values for the index for soils in the inland PNW range from 3.6 to 8.8, whereas 0 to 50 is the reported range of potential values; a range of 0-14, however is more realistic for soils within the inland PNW. Evaluation of soil health using POXC and one-day Cmin provides important information about SOM stabilization and nutrient cycling capacity, while the soil health index evaluated provides information on building the more active fraction of SOM and, through consideration of an important soil C/N ratio, offers insight on nutrient cycling capacity. Depending on management goals, either method of gauging soil health, POXC coupled with one-day Cmin or H_{index}, appears to have applicability within inland PNW cropping systems.

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CHAPTER 3

CLIMATE, MANAGEMENT, SOIL CARBON AND NITROGEN PROPERTIES, AND THEIR RELATIONSHIP WITH IMPORTANT SOIL PROCESSES: A SOIL HEALTH PERSPECTIVE

ABSTRACT

Certain soil biogeochemical processes are critical to soil productivity and environmentally significant; therefore, they are an important component of a soil health assessment. Within the inland Pacific Northwest, we selected four dryland sites and one irrigated site to assess the relationship of soil C and N properties, mean annual temperature (MAT) and precipitation (MAP), and tillage and cropping intensity with potential nitrogen mineralization (PNM), basal (BDR) and potential denitrification (PDR), and plant available nutrients (NO_3^-, NH_4^+, P, S, Ca, Mg, K, Mn, Fe, Zn, B, Cu) as measured from PRS™ probes (Western Ag Innovations, Saskatoon, Canada). Tillage practices included in the study ranged from tillage with a moldboard plow to no-till (NT) and cropping intensification systems ranged from winter wheat (WW)/fallow to perennial cropping systems. MAP across the study sites ranged from 200 to 663 mm and MAT ranged from 8.4^{o}C to 10.9^{o}C.

Multiple soil C and N properties displayed a significant positive correlation with PNM; however, soil organic carbon (SOC) (r = 0.59) and total N (r = 0.67) displayed the highest correlation. PNM was significantly correlated with 24-hour PRS™ – probe NO_3^- (r = 0.45) but not with 28 day PRS™ - probe NO_3^-. An increase in MAT was associated with a decrease in PNM (r = -0.73), while an increase in MAP was associated with an increase in PNM (r = 0.60). Management factors also significantly influenced PNM; PNM was negatively correlated with an

increase in tillage intensity (r = -0.32) and positively correlated with cropping intensity (r = 0.40).

PDR was positively correlated with several soil C and N properties, including SOC (r = 0.70), total N (r = 0.57), and PNM (r = 0.69), while BDR was only significantly correlated with initial soil inorganic N (r = 0.31). Across the four dryland sites, MAT was negatively correlated with PDR (r = -0.66) and to a lesser extent BDR (r = -0.34), while MAP was only correlated with PDR (r = 0.55). Tillage intensity was correlated with both BDR (r = 0.32) and PDR (r = 0.32); however PDR and BDR were not influenced by cropping intensity. This relationship, however, varied by site according to soil C and N properties and crop rotations with legumes comprising half or more of the rotations exhibited increased PDR. Additionally, the one irrigated site experienced BDR and PDR up to an order of magnitude greater than the dryland sites, mainly attributed to sandier soils and more accessible substrate. Plant available nutrients displayed varying correlations with soil C and N properties and management and climate factors.

A multivariate regression analysis showed that multiple indices could be combined to improve prediction of PNM (total n, water extractable carbon, MAT; $r^2 = 0.81$), 28 day PRS™ – probe total N (24-hour PRS™ total N, total inorganic N, tillage, cropping intensity; $r^2 = 0.62$), and PDR (total N, permanganate oxidizable carbon, C mineralized at 24 hours, MAT; $r^2 = 0.64$), but combining these indices did not improve prediction of BDR. This finding reveals that within the inland PNW, combining indices of more easily measured properties can improve the prediction of these more difficult-to-measure soil processes so important to soil health.

INTRODUCTION

An important objective of assessing soil health is assuring long-term soil productivity while minimizing or eliminating environmental deterioration (Doran & Parkin, 1994). Underlying these objectives are soil biogeochemical processes that are critical to soil productivity and are environmentally significant. Soil organic matter (SOM) is often associated with soil health as it is critical to many important soil properties and processes. SOM is associated with building soil aggregate structure, reducing erosion, enhancing water infiltration and retention, providing a source of energy and nutrients to soil organisms, and through mineralization, providing an important source of plant nutrients (Haynes, 2005). SOM is comprised of an assortment of constituents; however, soil organic carbon (SOC) is a dominant component of SOM (Weil et al., 2003) while total N is variable (Brady and Weil, 2010) but an important nutrient from a soil health perspective due to both its role in soil productivity and its potential to be an environmental pollutant. As such, SOC and total N are often targeted when evaluating SOM, and understanding the relationship between these soil health properties and important soil processes can make an assessment of soil health more impactful.

It is also critical to understand the influence of management options on soil health as they can undermine, stabilize, or enhance soil processes (Franzluebbers, 2002). Tillage and cropping intensification are important management choices as they can alter SOC and total N dynamics. Cultivation increases soil disturbance and is associated with reduced soil aggregation and increased oxidation of SOM (Six et al., 2002). Conversely, increasing primary production through reducing fallow represents a potential mechanism to increase SOM (West and Post, 2002) and maintain or enhance soil processes. Consequently, many have cited improved soil

health associated with no-till (NT) management and cropping intensification (Schomberg and Jones, 1999; Deen and Katkai, 2003; Liebig et al., 2004). However, NT has also been associated by some researchers with initially increasing bulk density, which has negative consequences for crop production and SOC inputs to the soil as well as for soil water nutrient dynamics and water runoff (Franzluebbers et al., 2007). The choice is further complicated by economic considerations, as adoption of NT can require a significant up-front investment in equipment.

Potential nitrogen mineralization (PNM) is often associated with soil health as it is driven by the microbial population and is an integrator of biotic and abiotic factors, including climate, management, and substrate availability and quality. This mineralization process not only represents the ability of the microbial population to decompose plant residue and SOM, but it also provides an important source of plant-available nutrients, two functions which are an important component of soil health (Dorin & Parkin, 1994).

Research is inconclusive regarding the correlation between plant N uptake and PNM, some demonstrating a strong correlation (Keeney & Bremner, 1966), and others mixed results (Thicke et al., 1993). Additionally, this correlation has been found to be dependent by some on the method of determining PNM. Specifically, a study by Curtin and McCallum (2004) found that N uptake by glasshouse-grown oats derived from mineralization was strongly correlated with aerobic N determined at 28 days ($r^2 = 0.79$), while anaerobic N measured at 7 days displayed a poor correlation with plant N uptake under the same conditions ($r^2 = 0.32$). Nonetheless, for non-leguminous crops, inorganic N availability represents a potential yield-limiting factor and as such, the N mineralized from SOM by the microbial population represents a potentially significant pool of N for crop growth (Cabrera et al., 1994); consideration of this

source of N represents an opportunity for maximizing N-use efficiency and minimizing environmental loss (Schomberg et al., 2009). Furthermore, management options such as cropping intensity and tillage practices, along with climate potentially alter the nature of SOM and soil microbial biomass; this alteration of SOM in turn will likely influence the PNM associated with a given soil (Franzluebbers et al., 1994), making it important to understand how management practices and soil C and N properties alter PNM.

While PNM is a component of the N cycle that represents an important source of N, denitrification is a component of the N cycle that represents not only a loss of N from the soil N pool, but also a source of nitrous oxide (N_2O) in the atmosphere, a major greenhouse gas with global warming potential 298 times that of CO_2 (Pittelkow, 2013). Agriculture is considered the largest source of anthropogenic N_2O, responsible for 70% of atmospheric N_20 emissions from this subgroup, the major source being agricultural soils (Kroeze, 1999). In particular, soil denitrification is responsible for 5% of the overall anthropogenic greenhouse effect (IPCC, 2007). While a certain amount of denitrification from agricultural soils is inevitable, a better understanding of the influence of management as well as soil C and N properties on denitrification represents an opportunity for mitigation of this anthropogenic source. Furthermore, as two tenets of soil health are promotion of plant available nutrients and minimization of environmental impact, both of which are endangered by denitrification, improved understanding of denitrification represents an opportunity for improving soil health.

In addition to PNM and denitrification, plant macro- and micronutrient availability is an important soil factor that influences productivity and subsequently soil health. Plant nutrient

availability is dependent on a number of factors, including SOM, texture, cation exchange capacity (CEC), and management factors such as tillage (Havlin et al., 1999).

Ion exchange resins have a long history in agricultural research (Schlenker, 1942) and are intended to measure plant-available nutrients and their release rate (Qian and Schoenau, 2001). In assessing the relationship between conventional soil tests involving chemical extraction and those involving exchange resins, Pampolino and Hatano (2000) found that similar dynamics governing the flow of phosphorus and potassium to plant roots also governed the rate at which these ions were adsorbed to resins in a laboratory setting, therefore concluding that exchange resins accurately represent plant-available nutrients. Qian and Schoenau (1995) found N uptake by canola in a two-week period was more closely approximated by exchange resins than that measured by incubation and extraction with $CaCl_2$ and cited others who have documented a cumulative inhibitory mineralization effect associated with traditional incubation/extraction methods. They observed that exchange resins are not subject to this phenomenon since they act as an ion sink and are influenced by the kinetics of nutrient release and transport that more traditional soil tests do not capture (Qian and Schoenau, 2005).

Similar to their 1995 study, Qian and Schoenau (2005) found that N adsorbed to the exchange membrane of plant root simulators (PRS^{TM}) probes (Western Ag Innovations, Saskatoon, Canada) used in a 2-week aerobic incubation closely correlated to plant N uptake across a range of soil types and management histories. Furthermore, Walley et al. (2002) found NO_3^- N adsorbed to PRS^{TM} probes after a two-week incubation was significantly correlated with both wheat yield and plant N accumulation.

In consideration of these important soil processes – PNM, denitrification, and plant macro- and micronutrient supply – and their importance to soil health, the objectives of this study were to 1) identify the relationship of measured soil C and N properties with PNM, denitrification, and nutrient supply, 2) explore the influence of mean annual temperature (MAT) and mean annual precipitation (MAP) within the inland Pacific Northwest (PNW) on PNM, denitrification, and nutrient supply, and last 3) identify how tillage and cropping intensification influence PNM, denitrification, and nutrient supply.

METHODS AND MATERIALS

Site Descriptions

Research plots located in five long-term agricultural research centers within the dryland and irrigated cropping regions of the inland PNW comprise the basis of this study. These research plots are located at the following research centers: Kambitsch Farm near Genesee, ID, operated by the University of Idaho; Palouse Conservation Field Station near Pullman, WA; Pendleton Research Station near Pendleton, OR and Sherman Research Station near Moro, OR, both associated with the Columbia Basin Agricultural Research Center near Pendleton, OR; and Irrigated Agricultural Research Center near Prosser, WA. These five sites were selected based on the cropping systems present as well as the range of climactic conditions collectively represented by the sites. Together, the five sites span four agroecological classes (AECs), or land use classifications that represent unique biophysical and socioeconomic conditions that result in distinct cropping systems (Huggins et al., 2011). The five sites comprising this study span all four AECs of the inland PNW as defined by Huggins et al. (2011): (1) annual cropping (limited annual fallow); (2) annual crop-fallow transition (e.g. 3-yr rotations with fallow every

third year); (3) grain-fallow (e.g. 2-yr wheat-fallow rotation); and (4) irrigated. Following is a description of these sites. For the purposes of this study, unless otherwise noted, the winter wheat portion of rotations represents the crop present during sampling.

Kambitsch Farm, University of Idaho – Genesee, ID (AEC 1)

The Kambitsch experimental plots selected for this research originated in 2000 to study the effects of tillage on soil properties and crop growth. The experimental design is a split-plot randomized complete block design and sub-plots are 6.1 m by 80.5 m; however, as winter wheat was the only crop sampled, in the context of this study, the experimental design simplifies to randomized complete block design. Prior to 2000, the site was managed strictly with conventional tillage. The predominant soil type is a Palouse silt loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxeroll). The crop rotation present since 2010 includes winter wheat (WW) (*Triticum aestivum)* -spring cereal (SC) (barley - *Hordeum vulgare* or spring wheat) - spring legume (SL) (garbanzo – *Cicer arietinum* or spring pea - *Pisum sativum*) with tillage as the management variable (Table 2.1). Prior to 2010, crop sequences were not randomized and additional management details can be found in Johnson-Maynard et al. (2007). In 2010, whole plots were subdivided into three equal subplots with the present crop rotation randomized across these subplots. The whole plot tillage treatments that were present prior to 2010 remained the same after subdividing to allow for crop randomization within a given tillage treatment. CT plots are tilled a few days prior to planting for both fall and spring planted crops using a Glenco Soil Saver followed by a Will-Rich 2500 field cultivator. NT and CT plots are planted with a Flexi-Coil No-Till drill at 25.4-cm row spacing.

Palouse Conservation Field Station – Pullman, WA (AEC 1)

Soils at this site consist predominately of Palouse (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxeroll) and Thatuna (fine-silty, mixed, superactive, mesic Oxyaquic Argixerolls) silt loam. Plots range in size from a minimum of 11-m wide to accommodate field-scale equipment up to 30 m in width and from 100- to 350-m in length as needed to capture significant portions of soil and landscape variability. The plots selected for study include five cropping systems established in 2001 and arranged in a randomized complete block design with three replications. The five cropping systems include two perennial systems, two, 3-year annual cropping systems that are continuous NT planted and one organic system that is a combination of perennial and annual crops (Table 2.1). The perennial systems include a native prairie system and a perennial tall wheatgrass system. The native perennial system was established in accordance with Conservation Reserve Program (CRP) guidelines and planted with Idaho Fescue (*Festuca idahoensis*) and Bluebunch Wheatgrass (*Agropyron spicatum*). The perennial wheatgrass plots were planted with a tall wheatgrass, developed from a hybrid of annual wheat and *Thinopyrum*, a cool-season perennial grass known to produce large quantities of aboveground biomass. The annual, NT cropping systems include two rotations: WW-SB-SW and WW-SL-SW. These plots are seeded with a Cross Slot® inverted-T opener no-till drill at 25.4-cm row spacing. The organic cropping system is a reduced tillage alfalfa (*Medicago sativa*)-cereal-SL rotation managed according to organic agriculture protocols. The organic system was planted to a spring pea green manure crop during collection of the soil samples analyzed for this study.

Pendleton Station, Columbia Agriculture Research Center – Pendleton, OR (AEC 2)

The management variables studied at this site are tillage and cropping intensity. Three different rotations were selected for study and consist of WW-NT fallow rotation under NT initiated in 1982, a WW-fallow rotation with CT initiated in 1997, and a WW-winter pea (WP) (*Pisum sativum)* rotation under NT initiated in 1997 (WP was inserted in the rotation in 2012; prior to 2012 the rotation was WW-NT fallow). Prior to 1997, these latter two rotations were under CT that used a mold-board plow. Soils in these plots are predominately a Walla-Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls). Plots are 2.0 m by 33.5 m and the experimental design is a factorial design using tillage and fertilizer rate (0 and 120 kg/ha banded) as the treatments with four reps for each factorial combination Only fertilized plots in WW were selected for this study, and the plots were subsequently modeled as randomized complete block design (Table 2.1). For all plots, WW is planted in mid-October and harvested in mid to late July. A moldboard plow is used on CT plots for primary tillage in spring of the fallow year. These plots are also rod-weeded as necessary through the summer fallow season until fall planting of WW. All plots are seeded with a Noble No-Till modified deep furrow drill at 25.4-cm row spacing.

Sherman Station, Columbia Agriculture Research Center – Moro, OR (AEC 3)

Experimental plots located in Moro, Oregon, were initiated in 2003 to compare NT and CT for annual cropping, as well as two- and three-year rotations with and without a fallow period. The predominate soil type at the site is a Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxeroll). The following four rotation and tillage treatments were selected for this study: WW-fallow under CT, and WW-WP, WW-fallow, WW-SB-fallow all

under NT management (Table 2.1). Plots are 15 m by 105 m, and the experimental design is a randomized complete block design with three blocks. CT plots are tilled in the spring using a chisel plow and rod weeded as necessary from May to August. Winter wheat is seeded in September or early October at 40-cm row spacing. NT plots are direct seeded using a Fabro drill at 30-cm row spacing.

***Prosser Irrigated Agricultural Research Station – Prosser, WA* (AEC 4)**

This experiment was established in the fall of 2011 to study winter cover crop and NT management effects on crop productivity, water use efficiency, and N and C cycling. Due to the short history of this site, only plots not under a winter cover crop were selected for the purposes of this study and tillage was selected as the management variable. The predominate soil type is a Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids). The crop rotation is WW-Sweet Corn (*Zea mays)*-potato (*Solanum tuberosum*); all crops are irrigated throughout the growing season as neededAll plots, NT and CT, are disced prior to potato planting and after harvest of potatoes prior to planting WW. Otherwise, NT pots receive minimum disturbance. WW is planted using a Fabro drill at 16.5-cm row spacing. Plots are 4.9 m by 14.6 m and the experimental design is randomized complete block design (Table 2.1).

Tillage and Cropping Intensity

These five study sites represent a range of tillage and cropping intensities. The Natural Resources Conservation Service (NRCS) has developed a system of quantifying soil disturbing activities known as the soil tillage intensity rating (STIR) (USDA-NRCS, 2006). The STIR was developed by the NRCS for use in calculating potential soil erosion utilizing the revised universal

soil loss equation (RUSLE2) (USDA-NRCS, 2006). The rating captures the range and severity of operations for an entire rotation, from spraying herbicide to plowing, planting and harvesting. The final STIR value is annualized based on the set of operations required for the entire rotation (Table 2.1). More on this rating and how it was derived for each site can be found in Appendix A.

The NRCS establishes a STIR of 30 as the maximum value for NT operations (USDA-NRCS, 2011). In the previous site descriptions and in subsequent tables, all treatments with a STIR exceeding 30 are referred to as CT, while those under 30 are referred to as NT. The primary tillage implement for CT plots are listed in Table 2.1. Prosser is the deviation from this dichotomy, as plots managed primarily under NT are subject to greater disturbance due to the presence of potatoes in rotation, and consequently plots at Prosser managed as NT have a STIR greater than 30 (Table 2.1).

Cropping intensity was captured by assigning a value to each crop in a rotation based on the duration of growing plant cover (months) in a 12-month period. The following values were used for this study: perennial crops – 0.83 (10 months divided by 12 months), fall planted crops – 0.75 (9 months divided by 12 months), spring planted crops – 0.33 (4 months divided by 12 months). The intensity rating for a rotation was derived by summing this value for each crop in the rotation and averaging across the length of the rotation (Table 2.1). More details on calculating cropping intensity values for each cropping system are available in Appendix A.

Table 2.1 Five study locations with management and site information.

Location	Experimental Design	Soil Type	MAP† (mm)	MAT† (°C)	Crop Rotation‡	Cropping Intensity	Year Established	Tillage	STIR‡ Rating	Equipment
Kambitsch Farm - Genesee, ID (N 46.58°, W 116.95°)	Rondomized Complete Block Design - (4 reps)	Palouse Silt Loam	663	8.6	WW - SC - SL	0.47	2000	No Till	14.4	Double Opener
								Conventional	88.3	Chisel Plow
Palouse Conservation Field Station - Pullman, WA (N 46.73°, W 117.18°)	Randomized Complete Block Design (3 reps)	Palouse/Thatuna Silt Loam	533	8.4	Native (CRP) Grasses	0.83	2001	N/A	0.15	N/A
					Perennial Tall Wheat Grass	0.83		N/A	0.45	
					Alfalfa - cereals - SL (organic)	0.49		No Till	22.8	Sweep/ Single Opener
					WW - SB - SW	0.47		No Till	6.3	Single Opener
					WW- SL - SW	0.47			5.2	
Columbia Basin Agriculture Reseach Center - Pendleton, OR (N 45.44°, W 118.37°)	Randomized Complete Block Design (4 reps)	Walla Walla Silt Loam	417	10.3	WW - Fallow	0.38	1982	No Till	12.9	Modified Deep Furrow
					WW - WP	0.75	1997		25.2	
					WW - Fallow	0.38	1997	Conventional	88.2	Mold-board
Columbia Basin Agriculture Agriculture Reseach Center - Moro, OR (N 45.48°, W 120.69°)	Randomized Complete Block Design (3 reps)	Walla Walla Silt Loam	288	9.4	WW - chem fallow	0.38	2003	No Till	7.4	Double Opener
					WW - WP	0.75			14.4	
					WW - SB - Fallow	0.36			9.7	
					WW - Fallow	0.38		Conventional	70.9	Chisel Plow
WSU Irrigated Agricultural Research Center - Prosser, WA (N 46.29°, W 119.74°)	Rondomized Complete Block Design (4 reps)	Warden Silt Loam	200	10.9	WW - Sweet Corn - Potato	0.54	2011	No Till	68.6	Double Opener / Disc§
					WW - Sweet Corn - Potato			Conventional	78.1	Ripped/Disc

† MAP = mean annual precipitation; MAT = mean annual temperature (Climate data from NOAA for 1955 to 2012; Appendix B).

ŧ WW = winter wheat; SC = spring cereal; SL = spring legume; SB = spring barley; SW = spring wheat; WP = winter pea.

‡ STIR = Soil Tillage Intensity Rating (Appendix A).

§ No-till disced during potato sequence.

Soil Sampling

Each site was sampled in June and July of 2013, prior to harvest, to a depth of 10-cm, collecting 50 to 60 samples across each plot using a hand-operated soil probe (2.0 cm inside diameter). Four bulk density cores (3.0 cm inside diameter) were also collected from each subject plot using a hand-operated soil probe; these samples were also used to determine field water content. All samples were immediately placed on ice in the field and transferred to cold storage at 4°C until further processing.

Laboratory Analysis

Physical Characterization and Soil pH

Bulk density and water content represent the physical indicators comprising this study. Gravimetric soil water content was determined from the bulk density cores after drying at 104°C for 24 hours. Bulk density was determined from the oven-dried weight of samples and the volume of the core sampler following the method of Veihmeyer and Hendrickson (1948). In addition to these physical properties, soil pH was also measured using a 1:1 soil-water mixture (Eckert, 1991).

Soil Carbon Fractionation

Total soil C (SOC) and N were determined by dry combustion using a CHN autoanalyzer (LECO CHN-1000, Leco Corp., St Joseph, MI, USA) (Tabatabai and Bremner, 1970). Acid hydrolysis was performed with a modified version of the method described by Paul et al. (1997). In short, using a roller grinder 1.0 g of air-dry soil was ground to a fine powder and refluxed at 115°C for 16 hours with 6.0-M HCl. This suspension was then washed with deionized water through a glass-fiber filter and the recovered sample dried at 40°C for 72

hours. Samples were then analyzed for total C and N as mentioned previously and the hydrolyzability of samples calculated based on SOC and total N before and after acid hydrolysis.

Microbial biomass C and N (MBC/MBN) was performed on 10-g oven-dry weight soil using the chloroform fumigation-extraction method as outlined by Voroney et al. (2008). Soils were brought to field capacity (estimated at 25% water content for Kambitsch, PCFS, Pendleton, and Moro and 20% for Prosser) and incubated at 20°C for 48 hours prior to fumigation with ethanol-free chloroform. Instead of a 0.5-M K_2SO_4 extraction, fumigated and non-fumigated soils were extracted using 30 ml of DI water, shaken for 30 minutes using an oscillating shaker then filtered through 0.2-µm nylon filter after centrifuging for 5 minutes at 3200 rpm (1500g). The filtrate was frozen until analyzing for C and N on a high-temperature combustion Shimadzu TOC analyzer.

Water extractable C and N (WEOC, WEON) analyses were performed according to established laboratory protocol at the USDA/ARS Soil Biogeochemistry lab at Washington State University. Soils were dried at 40°C for 24 hours and sieved to 2.0 mm prior to adding 12.5 ml of 18-MΩ water (purified to remove C) to 5.0-g oven-dry weight equivalent soil. This soil water mixture was shaken for one minute on an oscillating shaker, centrifuged for five minutes at 5000 rpm, then filtered through 0.2-µm nylon filter paper. The collected filtrate was frozen until analyzing for C and N on a high-temperature combustion Shimadzu TOC machine. Samples were also analyzed for inorganic N and WEON determined from subtracting out this inorganic fraction. Carbonates were assessed using the same high-temperature combustion Shimadzu TOC machine with a 1.0-M HCl solution; however no carbonates were detected and all C values presented can be considered representative of organic C.

Permanganate oxidizable carbon (POXC) was performed according to the method of Weil et al. (2003) in which 0.02-M $KMnO_4$ is used. This methodology was developed by Weil et al. (2003) as a sensitive analysis to capture a representative portion of active soil carbon that is most influenced by management, as opposed to the method developed by Blair et al. (1995) that attempts to capture and define the entire active carbon pool using a more concentrated permanganate solution. Additionaly, the method developed by Weil et al., (2003) is available in a field kit version, making this a low-cost and highly accessible soil property to meaasure. This procedure was performed in triplicate on 2.5-g oven-dry weight equivalent soil that was air dried for 24 hours and sieved to 2.0 mm. Absorbance was measured on a Spectra Max M2 single cuvette reader set at 550 nm as recommended by Weil et al. (2003).

Potential Carbon Mineralization

Measurement of carbon mineralization (Cmin) from re-wetted soils was performed on laboratory-incubated soil in triplicate as a measure of active carbon and soil microbial activity. Soils were oven dried at 40°C for 24 hours, then sieved to 2.0 mm (Haney et al., 2008). Processed soils were then packed to a dry bulk density of 1.0 g cm^{-3} in 40-ml glass vials with rubber top septa through which gas samples were collected using a syringe and needle at the designated times. Prior to bringing samples to field capacity, they were covered with a breathable film which allows oxygen exchange while preventing moisture loss and were incubated at 20°C for 24 hours. After this incubation time, water was added to bring samples to field capacity (estimated at 25% water content for Kambitsch, PCFS, Pendleton, and Moro and 20% for Prosser), which was designated as time zero. Gas samples were collected at 24 hours, and 3, 7, 10, 17, and 24 days. At these sampling times, vials with soils at field capacity

were flushed with a breathing-air mixture containing approximately 200-ppm CO_2, and gas samples collected immediately after flushing on every tenth sample and two hours after flushing from every sample. The CO_2 evolution rate was calculated as the difference between average time zero CO_2 and CO_2 measured at two hours (McLauchlan and Hobbie, 2004). Samples were run on a Shimadzu gas chromatograph equipped with an automated valve system for routing gas samples to the electron capture (ECD) and flame ionization (FID) detectors.

Potential Nitrogen Mineralization

Anaerobic nitrogen mineralization at 28 days was determined at the five sites in this study (Table 2.1) according to the methods outlined by Curtin and Campbell (2008), with a slight deviation in soil preparation and procedure. Soils were sieved to 2.0 mm rather than 4.0 mm, and rather than using field moist soils, soils were dried at 40° C for 24 hours. Additionally, samples were incubated for 28 days with 12.5 ml of deionized water at a constant temperature of 40° C. Time zero samples were immediately extracted with 1-M KCl and inorganic N determined on a Lachat (Hach, Co; Loveland, CO). All samples, including time zero and incubated samples, were performed in triplicate and net N mineralization was measured as the average difference between time zero NH_4^+ and 28-day NH_4^+. Herein, 28-day PNM will be referred to as PNM.

Basal and Potential Denitrification

Basal Denitrification (BDR) and potential denitrification (PDR) were performed in a manner similar to Drury et al. (2008a) with slight deviations. In preparation for this analysis

field-moist soil which had been stored at 4°C for less than 1 month was sieved to 4-mm. Samples consisting of 20.0 g oven-dry equivalent soil were then weighed into half-pint wide-mouth canning jars, in triplicate. For both BDR and PDR, samples were incubated for 24 hours at room temperature (20°C) to allow time for samples to equilibrate. Following this incubation period, BDR samples were brought to field capacity (estimated at 25% water content for Kambitsch, PCFS, Pendleton, and Moro and 20% for Prosser) by the addition of the appropriate amount of deionized water while a 25.0 ml solution containing 300 ug glucose-C g^{-1} soil and 50 ug NO_3-N g^{-1} was added to PDR samples. An anaerobic environment was created by flushing with N_2 gas through the rubber septa for 60 seconds. Immediately following flushing, a headspace volume equivalent to 10% of the total headspace volume was removed and an equivalent amount of acetylene was injected through the rubber septa. Gas samples (9.0 ml) were collected for both BDR and PDR samples at two and four hours and injected into 5.9-ml exetainers that had previously been flushed with N_2. The N_2O concentration of samples was measured on a gas chromatograph equipped with an automated valve system for routing gas samples to the electron capture (ECD) and flame ionization (FID) detectors. BDR and PDR rates are the slope of the regression line when plotted versus time.

PRS^{TM} - Probe Incubations

PRS^{TM}-probe incubations were performed in triplicate on 275 g of oven-dry equivalent soil. Prior to incubation, field moist soil samples were air dried for 48 hours to achieve uniform water content. Air-dried soils were then brought to field capacity (estimated at 25% water content for Kambitsch, PCFS, Pendleton, and Moro and 20% for Prosser) and packed into 335 cm^3 plastic vessels to a uniform oven-dry density of 1.0 g cm^{-3}. Immediately after adding water

and packing to the desired density, one anion and one cation PRS™ probe were inserted into each vessel (time zero), the total weight noted, and incubated at room temperature (20°C). Probes were pulled at 24 hours, and new probes reinserted into the same slots created by the initial probes. These probes were then pulled at 14 days (total burial length of 13 days) and new probes reinserted and incubated until day 28 (total burial length of 14 days). Water was periodically added to keep incubations at starting water content. At the end of each period, probes were washed with deionized water and stored at 4°C until shipping to Western Ag Innovations for elution and determination of adsorbed NO_3^-, NH_4^+, Ca, Mg, P, K, S, Mn, Fe, Zn, and B. PRS™ probes have an exchange resin surface area of 10 cm^2, and results were reported in µg 10 cm^{-2} per burial time. Due to the nonlinear relationship of ion adsorption, results cannot be divided by burial time; however values from each burial can be summed to provide a cumulative value for each nutrient across the duration of the incubation, as was done to determine cumulative 28-day PRS™-probe values in this study.

Statistical Analysis

Treatment effects on soil properties were analyzed using General Linear Model in SAS System for Windows Version 9.3 (SAS Institute, 2012) and means were separated using Fisher's protected Least Significant Difference (LSD) test at the $p = 0.10$ level. Within a site, sources of variation in the statistical model were field (block) and agroecosystem treatment. Tukey's mean separation procedure was used to identify significant differences when the global F-test was non-significant ($p > 0.10$). Unless specifically stated otherwise, all statistical differences represent $p < 0.10$. In performing multivariate analysis, model entry was also set at $p < 0.10$. A less rigorous alpha was selected for this study due to both the short management histories

associated with some of the sites (Table 2.1) and the inherent spatial variability of many of the soil C and N properties measured. In consideration of these two factors, an alpha of 0.10 was considered a judicious step towards minimizing type II errors (failing to reject a false null hypothesis).

RESULTS AND DISCUSSION

Potential N Mineralization and Soil Properties

A range of correlations were found between PNM and soil C and N properties (Table 2.2). Within soil C properties, correlations (r) ranged from 0.40 for MBC to 0.59 for SOC, and within soil N properties, correlations (r) ranged from 0.47 for WEON to 0.67 for total N and HN (Table 2.2). While PNM is microbially driven, MBC displayed one of the lowest correlations of soil C properties with PNM (r = 0.40) and MBN was not significantly correlated with PNM (Table 2.2). Bengtsson et al. (2003) suggested microbial biomass measured by chloroform fumigation is poorly related to PNM because it does not differentiate between growth rates of different microbial populations, but rather extracts the total microbial biomass; consequently, more active microbes and their contribution to nitrogen turnover are obscured by less active microbes. Due to the variation in composition of SOM, ranging from fresh crop residues to humic substances, Curtin and McCallum (2004) concluded SOC and total N often do not provide a good indication of PNM.

Contrary to this notion, in a review of 100 published studies on N cycling across multiple terrestrial ecosystems, Booth et al. (2005) found that bulk soil C and N explained 42% of the variation in gross mineralization, which was greater than either microbial biomass (27%) or respiration (25%). Similar to results by Booth and coworkers (2005), in the present study, SOC

and total N, along with HN, displayed the strongest correlations of soil C and N properties with PNM (Table 2.2). Soil pH also displayed a significant negative correlation with PNM (r = -0.62), reflective of increased biomass production resulting from fertilization and subsequently greater soil C and N, but also resulting in increased soil acidity.

Bulk soil C/N ratio were all below 20, ranging from 9.3 at Prosser to 13.8 at PCFS (Table 2.3), indicating N was not a limiting factor to PNM, and subsequently the bulk soil C/N ratio was not significantly correlated with PNM (Table 2.4). Likewise, the water extractable C/N ratio and hydrolyzable C/N ratio were not significantly correlated with PNM, also reflective of the non-limiting nature of lower C/N ratios towards PNM.

In contrast, the C/N ratios of the NHC/NHN fraction often exceeded 20 (Table 2.3) and were positively associated with PNM (Table 2.4). This C/N ratio of the non-hydrolyzable fraction reflects an older and more biochemically recalcitrant fraction of soil C and N, as indicated by studies revealing it has a longer turnover time than the SOC (Paul et. al, 2006). It is, however, not immune to microbial degradation, as has been demonstrated by studies showing its susceptibility to loss under increased disturbance (Poirier et al., 2005; Paul et al.; 2006) and to the priming effect through fresh additions of labile C (Thiessen et al., 2013). The positive correlation between PNM and this C/N ratio may therefore reflect greater substrate availability, as also indicated by the positive association between PNM and the non-hydrolyzable fractions of C and N (Table 2.2). The microbial C/N ratios in the present study ranged from 15.2 to 38.3 (Table 2.3). Considering that soil microorganisms maintain a C/N ratio less than the surrounding environment (Bengtsson et al., 2003), the greater C/N ratios of the microbial biomass fraction in the present study are not reliable. Extraction efficiencies are typically

applied to microbial biomass calculations, ranging from 0.25 to 0.45 for MBC and 0.18 to 0.54 for MBN (Varoney et al., 2008). These extraction efficiencies are, however, based on chemical extractants or addition of labeled C substrate, whereas in the present study deionized water was used. The greater microbial C/N ratios in the present study are therefore likely the result of a higher extraction efficiency associated with MBC compared to MBN. In the absence of calibrated extraction efficiencies for deionized water, the microbial C/N ratios in the present study are not accurate; MBC and MBN considered individually, however, can still be considered a reliable representation of microbial biomass in assessing treatment differences.

The C and N demands of the microbial population influence whether net N mineralization or immobilization occurs (Sylvia et al. 2005). Microorganisms typically have a lower C/N ratio than the soil they inhabit; assuming a microbial C/N ratio of 10, a 50% microbial use efficiency indicates that at soil C/N ratios above 20, microorganisms will immobilize inorganic N from the soil, whereas at C/N ratios below 20, they will be C limited and net N mineralization will result (Bengtsson et al., 2003). Across multiple ecosystems, Booth et al. (2005) found that both substrate quantity and soil C/N ratios influence N mineralization rates. Conversely, Bengtsson et al. (2003) found that in forests soils, microbial biomass and activity as measured by ATP content more so than soil C/N ratios were significant in N transformations. In a study analyzing the role of C quantity and quality on N transformations in cereal based rotations, Herrmann and Witter (2008) found that consideration of the C/N ratio of the free-light fraction of SOM, representative of undecomposed organic matter, was an important consideration in N immobilization. This variety of results in the literature regarding soil C/N ratios and N transformations indicates that there are important considerations around the

paradigm that soil C/N ratios represent an important control on N transformations. Variations in C/N ratios of different pools of SOM, along with differences in assimilation efficiency of the microbial biomass between different sites are important considerations and can confound the relationship between soil C/N ratios and N transformations (Bengtsson et al., 2003).

In this study, cumulative Cmin at 10 days displayed the highest correlation with PNM (r = 0.40) (Table 2.2). Considering that PNM is microbially driven and CO_2 evolution a direct result of this process, stronger correlations were anticipated. Two factors may have contributed to these low correlations: 1) varying gross immobilization rates, and 2) the anaerobic nature of the N mineralization incubation performed. As previously mentioned, net mineralization is partially dictated by the C/N ratio of the soil; however it is also the product of two opposing processes, gross mineralization and gross immobilization (Luxhoi et al., 2006). Soil overall C/N ratios within this study where within range to promote net N mineralization; however material undergoing decomposition represents an important consideration in N transformations. Herrmann and Witter (2008) found that the concentration of SOM undergoing decomposition, represented by the free-light fraction, exhibited a significant correlation with gross immobilization (r^2 = 0.90) and the C/N ratio of this fraction played an important role in N transformations and could obscure the relationship between Cmin and gross mineralization. Luxhoi et al. (2006) found similar results when evaluating mineralization and immobilization in relationship to C/N ratios of plant materials. Their findings revealed a significant correlation between CO_2 evolution rate and both gross immobilization and mineralization rates, but not between CO_2 evolution rate and net mineralization rate. In the present study, neither the C/N ratio of plant material nor the free-light fraction was determined; the diversity of crops

comprising the rotations, however, represent a range of C/N ratios. For example, a representative wheat straw has a C/N ratio of 80, while legumes such as alfalfa are typically lower at approximately 13 (Sylvia et al. 2005). This diversity of plant inputs, therefore, potentially confounded the relationship between Cmin and PNM.

It is also important to consider the nature of both the PNM and Cmin incubations. CO_2 is the product of heterotrophic organisms using oxygen as a terminal electron acceptor. Anaerobic respiration is carried out by anaerobic or facultative microbes and the terminal electron acceptor is often nitrate, sulfate, or CO_2 (Sylvia et al., 2005). While anaerobic respiration produces CO_2, the Cmin analyses was performed under aerobic conditions, which is energetically a more efficient process and a possible reason why Cmin values in this study do not correlate well with anaerobic PNM. Franzluebbers et al. (1996) noted aerobic PNM at 21 days displayed a correlation coefficient (r^2) of 0.85 with one-day Cmin across a range of silt and clay loams from Texas. Lower correlations have been noted by others, however, such as Curtin and McCallum (2004), who found that Cmin displayed a correlation coefficient (r^2) of 0.36 with aerobic PNM, and a slightly lower correlation of 0.25 with anaerobic PNM, and concluded that Cmin was not a reliable surrogate for PNM.

Potential N Mineralization and N Supply

PNM was significantly correlated with 24-hour PRS™-probe NO_3^- (r = 0.45), but was not correlated with 28-day cumulative PRS™-probe NO_3^- (Table 2.5). Multiple studies have found that NO_3^- adsorbed to PRS™ probes is related to plant N uptake, as, for example, in Nyiraneza et al. (2009), who reported that in-field NO_3^- adsorbed to PRS™ probes over the duration of corn maturation in Quebec, Canada, was significantly related to corn N uptake (r = 0.95) as well

as corn yield (r = 0.91). Walley et al. (2002) reported weaker, yet still significant, correlations between NO_3^- adsorbed to PRS™ probes during a laboratory incubation and spring wheat N uptake (r = 0.32) and yield (r = 0.37). Nyiraneza and coworkers (2009) also reported PNM from a seven-day anaerobic incubation was correlated with corn N uptake (r = 0.79) and yield (r = 0.85). In the present study, however, the fact that PNM from a longer incubation is not correlated with NO_3^- from an equally long PRS™-probe incubation suggests that PNM as measured in this study is a poorly related to plant N uptake.

Potential and Basal Denitrification and Soil Properties

PDR and BDR were significantly correlated (r = 0.37), and despite the added NO_3^- and C to the PDR incubation, PDR still exhibited a significant correlation with SOC (r = 0.70) and total N (r = 0.57) and the other soil C and N pools measured accept for MBC (Table 2.2). Others have found similar correlations with soil C and N and PDR (Staley et al; 1990; D'Haene et al., 2003). It is also worth noting that PDR was significantly and positively associated with one-day Cmin, but negatively associated with the microbial metabolic quotient (qCO_2). This correlation indicates that an increase in microbial activity and efficiency is associated with an increase in PDR and infers that as denitrification is a microbially mediated process, more efficient use of energy sources by denitrifiers would allow for an increased opportunity for denitrification.

BDR, on the other hand, did not display the significant correlations displayed by PDR and was correlated only with soil extractable inorganic N (r = 0.31) and soil pH (r = -0.29) (Table 2.2). This lack of correlation between BDR and other soil C and N pools may be partially explained by the greater coefficient of variations (CV) for BDR compared to PDR; for BDR, CVs ranged from 20% to 128%, while for PDR CVs ranged from 14% to 62%. A significant correlation between

BDR and soil NO_3^- and the lack of correlation with soil C properties is indicative that NO_3^- may have been the limiting factor in BDR. This is consistent with the fact that many researchers report a flux in in-situ denitrification following a fertilizer event containing inorganic N (Aulakh & Rennie, 1986; Drury et al., 1998; Dusenbury et al., 2008). The negative correlation between pH and BDR, as well as PDR (Table 2.2), is indicative of fertilization producing not only more acidic conditions, but also resulting in greater soil C and N availability from increased biomass production.

As with PNM, C/N ratios were poorly correlated with PDR and BDR (Table 2.4). Others have noted it is the C/N ratios of fresh crop residues that critically influence denitrification. For example, Chen et al. (2013) found that in both field and laboratory studies, crop residues generally enhanced N_2O emissions under aerobic conditions but that the C/N ratio of the crop residue was a significant factor. At C/N ratios less than 45, the effect was positive; at C/N ratios between 45 and 100 the effect was moderate, and at C/N ratios greater than 100, crop residues had a negative effect on N_2O production. This relationship between crop C/N ratios and denitrification has also been noted in native systems, such as in the observation by Tiemann and Billings (2008), who observed that a shift from C4 grasslands to C3 grasslands, which have lower C/N ratios, was related to an increase in N_2O production. This relationship with C/N ratios of crop residues indicates that as N limits microbial growth and is assimilated to meet microbial needs, less N is available for mineralization and subsequently for denitrification.

Potential and Basal Denitrification and N Supply

In this study, PDR was significantly correlated to both PNM ($r = 0.69$) and 28-day PRS™-probe NO_3^- ($r = 0.27$) (Table 2.5). Similarly, Alotaibi and Schoenau (2013) found that a decrease

in N_2O emissions was associated with a decrease in inorganic N adsorbed to PRS^{TM} probes. Tiemann and Billings (2008) reported N_2O emissions were highest when both moisture and inorganic N availability were highest. These published results along with the significant correlations in the present study between PDR and inorganic N supply are consistent with inorganic N as a limiting factor in denitrification and also suggests that soils with a greater capacity to mineralize N are associated with an increase in N_20 emissions. Considering that soil C is also critical to the turnover of N as a microbial energy source, results in the present study are consistent with the notion that abundant soil C and inorganic N, along with the presence of anerobiosis, are the three most commonly cited abiotic and biotic edaphic properties that influence N_2O emissions (Hangs et al., 2013).

Nutrient Supply and Soil Properties

Flow of ions to roots is driven either by diffusion (P, K, Zn, Fe) or mass flow (N, Ca, Mg, S, Mn, B, Cu) (Havlin et al., 1999). The lack of a water potential gradient in laboratory incubations results in the prevalence of diffusion of nutrients, which is a slower process than mass flow and reliant upon a concentration gradient. The prevalence of diffusion in the present study is supported by the fact that a majority of soil cations and anions measured exhibited significant correlations (r) across incubation time periods (Table 2.6). Due to the prevalence of diffusion, soil texture has the potential to influence nutrient diffusion through its impact on tortuosity (Havlin et al., 1999). Courser soils have a lower tortuosity, and for a given diffusion gradient and water content, courser soils will have greater diffusion rates. For this reason, Prosser was excluded from cross-site correlations involving PRS^{TM} nutrients as Prosser has sandier soils than

the other sites, a situation which confounds results from the other four sites of similar soil texture.

PRS™ - Probe N, P, S and Soil Properties

Multiple soil C and N pools exhibited a significant positive relationship with NO_3^- at 24 hours, while only initial extractable N exhibited a significant relationship with 28-day NO_3^- (r = 0.42) (Table 2.2). The significant relationship between initial soil extractable N and adsorbed NO_3^- at 24 hours and 28 days (Table 2.2) indicates initial inorganic N in the soil at the beginning of the incubation accounted for an important pool of the N adsorbed at 28 days. Soil C/N ratios and their role in total N at 24 hours and 28 days were examined and were not significant (Table 2.3). This outcome is likely the result of overall narrow C/N ratios that are subsequently not a limiting factor in N turnover (Table 2.4).

A shift in relationship between 24-hour and 28-day PRS™ values and soil C and N properties are potentially insightful. The 24-hour PRS™ values capture in-situ conditions at time of sample collection and are dependent on the cumulative effect of field conditions and processes influencing nutrient availability prior to time of sampling. The 28-day PRS™ values are more influenced by incubation conditions; optimal moisture and temperature conditions along with mixing of the soil favor enhanced microbial activity and diffusion compared to field conditions. A significant positive relationship between 24-hour NO_3^- and POXC (r = 0.49), SOC (r = 0.49), total N (r = 0.51) and WEON (r = 0.40) is indicative of greater C and N substrate availability resulting in greater in-situ mineralization (Table 2.2). This finding is also supported by the significant relationship between 24-hour NO_3^- and PNM (Table 2.5). At 28 days, these

significant relationships with soil C and N properties do not exist, reflecting the shift in conditions associated with incubation conditions.

When analyzed across all five sites, P and S availability at 28 days exhibited few significant relationships with soil C and N properties; with the removal of Prosser, however, from the cross-site analysis, 28-day P is significantly correlated with POXC (r = -0.38), total N (r = -0.26), and HN (r = -0.27), as is 28 day S with POXC (r = -0.35), total N (r = -0.37), and HN (r = -0.35) (Table 2.2). This negative relationship between soil C and N properties and P and S availability at 28 days may be indicative of greater rates of gross immobilization of P and S occurring during incubation than in-situ as a result of enhanced microbial activity and C/P and C/S ratios.

Furthermore, these relationships do not exist with 24-hour P and S (data not shown). Increased gross immobilization would result in less of a diffusion gradient and thereby result in slower diffusion rates and less cumulative adsorbed P and S to the exchange resin. This is also supported by the absence of the negative correlation between P and S with the inclusion of Prosser in the analysis (data not shown). Prosser contains sandier soils and diffusion of P and S through sandier soils would be less impacted by a small shift in concentration gradient of these nutrients; this is the result of a decrease in tortuosity associated with courser-textured soils and a resulting increase in the rate of diffusion for a given diffusion gradient (Havlin et al., 1999).

Tabatabai and Dick (1979) observed that P mineralization was significantly associated with SOC (r = 0.90) and increased steadily with increasing SOC content at pH below 7.0. However, Havlin et al. (1999) notes that C/P ratios greater than 300 and C/S ratios greater than 200 promote immobilization. This cannot be confirmed in this study as soil S and P were not

measured. However, these results indicate that during periods in which microbial activity is enhanced, such as following a rain event when C substrate is abundant and soil temperatures are optimal, increased gross immobilization may occur if P and S are less than optimal for microbial needs. Cole et al. (1978) studied the dynamics of P turnover in relation to C additions comparable to the C content of root exudates in 24-day incubations. They found that increased C levels resulted in a concomitant increase in both microbial activity and P immobilization, and that much of the immobilized P was recovered through chloroform fumigation. Similarly, in investigating S mineralization/immobilization, Niknahad-Gharmakher et al. (2012) found that short-term dynamic S availability was closely tied with the C/S ratio of plant material, and that S availability could be predicted by C/S ratios of plant materials.

Soil pH was significantly correlated with both 24-hour NO_3^- (r = -0.60) and 28-day NO_3^- (r = -0.23), as well as with P (r = 0.42) and S (r = 0.32). As with PNM, the negative relationship between soil pH and NO_3^- reflects increased biomass production resulting from fertilization to match greater crop demand and also resulting in a corresponding increase in soil acidity. The positive correlation between P and soil pH can be explained by P adsorption to Fe/Al oxides, as this is promoted under more acidic conditions (Havlin et al., 1999); in the present study, soils were acidic and pH ranged from 4.69 to 5.93. The influence of soil pH on S availability is less clear; however, neutral pH encourages microbial activity and S mineralization (Havlin et al., 1999), and this theory is supported in the present study by the positive correlation between S availability at 28 days and soil pH (Table 2.2).

PRS™- Probe K, Ca, Mg and Soil Properties

Multiple soil C and N properties exhibited a negative relationship with K, including POXC (r = -0.43), SOC (r = -0.30), and total N (r = -0.36), while Ca was positively correlated with POXC (r = 0.32). Mg was also negatively correlated with multiple soil C and N properties, including SOC (r = -0.42) and total N (r = -0.40). Sources of plant available Ca and Mg in soils include mineral dissolution and CEC as well as SOM. Plant available K sources are similar; however, mineral weathering and release of K occurs at a much slower rate than for Ca and Mg (Havlin et al., 1999). SOM influences the plant available amount of these nutrients in soil both as a direct source and as a source of CEC. This relationship between POXC and Ca may be reflective of greater SOM-derived Ca as well as greater CEC and subsequently greater Ca supply associated with an increase in SOM.

The ratio of Ca in solution to other cations is also an important consideration that may explain the negative relationship of soil C and N properties with K and Mg; high Ca/Mg ratios can inhibit Mg, and the activity of K is also inversely proportional to Ca activity (Havlin et al., 1999). This influence of Ca on K is reflected in the significant negative correlation between these two nutrients (r = -0.37). In a study involving exchange preferences of SOM, Cofie and Pleysier (2004) demonstrated a Ca preference over K of the exchange sites associated with SOM, indicating a direct relationship between exchangeable Ca associated with SOM, and consequently a negative relationship associated with K.

The negative relationship between Ca and Mg and the water extractable portion of C and N (Table 2.2) may be explained by polyvalent cation bridging, a mechanism which results in stabilization of dissolved organic matter, whereby polyvalent cations act as a bridge between

negatively charged organic matter and clay particles (Whittinghill and Hobbie, 2012). Roychand and Marschner (2014) demonstrated the ability of Ca to bind WEOC in soils by incrementally increasing both clay and Ca in a sandy soil and found a negative correlation with respiration and Ca additions resulting from stabilization of WEOC. This relationship was not detected in the 24-hour results (data not shown) as cation bridging is active in field conditions as well and would have required desorption of already stabilized WEOC, followed by sorption with Ca and Mg during the initial 24 hours of the incubation. This finding indicates that over prolonged periods of high soil moisture, a portion of Ca and Mg in soil solution become unavailable to plants while contributing to SOM stabilization.

Soil pH was positively correlated with both K ($r = 0.42$) and Mg ($r = 0.27$) and not significantly related with Ca. Acid soils are associated with a decrease in Mg and K availability resulting from the presence of Al on exchange sites; an increase in pH promotes the formation of insoluble Al and subsequently frees exchange sites for K and Mg (Havlin et al., 1999). This same mechanism also influences Ca, however, to a lesser extent due to higher levels of Ca that are typically present in soils relative to K and Mg.

PRS™- Probe Micronutrients and Soil Properties

The macronutrients displayed few significant correlations with soil C and N properties (Table 2.2). Mn displayed the most, and was significantly correlated with SOC ($r = 0.42$), POXC ($r = 0.31$), and total N ($r = 0.35$). This may be an indirect relationship with SOM, and driven more by redox potential and greater soil acidity associated with an increase in SOM. While not detected in this study, other studies have shown a correlation between organic matter and Zn (Tagwiri et al., 1992; Wei et al., 2006) and Fe content of soils (Wei et al, 2006). The negative

correlation between Cu and WEOC (r = -0.32) is consistent with other findings, which have shown that up to a point, SOM can increase Cu availability, but excessive SOM can result in immobilization of Cu due to the formation of complexes between organic matter and Cu (Rengel et al., 1999; Wei et al, 2006). This may also indicate why WEOC correlated with Cu only at 28 days and not 24 hours (data not shown), as optimal moisture conditions would have resulted in the formation and increased mobility of WEOC compared to drier field conditions.

While the lack of correlations in the present study between soil C and N properties and micronutrients does not support SOM as critical to micronutrient supply, SOM theoretically influences micronutrients both as a source and by increasing solubility through the formation of chelates, which protect micronutrients from precipitation reactions that would render them unavailable to plants (Brady and Weil, 2010). Soil pH in the present study did not exert a strong influence on micronutrient availability and was significantly related only to Mn (r = -0.37). Soil pH, however, is considered important to micronutrient availability through its influence on redox potential; divalent metals decrease in solubility one-hundred fold for every unit increase in pH (Rengel et al., 1999). SOM also releases organic acids, leading to a decline in pH, and possibly resulting in an acceleration of the dissolution of non-available micronutrients (Wei et al., 2006), further supporting the importance of SOM to micronutrient availability.

Table 2.2 Pearson correlations of PNM, BDR, PDR, and PRS™ - probe nutrients with soil pH and soil C and N properties*.

	Property†	pH	$Cmin_{0-1d}$	$Cmin_{0-3d}$	$Cmin_{0-10d}$	$Cmin_{0-17d}$	$Cmin_{0-24d}$	qCO_2	POXC	SOC	Total N	NHC	NHN	HC	HN	TN_{IN}	MBC	MBN	WEOC	WEON
	PNM	-0.62	0.28	0.31	0.40	0.34	0.26	-0.39	0.52	0.59	0.67	0.56	0.46	0.56	0.67	0.65	0.40	ns	0.50	0.47
	BDR‡	-0.29	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.31	ns	ns	ns	ns
	PDR‡	-0.56	ns	ns	0.24	ns	ns	0.56	0.65	0.70	0.57	0.55	0.61	0.72	0.43	0.54	ns	0.47	0.41	-0.43
PRS™ - Probe Nutrients∓	NO_3^- (24 hr.)	-0.60	0.36	0.33	ns	ns	ns	-0.35	0.49	0.49	0.51	0.43	0.44	0.43	0.49	0.85	0.28	ns	0.25	0.40
	NO_3^- (0-28d)	-0.23	0.32	0.29	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.42	ns	ns	ns	ns
	NH_4	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	-0.25	ns
	P	0.42	ns	ns	ns	ns	ns	0.29	-0.38	ns	-0.26	ns	ns	-0.28	-0.27	-0.28	ns	ns	ns	ns
	S	0.32	ns	ns	-0.27	ns	ns	ns	-0.35	-0.36	-0.37	-0.28	-0.25	-0.29	-0.35	ns	ns	ns	-0.33	-0.25
	K	0.42	ns	ns	ns	ns	ns	ns	-0.43	-0.30	-0.36	ns	ns	-0.33	-0.37	-0.30	ns	ns	ns	ns
	Ca	ns	0.30	0.29	ns	ns	ns	-0.28	0.32	ns	ns	ns	ns	ns	ns	ns	ns	ns	-0.34	-0.36
	Mg	0.27	ns	ns	ns	ns	ns	ns	ns	-0.42	-0.40	-0.46	-0.35	-0.33	-0.39	ns	ns	ns	-0.53	-0.36
	Fe	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Mn	-0.37	ns	ns	ns	ns	ns	ns	0.31	0.42	0.35	ns	ns	0.35	0.38	0.49	ns	ns	ns	0.46
	Cu	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	-0.28	ns	ns	ns	-0.32	ns
	Zn	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	-0.26	ns
	B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$)

† PNM = potential nitrogen mineralization at 28 days; BDR = basal denitrification; PDR = potential denitrification; pH = soil pH from 1:1 extract; Cmin = carbon mineralization at 1, 3, 10, 17, and 24 days; qCO_2 = microbial metabolic quotient; POXC = permanganate oxidizable carbon; SOC = soil organic carbon; NHC = non-hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HC = hydrolyzable carbon; HN = hydrolyzable nitrogen; TN_{IN} = total inorganic N from KCL extraction; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen.

‡ Prosser excluded from cross-site analysis of PDR and BDR.

∓ PRS™ - probe nutrients are cumulative 28 day values unless otherwise noted. Prosser excluded from cross-site analyses of PRS™ nutrients with other soil properties.

Table 2.3 Soil C/N ratios of various soil C and N properties across five study sites*.

Site	Treatment†	C:N‡	NHC:NHN	HC:HN	WEOC:WEON	MBC:MBN‡
Kambitsch	WW/SB/SL - NT	12.8 a (8)	26.5 (17)	8.7 (4)	14.9 (29)	16.9 (9)
	WW/SB/SL - Till	12.0 b (7)	22.9 (17)	8.3 (17)	11.2 (38)	20.6 (25)
PCFS	WW/SL/SW - NT	13.2 (5)	27.1 (8)	8.1 (4)	13.8 (24)	22.0 (11)
	WW/SB/SW - NT	13.8 (10)	26.8 (4)	8.6 (19)	12.1 (25)	28.1 (61)
	Alf/SC/SL (organic) - NT	12.2 (9)	25.5 (23)	8.1 (1)	15.3 (9)	33.8 (59)
	Perrenial Tall Wheat Grass	13.0 (1)	29.7 (12)	8.3 (12)	15.9 (5)	34.8 (42)
	Native/CRP Grass	12.4 (5)	26.1 (8)	8.4 (13)	13.7 (5)	38.3 (75)
Pendleton	WW/ NT Fallow - NT	13.7 a (4)	26.6 a (18)	9.0 (16)	15.1 a (3)	21.6 (39)
	WW/Pea - NT	13.1 a (4)	26.1 a (10)	8.2 (8)	14.8 a (2)	24.6 (62)
	WW/Fallow - Till	12.2 b (4)	21.2 b (7)	8.2 (19)	13.6 b (6)	17.9 (36)
Moro	WW/WP - NT	13.3 (7)	26.9 (27)	9.0 (14)	14.7 b (4)	18.8 (46)
	WW/NT Fallow - NT	13.5 (13)	21.0 (21)	10.5 (18)	15.4 ab (3)	16.0 (11)
	WW/SB/NT Fallow - NT	12.1 (3)	25.0 (20)	8.0 (10)	15.2 ab (1)	15.2 (24)
	WW/Fallow - Till	13.2 (9)	22.7 (18)	9.3 (8)	15.6 a (1)	23.1 (20)
Prosser	WW/Sw. Cn./Potato - NT	9.3 (6)	19.9 (7)	7.2 (11)	16.1 (44)	23.6 (45)
	WW/Sw. Cn./Potato - Till	9.3 (4)	21.2 (10)	7.1 (4)	13.1 (10)	21.0 (9)

* Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

ŧ C:N = bulk soil C/N ratio (SOC:total n); NHC = non-hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HC = hydrolyzable carbon; HN = hydrolyzable nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen.

‡ No extraction efficiencies applied to this ratio; MBC/MBN ratio not reliable.

Table 2.4 Pearson correlations between PNM, BDR, PDR, and PRS™ – nitrogen with various soil C/N ratios across five study sites*.

				PRS™ Probe Nutrients		
Property†	PNM	BDR‡	PDR‡	NO_3^- (24 hr.)	NO_3^- (0-28d)	NH_4^+ (0-28d)
C:N	ns	ns	ns	ns	ns	ns
NHC:NHN	0.34	ns	ns	ns	ns	-0.23
HC:HN	ns	ns	ns	ns	ns	ns
WEOC:WE	ns	ns	ns	ns	ns	ns

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† C:N = bulk soil C:N ratio (SOC:total n); NHC = non-hydrolyzable carbon; NHN = non-hydrolyzable nitrogen; HC = hydrolyzable carbon; HN = hydrolyzable nitrogen; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen.

ŧ Prosser excluded from cross-site analysis of PDR and BDR.

Table 2.5 Pearson correlations between PNM, BDR, PDR, and PRS™ – probe nutrients across five study sites*.

				PRS™ - Probe Nutrients∓											
Property†	PNM	BDR‡	PDR‡	NO_3^- (24 hr.)	NO_3^- (0-28d)	NH_4^+	P	S	K	Ca	Mg	Fe	Mn	Cu	Zn
BDR‡	ns														
PDR‡	0.69	0.37													
PRS™ - Probe Nutrients∓															
NO_3^- (24 hr.)	0.45	ns	ns												
NO_3^- (0-28d)	ns	ns	0.27	0.62											
NH_4^+	ns	ns	ns	ns	0.24										
P	ns	ns	ns	-0.34	ns	ns									
S	-0.47	ns	-0.42	ns	ns	ns	ns								
K	ns	-0.33	ns	ns	ns	ns	0.70	0.25							
Ca	ns	ns	ns	0.33	0.45	0.33	-0.38	0.34	-0.37						
Mg	-0.47	0.30	-0.27	ns	0.40	ns	-0.25	0.42	ns	0.67					
Fe	ns	ns	ns	0.36	0.80	ns	ns	0.29	ns	ns	0.40				
Mn	ns	0.34	ns	0.55	0.43	0.26	ns	ns	ns	ns	ns	0.35			
Cu	ns	ns	ns	ns	0.61	0.29	ns	0.40	ns	0.39	0.49	0.72	ns		
Zn	ns	ns	ns	ns	ns	0.46	ns	ns	ns	ns	ns	0.30	ns	0.41	
B	ns	-0.32	ns	ns	ns	ns	ns	ns	ns	0.30	ns	ns	ns	ns	ns

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† PNM = potential nitrogen mineralization at 28 days; BDR = basal denitrification; PDR = potential denitrification.

‡ Prosser excluded from cross-site analysis of PDR and BDR.

∓ PRS™ - probe nutrients are cumulative 28 day values unless otherwise noted.

Table 2.6 Pearson correlations for PRS™ - probe nutrients across incubation time periods and five study sites*.

Nutrient	24-hr vs. 14 day	24-hr vs. 28 day	14-day vs. 28 day
NO_3^-	0.66	0.27	0.55
NH_4^+	ns	ns	ns
P	0.65	0.73	0.68
S	ns	ns	0.7
K	0.76	0.78	0.82
Ca	0.66	0.51	0.6
Mg	0.22	0.4	0.47
Fe	0.38	ns	0.43
Mn	0.85	0.72	0.67
Cu	0.47	0.35	0.64
Zn	ns	ns	ns
B	ns	ns	ns

***** Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

Mean Annual Temperature and Precipitation, Potential N Mineralization, and Potential and Basal Denitrification

The four non-irrigated sites selected for this study span a mean annual precipitation (MAP) gradient that increases by 130% from Moro (288 mm) to Kambitsch (663 mm), and inversely, a mean annual temperature (MAT) gradient that decreases by 23% from Pendleton (10.3°C) to PFCS (8.4°C). The Prosser site was excluded from this analysis because it is an irrigated site. PNM was significantly correlated with both MAP (r = 0.60) and MAT (r = -0.73), as was PDR with MAP (r = 0.55) and MAT (r = -0.64), while BDR was significantly correlated only with MAT (r = -0.34) (Table 2.7). MAT tends to influence decomposition more so than productivity where growing degree days are sufficient, while MAP in drier regions increases productivity, and thus inputs of SOM to the soil more than it increases decomposition (Weil and Magdoff, 2004). Therefore, considering the importance of soil C and N properties to PNM, PDR,

and BDR already established, this relationship between these N transformations and MAP and MAP is reflective of the influence of climate on soil C and N properties.

Similarly, in a study by Chapman et al. (2013), a high degree of the variability in N mineralization observed across a range of natural ecosystems across the United States was explained by MAT, MAP, as well as total N and N deposition. In a study of mineral soils across the United States, Colman and Schimel (2013) concluded that the direct drivers of N mineralization were soil C and N as well as clay content and that precipitation drives N mineralization indirectly through its influence on soil C and N content. Regarding PDR, Niboyet et al. (2011) examined the effects of climate on PDR and found that experimentally increasing precipitation 50% for 8 years resulted in a 22% increase in PDR, and long-term additions of 7 g N m^2 annually increased PDR 34%. Niboyet and coworkers (2011) did not detect sensitivity of PDR to warming of 1^oC for 8 years. This study may not have included a significant enough temperature gradient to induce changes in PDR through changes in soil C and N, nor have implemented it for a long enough period of time. In contrast, the temperature gradient in the present study spans 2.9^oC and represents long-term climate conditions rather than shorter-term increases that have been experimentally induced.

Mean Annual Temperature, Precipitation and Nutrient Supply

PRS^{TM} - Probe N, P, and S

Similar to PNM, PRS^{TM}-probe 24-hour NO_3^- availability is positively correlated with MAP (r = 0.51) and negatively correlated with MAT (r = -0.30) (Table 2.8). This reflects increased substrate availability for in-situ mineralization of N associated with increased precipitation and lower temperatures. While higher temperatures are associated with greater rates of

decomposition, the decrease in substrate associated with an increase in MAT appears to result in lower in-situ NO_3^- availability. This relationship between climate and 24-hour NO_3^- availability was not detected at 28 days (Table 2.8) and is indicative of optimal temperature and moisture conditions along with soil mixing associated with incubations enhancing N availability.

Phosphorus availability at 28 days displayed a negative relationship with MAP (r = -0.53); this may reflect the influence of soil pH on P availability. With increasing soil pH, adsorption of P to Fe/Al oxides decreases (Havlin et al., 1999), rendering P more available as pH approaches neutral. Additionally, the greater C substrate associated with an increase in MAP may result in P immobilization. In a study on the influence of climate factors on nutrient transformations, Meeteren et al. (2007) found a significant relationship between microbial immobilization of P from plant litter and temperature and moisture (r^2 = 0.69), with moisture being the dominant factor driving immobilization.

S mineralization is sensitive to temperature (Havlin et al., 1999), and this is reflected in the present study where S availability increases with an increase in MAT (r = 0.58). As with P, S immobilization may also be behind this relationship between MAT and S availability at 28 days, as greater C substrate is associated with lower MATs and high C/S ratios are associated with S immobilization (Havlin et al., 1999).

PRS™ - Probe K, Ca, and Mg

An increase in MAP is associated with decreased 28-day K availability (r = -0.65). This is contrary to observations that K leaching losses are small, except in cases of sandy soils or high incidences of flooding, neither of which are factors in the present study. This relationship is more likely reflective of increased 28-day Ca availability associated with an increase in MAP (r =

0.59); as cited previously, increased Ca activity is associated with a decrease in K activity (Havlin et al., 1999). This positive correlation between Ca and MAP also indicates that leaching of non-acidic cations such as Ca, which can occur as H displaces cations, is not measurably reducing Ca availability.

This same observation is also true for 28-day Mg availability, which is not significantly related to MAP (Table 2.8). The positive correlation between MAT and Mg (r = 0.45) may be reflective of the role of soil pH in Mg availability; Mg availability increases as pH approaches neutral and in the present study soil pH was acidic and increased with increasing MAT (r = 0.60).

PRS™ - Probe Micronutrients

Micronutrients availability displayed few significant correlations with MAP and MAT (Table 2.8). Relationships that did exist between climate variables and micronutrients included the following: Fe, significantly correlated with MAT (r = 0.26), Cu, significantly correlated with MAT (r = 0.26), and B availability at 24 hours, significantly correlated with MAP (r = 0.30). While SOM is considered an important factor and source of micronutrients, the lack of correlation between micronutrients and MAT and MAP is consistent with the observed poor correlations between micronutrients and soil C and N properties previously discussed (Table 2.2). These poor correlations between MAP, MAT, and micronutrients also existed for 24-hour PRS™-probe values (data not shown).

Table 2.7 Pearson correlations of climate and management variables with PNM, BDR, and PDR across five study sites*.

Property†	MAT‡	MAP‡	STIR	Intensity
PNM	-0.73	0.6	-0.32	0.4
BDR	-0.34	ns	0.32	ns
PDR	-0.66	0.55	0.32	ns
pH	0.60	-0.77	0.37	-0.28

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† MAT = mean annual temperature; MAP = mean annual precipitation; STIR = soil tillage intensity rating; intensity = cropping intensity; PNM = potential nitrogen mineralization; BDR = basal denitrification; PDR = potential denitrification; pH = soil pH from 1:1 extract.

‡ Prosser excluded from cross-site analysis involving climate variables.

Table 2.8 Pearson correlations between climate variables and PRS™ - probe nutrients across four dryland sites*.

Property†	NO_3^- (24 hr.)‡	NO_3^- (0-28d)	NH_4^+	P	S	K	Ca	Mg	Fe	Mn	Cu	Zn	B
MAP	0.51	ns	ns	-0.53	ns	-0.65	0.59	ns	ns	ns	ns	ns	ns
MAT	-0.30	ns	ns	ns	0.58	0.42	ns	0.45	0.26	ns	0.26	ns	ns

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† MAP = mean annual precipitation; MAT = mean annual temperature.

‡ PRS™ - probe nutrients are cumulative 28 day values unless otherwise noted.

Management and Potential N Mineralization

PNM ranged from a high of 106.6 mg N kg^{-1} soil for the organic system at PCFS to 18.7 mg N kg^{-1} soil for the conventional WW-fallow rotation at Pendleton (Table 2.9). Significant differences in PNM within sites occurred at Pendleton and Moro. At Pendleton, NT without cropping intensification resulted in a 188% increase in PNM compared to CT, while at Moro inclusion of a legume in rotation resulted in 80% greater PNM than WW-fallow NT and 70% greater PNM than WW-SB-fallow NT. In contrast to Pendleton, Moro NT with fallow did not result in significantly greater PNM compared to CT with fallow (Table 2.9). While no significant differences were observed at the other sites, the impacts of STIR and cropping intensity on PNM across the region are evident from the significant correlation of PNM with these management variables (Table 2.7).

In a study by Soon et al. (2007) on management impacts on PNM, a 7-day anaerobic incubation identified significantly greater PNM in the top 5 cm associated with NT (94.1 mg N kg^{-1}) than for CT (58.4 mg N kg^{-1}) for a sandy loam with 8 years of management and a four-year rotation including wheat and a legume. In contrast to results found at Moro, Soon and coworkers (2007) did not identify any significant effect in the top 5 cm (or 15 cm) resulting from inclusion of pea in rotation when it was the previous crop to wheat. Wood et al. (1990) found that PNM associated with NT was significantly greater under more intensely cropped systems after 3.5 years of management in a semi-arid environment receiving 400 mm of annual precipitation. Similarly, in the present study, cropping intensification resulted in significantly increased PNM with a legume in rotation at Moro (Table 2.9), and is positively correlated with

PNM across all sites (Table 2.7). In general, research has shown the sensitivity of PNM to tillage practices and cropping intensity (Woods and Schuman, 1988; Wood and Edwards, 1992).

Management and Potential and Basal Denitrification

The CV for PDR was generally lower than for BDR; CVs for BDR ranged from 21% to 128%, and for PDR they ranged from 14% to 62% (Table 2.9). Accordingly, BDR did not significantly differ within any of the sites, while PDR showed significant differences at 3 of the 5 sites (Table 2.9). Prosser and Moro were the only sites for which PDR did not reveal any significant differences. However, it is notable that in most instances Prosser showed an order of magnitude greater BDR and PDR than the other sites did. Prosser is unique compared to the other sites in several regards: it is irrigated, has a sandier soil, and has a unique crop rotation, which includes WW, sweet corn, and potato.

It is not possible to say which of these factors may have contributed to greater BDR and BDR at Prosser compared to other sites. Drury et al. (1991) found that a sandy loam soil had lower background denitrification than other clay loam soils; there did not, however, appear to be any clear trend between soil type and background denitrification in their study. Furthermore, Drury at al. (2008b) found monoculture corn had greater in-situ denitrification compared to more diverse rotations and partially attributed this to greater fertilizer requirements of monoculture corn. However, background inorganic N levels do not help to explain the difference as Prosser NH_4^+ and NO_3^- are on the same order of magnitude as other sites (data not shown). Several have found that soil aggregate structure influences denitrification by controlling microbial access to substrate (Christensen and Christensen, 1991; Drury et al., 1998). Soils in this study were not subjected to structural analysis, so it is not

possible to say if this was a contributing factor; sandier soils at Prosser, however, may have contributed to greater microbial access to substrate compared to the other sites, as sandier soils are associated with reduced aggregate structure.

Across sites with significant differences, results were inconsistent with regard to the influence of tillage on PDR, indicating more subtle factors were contributing to PDR rates. At Kambitsch, CT resulted in a 120% increase in PDR relative to NT; conversely, at Pendleton, a drier site than Kambitsch, NT resulted in a 97% increase in PDR compared to the same cropping rotation under CT.

Some have found the most limiting factor to denitrification to be C substrate supply across a range of soil physical and chemical properties (Drury et al., 1991). As NT is often associated with restoring or increasing soil C levels relative to CT (Brown and Huggins, 2012), NT represents a potential increase in denitrification. Consistent with this finding, some studies have shown an increase in N_20 production under NT management (Ball et al., 1999; Liu et al., 2007). Others, however, have shown a decrease in N_2O production associated with NT (Mosier et al., 2006).

In the present study, differences in soil C may be behind the inconsistency in the influence of tillage on PDR; at Kambitsch, WEOC, a labile and microbially available form of C, was 19% greater under CT than NT, and MBC was also 35% greater under CT than NT. In contrast to this, at Pendleton WEOC and MBC were 80% and 33% greater, respectively, under NT than CT. These contrasting results at Kambitsch and Pendleton considered in lieu of these important soil C pools are consistent with the role of C in denitrification and explain the contrasting results regarding the impact of tillage on PDR.

Rather than management or soil C levels, time and climate have been shown by some to be the broader drivers of denitrification. Six et al. (2004) concluded that following the adoption of NT, N_2O emissions are higher than in CT for the first 10 years, and after 20 years there is no difference between the two systems in dry climates while in humid climates, NT has reduced N_2O emissions relative to CT. Similarly, a model simulation by Mummey et al. (1998) indicates that relative N_2O emissions associated with tillage systems is dependent on climate; NT systems in warm and wet regions can expect comparable or reduced N_2O emissions compared to CT, while in drier regions, such as the inland Pacific Northwest, NT simulations of denitrification indicate an increase in N_2O emissions relative to CT, mainly due to increased soil moisture associated with NT. Mummey and coworkers (1998) concluded that with the adoption of NT, over time the active pool of SOM will increase and result in tighter N cycling and therefore reduced N_20 emissions.

Regarding cropping intensification, rotations in the present study in which legumes comprised half or more of the rotation consistently increased PDR. At Pendleton, WW/WP NT resulted in 81% greater PDR than WW/fallow NT and 256% greater PDR than WW/fallow CT (Table 2.9). At PCFS, significantly greater PDR was measured in a NT organic setting with pea present during time of sampling (Table 2.9), and was 94% greater than the next highest measured PDR, represented by WW/SB/SW NT. While not significantly different, similar results were found at PCFS for BDR (Table 2.9).

Due to differing methodologies, it is difficult to compare denitrification results across studies; however, BDR results from this study were up to an order of magnitude lower than results published in other studies (Drury et al., 1991; Guo et al.; 2011); this was also the case for

PDR compared to certain published studies(Staley et al., 1990; Luo et al., 1996), yet compared to other published results, PDR and BDR results in the present study were comparable to published results (Staley et al., 1990; D'Haene et al., 2003). Field measurements of denitrification in semi-arid climates have been shown to be episodic, with major events associated with fertilization (Burton et al., 2007), freeze-thaw cycles (Dusenbury et al., 2008), and rainfall events after prolonged dry periods (Beauchamp et al., 1996) and following the addition of fresh plant residue (Aulakh and Rennie, 1986; Chen et al., 2013). Due to this episodic nature and the number of variables that influence in-field denitrification, laboratory measured denitrification cannot be directly correlated with field denitrification, except in unique circumstances favorable to denitrification, in which peak field values have been shown to be of the same order of magnitude as PDR (D'Haene et al., 2003).

In general, studies of the impact of management indicate that NT results in greater PDR than CT (Staley et al., 1990), and that cropping diversification has potential to increase PDR (Guo et al., 2011). Aulakh et al. (1986) investigated both in-situ denitrification and laboratory denitrification from incubations for soils from dryland cropping systems under WW-fallow and continuous WW, both CT and NT. Aulakh and coworkers (1986) found both in-situ denitrification and denitrification from laboratory incubations to be significantly higher for NT systems in both cases. As was concluded by Mummey et al. (1998), Aulakh et al. (1986) concluded that soil moisture was the main factor contributing to higher in-situ rates, and laboratory incubations also revealed a significantly higher denitrifier population associated with NT soils. In a review of both laboratory and field studies, Chen et al. (2013) found that when N

supplied by crop residues is equivalent to N supplied by synthetic fertilizers, N_2O production in crop amended plots is greater than for fertilized plots.

This phenomenon of greater N_2O production in crop amended plots compared to fertilized plots was explained by a greater O_2 demand from the stimulatory effects of crop amendments resulting in microsite anaerobicity (Chen et al., 2013). Li et al. (2013) applied plant residues of varying C/N ratios to soils under both aerobic and anaerobic conditions, and found that under aerobic conditions the addition of crop residues enhanced N_2O production regardless of C/N ratios, while under anaerobic conditions the addition of plant materials, even with low C/N ratios, reduced N_2O emissions. The mechanism behind this latter finding was explained by Li and coworkers (2013) as the result of two occurrences: 1) a reduction in NO_3^- availability resulting from a decrease in nitrification under anaerobic conditions, and 2) reduced O_2 availability caused by crop residue additions resulting in enhanced N_2O reductase activity and therefore greater reduction of N_2O to N_2.

The corollary of findings by Chen et al. (2013) and Li et al. (2013) is that denitrification rates increase with the addition of crop residues under both anaerobic and aerobic conditions, but that under anaerobic conditions crop amendments can further reduce O_2 supply through enhanced heterotrophic microbial activity, resulting in further reduction of N_2O to N_2 by increased enzyme activity. This phenomenon was not detected in the present study as the activity of N_2O reductase was inhibited by the addition of acetylene. Nonetheless, under NT, anaerobic conditions are greater than under CT (Mummey et al., 1998), and findings by Chen et al. (2013) and Li et al. (2013) suggest that increased cropping intensity under NT will increase denitrification rates but under field conditions mitigate N_2O production.

Table 2.9 PNM, BDR, and PDR by treatment across five study sites*.

Site	Treatment†	PNM‡	BDR	PDR
		mg N kg^{-1} soil	ug N_20-N kg^{-1} soil hr^{-1} (0-4 hrs.)	
Kambitsch	WW/SB/SL - NT	99.0 (34)	1.41 (21)	39.4 b (39)
	WW/SB/SL - Till	78.3 (24)	1.91 (34)	86.7 a (18)
PCFS	WW/SL/SW - NT	101.5 (5)	1.69 (45)	69.4 b (62)
	WW/SB/SW - NT	91.5 (20)	4.64 (128)	85.0 b (38)
	Alf/SC/SL (organic) - NT	106.6 (40)	9.70 (103)	164.5 a (30)
	Perrenial Tall Wheat Grass	97.4 (21)	1.50 (36)	77.9 b (24)
	Native/CRP Grass	102.9 (13)	3.33 (68)	72.6 b (31)
Pendleton	WW/ NT Fallow - NT	53.9 a (7)	0.63 (44)	18.1 b (27)
	WW/Pea - NT	56.9 a (32)	0.97 (33)	32.8 a (18)
	WW/Fallow - Till	18.7 b (41)	0.87 (53)	9.2 c (15)
Moro	WW/WP - NT	73.9 a (16)	0.80 (20)	21.6 (44)
	WW/NT Fallow - NT	41.1 b (19)	0.81 (48)	14.6 (14)
	WW/SB/NT Fallow - NT	43.5 b (18)	0.64 (47)	15.2 (28)
	WW/Fallow - Till	41.6 b (30)	1.60 (65)	20.0 (15)
Prosser	WW/Sw. Cn./Potato - NT	83.6 (23)	34.6 (66)	256.5 (22)
	WW/Sw. Cn./Potato - Till	77.0 (20)	23.7 (119)	178.7 (22)

* Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

‡ PNM = potential nitrogen mineralization at 28 days; BDR = basal denitrification; PDR = potential denitrification.

Management and Nutrient Supply

PRS^{TM} - Probe NO_3^-, NH_4^+, S, and P

PRS^{TM}-probe 24-hour NO_3^- values ranged from 6.8 to 37.6 ug 10 cm^{-2} 24 hrs^{-1} (Table 2.10). Significant differences in NO_3^- were observed at Pendleton and Moro after 24 hours and at all but Prosser after 28 days (Tables 2.10 and 2.11). In comparison, Adewale (2013) notes that for a WW yield goal of 5360 kg ha^{-1}, Western Ag Innovations recommends fertilizer N applications of 139 kg N ha^{-1} for 24-hour adsorbed PRS^{TM}-probe N values of 10 ug N 10 cm^{-2} and as 24-hour PRS^{TM}-probe N values approach 70 kg N ha^{-1} N, fertilizer recommendations drop to 117 kg N ha^{-1}.

Significant differences at 24 hours were positively associated with cropping intensification at both Pendleton and Moro (Table 2.12). At Pendleton and Moro, cropping intensification under NT with a legume has resulted in a 78% and 245% increase, respectively, in available NO_3^- compared to WW/fallow NT (Table 2.10). This result may be reflective of optimal temperature and moisture conditions during incubation and reflects greater mineralization of SOM under incubation conditions associated with increased C and N inputs from plant residues under more intensely cropped rotations. Cropping intensification was consequently significantly correlated with 28-day NO_3^- at Pendleton and Moro (Table 2.12).

With the treatment comparisons in this study, it is not possible to deduce if this finding is the result of intensification specifically with a legume, or merely the result of intensification. However, results at PCFS are worth a closer look; the organic rotation with 2 legumes and spring wheat had significantly greater NO_3^- than other rotations, and yet a single season of a spring legume in rotation (WW/SL/SW) did not result in greater NO_3^- availability at 28 days

(Table 2.11). This set of data indicates that greater utilization of legumes in rotation infers greater NO_3^- availability under optimal conditions, though utilizing a legume one in three years either does not have a measurable impact or its influence is limited in time to the following crop year. This observation is consistent with greater buildup of PNM with greater utilization of legumes.

Similarly, Qian and Schoenau (1995) found that continuous alfalfa resulted in significantly greater PRS^{TM}-probe NO_3^- than a canola/lentil/barley rotation. It is also significant that at Kambitsch and Moro, comparing strictly tillage treatments without a cropping intensification gradient, CT is associated with 75% and 82% greater NO_3^- at 28 days, respectively, than NT at both Kambitsch and Moro (Table 2.11). Consequently, STIR is significantly correlated with 28-day NO_3^- at Kambitsch; however, at Moro, cropping intensity rather than STIR is the significant management variable at 28 days (Table 2.12).

This increase in NO_3^- under higher disturbance systems may be the result of three possible mechanisms. Tillage may have resulted in bringing up NO_3^- to surface soils that had leached beyond the sampling depth during wetter field conditions, increasing its concentration in samples collected under CT plots. This explanation is supported by the fact that total inorganic N present in the soils prior to initiating the incubation as determined from KCl extractions was also greater under CT than for NT at both Kambitsch and Moro (data not shown). In this scenario, under NT this NO_3^- not detected by PRS^{TM} probes would still be available to plant roots. Second, greater plant uptake of NO_3^- under NT may have occurred earlier in the season due to improved soil water conservation under NT compared to CT, and resulted in less NO_3^- detected under NT at time of sampling when conditions were drier. Last,

surface placement of crop residues under NT may have resulted in N immobilization. This would subsequently reduce net N mineralization and the availability of NO_3^- present in the soil during sampling (Jowkin and Schoenau, 1998).

Jowkin and Schoenau (1998) conducted an in-field evaluation of NO_3^- supply using PRS^{TM} probes under CT and NT systems, and concluded that there were limited differences in NO_3^- availability between the two systems, determining that landscape position had a greater influence on NO_3^- than tillage, presumably resulting from moisture and SOM variability across different landscape positions. Furthermore, Hangs et al. (2013) found that fertilizer application was more important than time under NT in influencing PRS^{TM} cumulative NO_3^- after a six-week incubation. Walley et al. (2002) found NO_3^- adsorbed to PRS^{TM} probes after two-week incubations was significantly correlated with both wheat yield and plant N accumulation. Ultimately, while the influence of tillage on NO_3^- availability may be minimal compared to other considerations, this plant N accumulation represents SON available for mineralization the following season with the return of biomass to the soil and embodies the value of cropping intensification in increasing plant N availability.

Across the study area, available NH_4^+ is present in soils in much lower quantities than NO_3^- (Tables 2.10 and 2.11), reflecting favorable conditions for nitrification. The relative increases in NH_4^+ across the incubation period were also less than that observed for NO_3^-. No significant differences were detected in NH_4^+ at 24 hours, while at 28 days only at PCFS (Table 2.11), where WW/SB/SW NT was not significantly different than the organic rotation but was 52% greater than WW/SL/SW NT; this difference at PCFS was not significantly correlated with STIR or cropping intensity (Table 2.12).

S availability at 24 hours ranged from 2.51 µg S 10 cm^{-2} under WW/fallow CT at Moro to 9.66 µg S 10 cm^{-2} under WW/Sw. Corn/Potato at Prosser (Table 2.10). At 28 days, S availability ranged from 13.5 µg S 10 cm^{-2} under CRP at PCFS to 40.1 µg S 10 cm^{-2} under WW/fallow CT at Pendleton (Table 2.11). Western Ag Innovations provide fertilizer recommendations for 24-hour S values below 66 ug 10 cm^{-2} 24 hrs^{-1} (Adewale, 2013). Considering that 28-day S availability is below this level, significant differences between treatments at the low values observed in this study are likely to be trivial with regard to plant S requirements. Nonetheless, the CVs for 24-hour S availability were generally less than CVs for 28-day S availability; consequently, significant differences in S were more evident at 24 hours than with 28 days (Tables 2.10 and 2.11).

The 24-hour S data are negatively correlated with cropping intensity at PCFS (r = -0.47) and Pendleton (r = -0.65) and negatively correlated with STIR at Moro (r = -0.54) (Table 2.12). At Moro, NT has 134% greater S availability than CT within WW/fallow (Table 2.10). At Pendleton, 1 year of cropping intensification with winter pea under NT has resulted in 23% less S than WW/fallow NT, while there was no difference in S availability associated with tillage (Table 2.10). At PCFS, annual cropping under NT with a legume in rotation represented by WW/SL/SB NT had greater 24-hour S availability than perennial systems but not the other annual systems. Conversely, Hangs et al. (2013) found that S supplied by a perennial native system was greater than for NT systems, even though the NT systems had significantly greater extractable S, suggesting the importance of S mineralization from organic S sources. At PCFS, this may be the result of fertilization of the annual plots resulting in greater biomass

production, and subsequently greater organic S available for mineralization in surface soils under annual cropping systems.

Pendleton is the only site at 28 days with significant differences in S availability, with CT resulting in greater S availability than NT (Table 2.11). Subsequently, as with NO_3^-, this trend in S at Pendleton, where CT plots are moldboard plowed, may be the result of tillage bringing inorganic S to surface soils that had previously leached and exists beyond the sample depth for NT plots. Franzluebbers and Hons (1996) found SO_4^- to increase with depth as a result of leaching and found little difference between S availability resulting from management practices. Grant et al. (2003) found no significant influence of tillage on PRS^{TM}-probe S for two-week in-field incubations, but found that PRS^{TM}-probe S values during this incubation were sensitive to S fertilization type and season of application. This result supports that tillage has a minimal impact on S availability, and that other management factors are more important in dictating plant available S.

After 24 hours of incubation, P availability ranged from 0.50 µg P 10 cm^{-2} under WW/Sw. Corn/Potato CT at Prosser to 2.04 µg P 10 cm^{-2} under WW/SB/fallow NT at Moro (Table 2.10). At 28 days, P availability ranged from 1.60 µg P 10 cm^{-2} under WW/Sw. Corn/Potato CT at Prosser to 9.73 µg P 10 cm^{-2} under WW/SB/fallow NT at Moro (Table 2.11). As with S availability, Western Ag Innovations' PRS^{TM}-probe 24-hour P value below which fertilizer P is recommended, approximately 21.0 µg 10 cm^{-2} (Adewale, 2013), far exceeds both 24-hour and 28-day available P in this study. Fewer significant differences were observed in P availability than any of the other macronutrients, and significant differences were detected only at 24 hours for Prosser and no differences detected at 28 days (Tables 2.10 and 2.11). This lack of

significant differences is possibly reflective of the many factors influencing P availability, which is ultimately dictated by the flux of labile P into both solution P and non-labile P, also referred to as a soils P buffering capacity (Havlin et al., 1999). Many studies have found significant differences in extractable P of surface soils associated with tillage (Robbins and Voss, 1991; Unger 1991; Franzluebbers and Hons, 1996). However, considering the multiple factors influencing P availability, P adsorbed to exchange resins is more reflective of plant available P than extractions (Sharpley et al., 1994).

Neither STIR nor cropping intensity was significantly correlated with 24-hour and 28-day P at any of the sites (Table 2.12); when analyzed across sites, however, 24-hour P demonstrates a significant negative correlation with STIR (data not shown). This is indicative of the in-situ cumulative effect of reduced turnover of organic P associated with increasing tillage intensity. This result is supported by observations that phosphatase, associated with microbial utilization of organic P, increases under NT (Wang et al., 2011; Wei et al., 2014). It may also be the result of surface placement of residues and fertilizer associated with NT, resulting in redistribution of P compared to tilled systems. Franzluebbers and Hons (1996) found similar results in surface soils for extracted P when comparing NT and CT and cited several others who have found similar results in silt loam soils. Arcand et al. (2010) examined P turnover and availability using PRS^{TM} probes as influenced by buckwheat and rock phosphate and found that P concentration in residue was more important in determining P availability than total P supplied through residues, indicative of microbial P immobilization resulting from poor residue quality with a high C/P ratio. Therefore, NT along with cropping practices that decrease residue C/P ratios appears to have the greatest potential for increasing plant available P.

Additionally, greater anion availability resulting from mineralization can also help to increase P availability by competing with inorganic P for adsorption sites on clay or organic matter (Berg and Joern, 2006). This possibility is reflected in results from the present study, in which a significant negative correlation exists between P and NO_3^- availability (Table 2.5). Both are released through mineralization, but the negative correlation indicates that P availability is at the expense of NO_3^- availability, suggesting a similar competition for exchange sites between anions in the present study as described, by Berg and Joern (2006).

PRS^{TM} - Probe K, Ca, and Mg

At 24 hours, K availability ranged from 66.7 µg K 10 cm^{-2} under WW/Sw. Corn/Potato at Prosser to 317.7 µg K 10 cm^{-2} under WW/fallow NT at Pendleton (Table 2.11). Western Ag Innovations recommends fertilizer application of K for 24-hour PRS^{TM}-probe K values below approximately 171 ug cm^{-2} (Adewale, 2013). For all sites but Kambitsch, Prosser, and Pendleton's WW-fallow CT plot, K adsorbed at 24 hours exceeded this cutoff. At Prosser, the lower values may be the result of greater sand content compared to the other sites, as K leaching losses can be high in sandy soils (Noorbakhsh et al., 2008). At Kambitsch, lower 24-hour K values may be the result of higher Ca availability compared to other sites (Table 2.10), as Ca activity is known to have an inhibitory effect on K availability (Havlin et al., 1999). Significant differences in K availability occurred only at Pendleton after 24 hours and at Pendleton and Moro after 28 days (Tables 2.11 and 2.12). An increase in STIR at Pendleton is associated with a 105% and 77% decline in 24-hour and 28-day K availability, respectively. STIR is subsequently negatively correlated with K availability at both time periods (Table 2.13). At Moro, NT without cropping intensification did not result in significantly greater K at 28 days; annual cropping

represented by WW/WP NT did, however, result in 29% greater K availability than WW/fallow CT (Table 2.12). In evaluating the nutrient supplying power of NT cropland compared to native prairie, Hangs et al. (2013) found no difference in PRS^{TM}-probe K availability at 24 hours and 6 weeks between 10 years of NT and 32 years of NT; however, 32 years of NT without fertilization had the same K supplying power of native prairie, while 10 years of NT required fertilization to match the native prairie in K supplying power. This suggests that K supplying power is improved with longer duration under NT and is in agreement with results in this study, where significantly greater K availability under NT compared to CT was observed at Pendleton, the site with the longest history under NT (Table 2.1).

Calcium and Mg behaved similarly, exhibiting a significant correlation at 28 days (r = 0.67) (Table 2.5). In spite of this correlation, significant differences associated with treatments varied between these nutrients at both time periods (Tables 2.11 and 2.12). At 24 hours, significant differences in Ca associated with management occurred only at Moro, and for Mg at Moro, Pendleton, and PCFS. Annual cropping at Moro under NT is associated with significantly greater Ca and Mg than the other treatments at 24 hours (Table 2.10), and cropping intensity was significantly correlated with these differences (Table 2.12). At Pendleton and PCFS, STIR was significantly correlated with the variation in Mg; however, the relationship was positive at PCFS and negative at Pendleton (Table 2.12). This difference may be the result of greater Mg associated with the organic Alfalfa/cereal/SL rotation at PCFS, which also has a greater STIR. Differences after 28 days were greater in Ca than after 24 hours, while they were fewer in Mg. At Moro, cropping intensity remains significant in explaining the differences in Ca at 28 days,

while at Kambitsch and Pendleton an increase in STIR is associated with an increase in Ca availability (Tables 2.12).

Incidentally, at both Kambitsch and Pendleton, soil pH is significantly more acidic under NT compared to tilled plots. An increase in Ca solubility under a decrease in pH associated with NT at these sites may have resulted in enhanced Ca leaching losses, while tillage would mix a portion of leached Ca back into the surface and contribute to greater Ca under CT plots. A dearth of information in the literature on Ca and Mg measured with PRS™ probes under various management systems prevents comparison of results in this study to other studies; however, results suggest that an increase in cropping intensity can have a measureable impact on Ca and Mg, as indicated by results from Moro, while NT is associated with less Ca availability, as indicated by results from Kambitsch, Pendleton, and Moro.

PRS™ - Probe Micronutrients

Micronutrients showed sensitivity to both STIR and cropping intensity across the sites (Table 2.13). Within each site, no significant differences were observed in Zn at either time period, while differences in B were observed only at PCFS for both time periods (Tables 2.10 and 2.11). Both Zn and Cu at 24 hours were below the detection limit for PRS™ probes across all sites and may indicate a deficiency in these micronutrients in the region. At PCFS, the significant difference in B at 24 hours is negatively associated with STIR ($r = -0.50$); the perennial systems at PCFS are low disturbance and generally have higher B availability than the annual cropping systems. At Kambitsch, Fe, Mn, and Cu at 28 days were 89%, 135%, and 84% greater, respectively, under CT plots than NT, and STIR is significant in explaining this difference (Tables 2.12 and 2.14). At Moro, these micronutrients, Fe, Mn, and Cu, were also 73%, 71%, and 43%

greater, respectively, in CT compared to NT at 28 days (Table 2.11). Cropping intensification with WP under NT at Moro, however, resulted in 87% greater Mn and 35% greater Cu than CT with fallow (Table 2.11), and cropping intensification was subsequently significantly correlated with Fe (r = 0.74) and Mn (r = 0.90) at Moro (Table 2.13). At Pendleton, 28-day Cu was also 114% greater under CT than NT, while there was no significant difference between CT and NT for Fe and Mn (Table 2.11). As with Moro, an increase in cropping intensity with WP at Pendleton under NT was associated with a 60% increase in Fe above CT with fallow, while for Cu this increase in cropping intensification under NT increased Cu 86% compared to NT with fallow and resulted in no significant difference between CT and NT (Table 2.12). Hangs et al. (2013) found an increase in availability of Fe under 32 years of NT compared to 10 years of NT, suggesting that NT improves Fe availability.

Results in the present study suggest cropping intensification under NT is essential to maintaining micronutrient levels of Fe, Cu and Mn at comparable levels detected under CT. McLaren and Turkington (2010) noted that certain legumes in rotation increase Fe availability through citrate exudates, which enhances mobilization of Fe. Return of legume biomass to the soil may subsequently enhance Fe availability for rotational crops. A lack of information on PRS^{TM}-probe micronutrients under different agricultural systems in the literature prevents further comparison of results in the present study with other findings.

Table 2.10 PRS™ - probe nutrients at 24 hours across five study sites*.

Site	Treatment†	NO_3-N	NH_4-N	P	S	Ca	Mg	K	Fe	Mn	Cu	Zn	B
		μg 10 cm^{-2} 24 hrs^{-1}											
Kambitsch	WW/SB/SL - NT	22.7 (62)	2.90 (68)	0.85 (15)	9.64 (65)	566.2 (9)	106.9 (18)	125.2 (42)	1.58 (20)	0.95 (41)	0.24ŧ (23)	0.19ŧ (23)	1.48 (4)
	WW/SB/SL - Till	34.5 (43)	3.15 (59)	0.59 (33)	6.51 (20)	544.6 (10)	99.2 (13)	90.3 (21)	1.78 (38)	1.01 (121)	0.31ŧ (47)	0.23ŧ (96)	1.31 (51)
PCFS	WW/SL/SW - NT	37.8 (49)	2.07 (20)	1.48 (23)	6.87 a (52)	294.1 (21)	54.8 b (7)	209.2 (16)	1.93 ab (13)	5.56 b (45)	0.21ŧ (14)	0.25ŧ (26)	1.13 ab (16)
	WW/SB/SW - NT	29.9 (56)	2.53 (76)	1.35 (91)	5.06 ab (54)	308.7 (12)	66.6 ab (24)	179.3 (70)	2.80 a (62)	11.5 a (69)	0.28ŧ (33)	0.19ŧ (20)	1.15 ab (24)
	Alfalfa/cereal/SL (organic) - NT	24.9 (32)	1.85 (90)	1.53 (72)	4.05 ab (39)	432.8 (39)	109.6 a (58)	229.1 (85)	1.58 b (6)	1.03 b (62)	0.23ŧ (31)	0.25ŧ (71)	0.74 b (10)
	Perennial Tall Wheat Grass	16.7 (36)	1.18 (50)	1.41 (7)	3.38 b (13)	335.2 (29)	64.3 ab (34)	250.2 (30)	2.05 ab (16)	1.72 b (47)	0.20ŧ (10)	0.24ŧ (44)	1.55 a (40)
	Native/CRP Grass	12.2 (32)	0.89 (79)	1.48 (62)	3.07 b (22)	350.1 (16)	82.5 ab (21)	206.9 (73)	1.51 b (16)	0.60 b (17)	0.22ŧ (57)	0.19ŧ (20)	1.1 ab (52)
Pendleton	WW/ NT Fallow - NT	17.9 a (45)	1.74 (72)	1.11 (26)	6.20 a (22)	365.6 (23)	104.3 ab (20)	317.7 a (22)	1.66 (33)	0.63 a (27)	0.20ŧ (34)	0.28ŧ (77)	0.98 (36)
	WW/Pea - NT	23.9 a (33)	1.40 (89)	0.92 (36)	4.75 b (13)	385.3 (10)	113.2 a (11)	297.6 a (11)	1.82 (21)	0.55 a (42)	0.24ŧ (56)	0.27ŧ (67)	1.24 (28)
	WW/Fallow - Till	12.7 b (56)	2.37 (53)	0.71 (69)	6.49 a (14)	331.2 (13)	89.4 b (11)	154.6 b (12)	1.49 (10)	0.23ŧ b (43)	0.26ŧ (27)	0.26ŧ (34)	0.98 (26)
Moro	WW/WP - NT	23.4 a (12)	1.65 (95)	1.93 (15)	5.29 ab (23)	238.2 a (17)	79.6 a (26)	284.9 (27)	1.40 (4)	0.54ŧ (96)	0.21ŧ (31)	0.17ŧ (47)	0.88 (18)
	WW/NT Fallow - NT	4.17 b (90)	2.91 (75)	1.60 (25)	5.87 a (54)	134.9 c (28)	44.8 b (37)	185.3 (35)	1.65 (9)	0.15ŧ (1)	0.19ŧ (16)	0.37 (30)	1.16 (31)
	WW/SB/fallow - NT	4.43 b (81)	2.44 (10)	2.04 (13)	3.98 ab (45)	175.6 bc (3)	58.6 ab (14)	216.4 (25)	1.51 (31)	0.18ŧ (50)	0.20ŧ (17)	0.31 (41)	1.07 (5)
	WW/Fallow - Till	6.60 b (63)	2.09 (13)	1.33 (69)	2.51 b (22)	178 b (5)	54.5 b (25)	200.8 (45)	1.51 (24)	0.25ŧ (138)	0.18ŧ (39)	0.18ŧ (85)	1.16 (31)
Prosser	WW/Sw. Corn/Potato - NT	20.6 (35)	0.87 (56)	0.69 a (20)	9.66 (102)	240.1 (19)	75.3 (25)	105.0 (33)	1.62 (8)	0.97 (123)	0.27ŧ (33)	0.23ŧ (32)	0.98 (29)
	WW/Sw. Corn/Potato - Till	15.3 (59)	1.72 (95)	0.50 b (28)	2.67 (42)	183.5 (22)	57.0 (28)	66.7 (45)	1.61 (8)	0.43 (48)	0.26ŧ (10)	0.19ŧ (20)	1.04 (43)

* Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

ŧ Nutrient level below detection limit.

Table 2.11 PRS™ - probe nutrients at 28 days across five study sites*.

Site	Treatment†	NO_3-N	NH_4-N	P	S	Ca	Mg	K	Fe	Mn	Cu	Zn	B
		μg 10 cm^{-2} 28 $days^{-1}$											
Kambitsch	WW/SB/SL - NT	268.8 b (40)	10.1 (29)	2.52 (19)	25.4 (31)	2227 a (11)	386.8 (18)	394.9 (44)	13.2 b (36)	9.66 b (43)	1.15 b (35)	1.15 (107)	2.92 (13)
	WW/SB/SL - Till	469.3 a (25)	10.5 (34)	2.31 (21)	25.7 (23)	2813 b (12)	450.5 (19)	327.3 (21)	24.9 a (41)	22.7 a (52)	2.12 a (31)	1.11 (78)	2.69 (26)
PCFS	WW/SL/SW - NT	203.4 c (22)	6.97 b (6)	3.85 (9)	22.2 (31)	995.4 b (6)	174.9 b (5)	693.4 (19)	12.9 b (51)	24.7 b (51)	0.68 b (26)	0.73 (30)	2.17 bc (23)
	WW/SB/SW - NT	322.4 ab (62)	10.6 a (21)	4.83 (55)	20.3 (43)	1378 ab (32)	299.7 ab (53)	575.5 (72)	20.1 ab (51)	72.8 a (60)	0.99 b (33)	0.84 (18)	2.25 abc (12)
	Alfalfa/cereal/SL (organic) - NT	393.1 a (17)	8.54 ab (8)	5.37 (55)	20.5 (22)	1812 a (35)	436.9 a (46)	823.5 (91)	26.1 a (24)	16.3 b (27)	1.97 a (57)	1.03 (56)	1.68 c (34)
	Perennial Tall Wheat Grass	263.7 bc (45)	7.42 b (6)	5.02 (48)	13.6 (45)	1195 ab (21)	219.8 ab (8)	765.6 (42)	12.0 b (28)	10.1 b (14)	0.77 b (33)	0.68 (31)	2.91 a (21)
	Native/CRP Grass	240.4 bc (21)	7.07 b (36)	6.25 (87)	13.5 (66)	1510 ab (35)	332.4 ab (43)	713.6 (75)	10.6 b (37)	5.98 b (58)	0.81 b (33)	0.88 (58)	2.42 ab (30)
Pendleton	WW/ NT Fallow - NT	251.1 b (32)	8.04 (9)	3.56 (18)	29.9 b (16)	1569 b (18)	425.6 (17)	1138 a (15)	17.9 b (22)	9.69 (40)	0.99 b (18)	0.70 (32)	2.48 (16)
	WW/Pea - NT	447.5 a (8)	7.88 (8)	3.57 (44)	31.1 b (38)	1779 ab (22)	457.7 (18)	1011 b (6)	30.5 a (39)	20.0 (71)	1.84 a (29)	0.78 (19)	2.25 (23)
	WW/Fallow - Till	235.2 b (24)	9.12 (13)	3.09 (30)	47.1 a (20)	2076 a (20)	512.3 (17)	643.4 c (9)	19.1 b (22)	9.62 (7)	2.12 a (33)	0.77 (13)	3.07 (36)
Moro	WW/WP - NT	500.8 a (3)	9.05 (28)	6.67 (34)	30.5 (40)	1319 a (14)	431.3 (18)	1218 a (6)	32.9 a (24)	17.5 a (7)	1.85 a (1)	1.00 (22)	2.15 (22)
	WW/NT Fallow - NT	145.2 c (31)	8.37 (30)	7.55 (26)	26.1 (29)	979.0 b (10)	333.8 (8)	1046 ab (22)	13.6 c (36)	5.48 c (48)	0.96 c (10)	0.98 (28)	2.28 (2)
	WW/SB/fallow - NT	146.2 c (42)	10.1 (24)	9.73 (29)	26.1 (32)	1107 ab (24)	393.5 (27)	1071 ab (13)	14.6 bc (17)	5.57 c (50)	1.03 c (18)	0.99 (22)	2.12 (10)
	WW/Fallow - Till	264.8 b (21)	8.3 (16)	6.89 (41)	18.4 (43)	1083 ab (14)	357.1 (12)	942.8 b (21)	23.5 ab (34)	9.36 b (13)	1.37 b (33)	0.86 (32)	2.33 (34)
Prosser	WW/Sw. Corn/Potato - NT	307.3 (19)	7.40 (13)	1.81 (22)	24.5 (34)	1156 (6)	368.5 (18)	414.7 (26)	23.9 (30)	8.57 (32)	1.84 (22)	1.15 (23)	2.36 (23)
	WW/Sw. Corn/Potato - Till	320.6 (43)	7.91 (16)	1.60 (24)	16.0 (21)	1230 (11)	409.3 (4)	314.1 (29)	25.5 (34)	7.69 (49)	1.71 (26)	1.03 (18)	2.20 (18)

* Significant differences within sites indicated by different letters (significance at $p < 0.10$). Values in parenthesis are coefficient of variation.

† WW = Winter Wheat; SB = Spring Barley; SL = Spring Legume; SC = Spring Cereal; Alf = Alfalfa; CRP = Conservation Reserve Program; Sw. Cn. = Sweet Corn; NT = no-till.

Table 2.12 Pearson correlation between PRS™ - probe macronutrients and management factors across five study sites*.

		NO_3-N		NH_4-N		P		S		Ca		Mg		K	
Site	Management†	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days
Kambitsch	STIR	ns	0.72	ns	ns	ns	ns	ns	ns	ns	0.75	ns	ns	ns	ns
	Intensity	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PCFS	STIR	ns	0.48	ns	ns	ns	ns	ns	ns	ns	ns	0.45	0.46	ns	ns
	Intensity	ns	ns	ns	ns	ns	ns	-0.47	-0.52	ns	ns	ns	ns	ns	ns
Pendleton	STIR	ns	ns	ns	0.56	ns	ns	ns	0.70	ns	0.52	-0.52	ns	-0.88	-0.90
	Intensity	0.51	0.87	ns	ns	ns	ns	-0.65	ns	ns	ns	ns	ns	ns	ns
Moro	STIR	ns	ns	ns	ns	ns	ns	-0.54	ns	ns	ns	ns	ns	ns	ns
	Intensity	0.93	0.92	ns	ns	ns	ns	ns	ns	0.74	0.58	0.64	ns	0.51	ns
Prosser	STIR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Intensity	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† STIR = soil tillage intensity rating; Intensity = cropping intensity.

Table 2.13 Pearson correlation between PRS™ - probe micronutrients and management factors across five study sites*.

		Fe		Mn		Cu		Zn		B	
Site	Management†	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days	24-hrs.	28 days
Kambitsch	STIR	ns	0.65	ns	0.65	ns	0.72	ns	ns	ns	ns
	Intensity	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PCFS	STIR	ns	0.68	ns	ns	ns	0.69	ns	ns	-0.50	-0.57
	Intensity	ns	-0.50	-0.49	-0.46	ns	ns	ns	ns	ns	0.50
Pendleton	STIR	ns	ns	-0.79	ns	ns	0.58	ns	ns	ns	ns
	Intensity	ns	0.65	ns	0.55	ns	ns	ns	ns	ns	ns
Moro	STIR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Intensity	ns	0.74	0.50	0.90	ns	0.86	ns	ns	ns	ns
Prosser	STIR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Intensity	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

* Correlations significant at $p < 0.10$. ns = not significant ($p > 0.10$).

† STIR = soil tillage intensity rating; Intensity = cropping intensity.

Multivariate Analysis for Improved Prediction

Soil properties along with the climate and management factors included in this study were combined in a multivariate stepwise regression to attempt to improve on single variable correlations and identify the best set of variables across the inland PNW for predicting PNM, BDR, PDR, and total N at 28 days adsorbed to a PRS^{TM} probe (Tables 2.14, 2.15 and 2.16). These models are purely empirical and are not necessarily representative across a broad range of conditions but attempt to represent the value of multiple variables combined into indices in predicting these soil processes.

Potential N Mineralization

The model with the highest predictability of PNM, explaining 81% of PNM variation, included total N, WEOC, and MAT (Table 2.14). The value of a predictable index lies not only in its predictive capabilities, but also in the accessibility of the parameters. In acknowledgement of this, a model was run with a reduced soil property data set along with climate and management factors. The reduced data set included POXC, one-day Cmin, and total N adsorbed to a PRS^{TM} probe at 24 hours, all soil properties that are easily measured with commercialized field tests. However, the predictability of this model did not represent a significant improvement on the use of only climate and management factors (Table 2.14). In comparison, Schomberg et al. (2009) were able to predict 85% of the variability in a 41-week PNM incubation with total N and Cmin at 3 days. Schomberg and coworkers (2009) also reported that PNM from a 7-day anaerobic incubation was significantly correlated with PNM from the 41-week incubation ($r^2 = 0.63$).

Potential and Basal Denitrification

The model which best explained variability in PDR (r^2 = 0.64) consisted of soil properties with MAT, while a reduced dataset of soil properties along with climate and management factors performed no better than just climate factors (r^2 = 0.48) (Table 2.15). MAT was consistently the best significant variable in explaining variation in BDR, and when MAT was removed from the model, total inorganic N was the best explanatory variable (Table 2.15). The greater predictability of PDR over BDR is in keeping with the higher correlation of soil properties, management variables, and climate factors with PDR compared to BDR.

PRS™ - Probe Total N at 28 Days

A combination of management factors and soil properties, including STIR, cropping intensity, 24-hour PRS™ total N, and total inorganic N, explained 62% of the observed variation in 28-day total PRS™ total N (Table 2.16). A model with easily measured soil properties performed similarly, with 24-hour PRS™ total N, soil pH, STIR, and cropping intensity explaining 60% of the variation in 28-day total PRS™ total N. Considering that several studies have conveyed that total N adsorbed to PRS™ probes is indicative of plant N uptake (Walley et al., 2002; Nyiraneza et al., 2009), results from this study indicate that a significant portion of plant N uptake can be explained by management factors and easily measured soil properties.

Table 2.14 Multivariate regression analysis of PNM with climate, management, and soil properties across four dryland sites*.

Model	Entered Into Model†	Variables Selected	Parameter Estimate	Pr > F	Model R^2
1) Management, Climate Factors, Soil Properties	SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}, STIR, Intensity, pH, MAT, MAP	Total N	0.025	0.0018	0.79
		WEOC	0.288	0.003	
		MAT	-0.015	0.0006	
		Intensity	0.033	0.014	
2) Climate Factors, Management	MAT, MAP, STIR, Intensity, pH	MAT	-0.017	0.0007	0.70
		MAP	0.00008	0.0028	
		Intensity	0.032	0.07	
		STIR	-0.00028	0.007	
3) Management, Soil Properties	STIR, Intensity, pH, SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}	Total N	0.044	<0.0001	0.77
		WEOC	0.256	0.01	
		Intensity	0.033	0.036	
4) Climate Factors, Soil Properties	MAT, MAP, SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}, pH	Total N	0.028	0.0005	0.81
		WEOC	0.338	0.003	
		MAT	-0.015	0.006	
5) Management, Climate Factors, Reduced Soil Properties	POXC, $Cmin_{0\text{-}1d}$, TN_{IEM}, STIR, Intensity, pH, MAT, MAP	MAT	-0.0183	0.0002	0.71
		Intensity	0.041	0.02	
		POXC	0.143	0.0002	

* Model entry and selection set at $p < 0.10$ (Prosser excluded from analysis).

† PNM = potential nitrogen mineralization; SOC = soil organic carbon; POXC = permanganate oxidizable carbon; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; $Cmin_{0\text{-}1d}$ = carbon mineralized at 1day; TN_{IN} = total inorganic N from KCL extraction; TN_{IEM} = total PRS™ N at 24 hours; pH = soil pH from 1:1 water extract; STIR = soil tillage intensity rating; intensity = cropping intensity; pH = soil pH from 1:1 water extract. MAP = mean annual precipitation; MAT = mean annual temperature.

Table 2.15 Multivariate regression analysis of PDR and BDR with climate, management, and soil properties across four dryland sites*.

Model	Entered Into Model†	Dependent Variable	Variables Selected	Parameter Estimate	Pr > F	Model R^2
1) Management, Soil Properties, Climate Factors	SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN},TN_{IEM}, STIR, Intensity, pH, MAT, MAP	PDR	Total N	0.119	0.0001	0.64
			POXC	-0.435	0.02	
			$Cmin_{0\text{-}1d}$	0.605	0.053	
			MAT	-0.018	0.03	
		BDR	MAT	-0.0015	0.019	0.12
2) Climate Factors, Management	Temperature, Precipitation, STIR, Intensity, pH	PDR	MAT	-0.029	<0.0005	0.48
			MAP	-0.00009	0.066	
		BDR	Identical to Model 1			
3) Management, Soil Properties	STIR, Intensity, pH, SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}	PDR	Total N	0.144	<0.0001	0.59
			POXC	-0.454	0.004	
			$Cmin_{0\text{-}1d}$	0.546	0.09	
		BDR	TN_{IN}	0.0001	0.035	0.10
4) Climate Factors, Soil Properties	MAT, MAP, pH, SOC, Total N, POXC, WEOC, WEON, MBC, MBN, TN_{IN}, TN_{IEM}	PDR	Identical to Model 1			
		BDR	Identical to Model 1			
5) Management, Climate Factors, Reduced Soil Properties	STIR, Intensity, MAP, MAT, pH, POXC, $Cmin_{0\text{-}1d}$, TN_{IEM}	PDR	Identical to model 2			
		BDR	Identical to Model 1			

* Model entry and selection set at $p < 0.10$ (Prosser excluded from analysis).

† PDR = potential denitrification; BDR = basal denitrification; SOC = soil organic carbon; POXC = permanganate oxidizable carbon; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; $Cmin_{0\text{-}1d}$ = carbon mineralized at 1day; TN_{IN} = total inorganic N from KCL extraction; TN_{IEM} = total PRS™ N at 24 hours; pH = soil pH from 1:1 water extract; STIR = soil tillage intensity rating; intensity = cropping intensity; pH = soil pH from 1:1 water extract. MAP = mean annual precipitation; MAT = mean annual temperature.

Table 2.16 Multivariate regression analysis of 28-day PRS™ - probe total N with climate, management, and soil properties across four dryland sites*.

Model	Entered Into Model†	Variables Selected	Parameter Estimate	Pr > F	Model R^2
1) Management, Climate Factors, Soil Properties	SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}, STIR, Intensity, pH, MAT, MAP	TN_{IEM}	9.29	<0.0001	0.62
		TN_{IN}	-5.66	0.01	
		STIR	1.24	0.0009	
		Intensity	359.7	<0.0001	
2) Climate Factors, Management	MAT, MAP, STIR, Intensity, pH	STIR	1.68	0.0015	0.29
		Intensity	326.4	0.0026	
		pH	-0.0001	0.037	
3) Management, Soil Properties	STIR, Intensity, pH, SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}	Same as Model 1			
4) Climate Factors, Soil Properties	MAT, MAP, SOC, Total N, POXC, WEOC, WEON, MBC, MBN, $Cmin_{0\text{-}1d}$, TN_{IN}, TN_{IEM}, pH	TN_{IEM}	7.48	<0.0001	0.44
		Total N	-68.4	0.036	
5) Management, Climate Factors, Reduced Soil Properties	POXC, $Cmin_{0\text{-}1d}$, TN_{IEM}, STIR, Intensity, pH, MAT, MAP	TN_{IEM}	7.53	<0.0001	0.60
		pH	0.00012	0.05	
		STIR	0.94	0.02	
		Intensity	352.3	<0.0001	

* Model entry and selection set at $p < 0.10$ (Prosser excluded from analysis).

† PDR = potential denitrification; BDR = basal denitrification; SOC = soil organic carbon; POXC = permanganate oxidizable carbon; WEOC = water extractable organic carbon; WEON = water extractable organic nitrogen; MBC = microbial biomass carbon; MBN = microbial biomass nitrogen; $Cmin_{0\text{-}1d}$ = carbon mineralized at 1 day; TN_{IN} = total inorganic N from KCL extraction; TN_{IEM} = total PRS™ N at 24 hours; pH = soil pH from 1:1 water extract; STIR = soil tillage intensity rating; intensity = cropping intensity; pH = soil pH from 1:1 water extract. MAP = mean annual precipitation; MAT = mean annual temperature.

SUMMARY AND CONCLUSIONS

An increase in soil C and N properties is associated with an increase in PNM across the study area. The soil NHC/NHN ratio was the only soil C/N ratios of the various fractions measured in the study that was correlated with PNM. Cmin values were significantly correlated with PNM, and the correlation coefficients observed in this study were less than reported in some studies, while more in line with others. The anaerobic nature of the PNM incubation and the various rates of gross immobilization resulting from varying C/N ratios of crop residues were thought to explain the lower correlations between PNM and Cmin observed in this study. Across the four dryland sites, MAP is associated with an increase in PNM, while an increase in MAT is associated with a decrease in PNM. Both tillage and cropping intensification also have significantly impacted PNM. At Pendleton, the influence of tillage was most notable, where NT plots had significantly greater PNM than till pots. At Moro, cropping intensity significantly influenced PNM, where annual cropping with a legume in rotation resulted in greater PNM than other NT rotations at Moro with a fallow year.

A multivariate analysis of PNM with soil properties, climate variables, and management factors indicated that easily measured POXC along with cropping intensity and MAT explain 71% of observed PNM variation. A combination of total N, WEOC, and MAT, however, explained 81% of the overall variation in PNM across the four dryland sites in the study area and represents an improvement in single factor prediction of PNM.

An increase in PNM is associated with an increase in PDR ($r = 0.69$), while PNM and BDR were not significantly related. BDR had greater CVs than PDR and multiple soil C and N properties exhibited a higher degree of correlation with PDR than with BDR. Across the four

dryland sites, MAT was significantly related to both BDR (r = -0.34) and PDR (r = -0.66), while only MAP was significantly related to PDR (r = 0.55). BDR did not differ significantly between treatments, while PDR was significantly greater for crop rotations with a legume comprising at least half of the rotation. The influence of STIR on PDR was not consistent across sites, and this was tied to variable soil C and N properties across sites with regard to STIR, particularly WEOC and MBC.

Considered in combination with the literature, results in the present study support that an increase in cropping intensity is associated with an increase in denitrification; as indicated in the literature, however, cropping intensification under NT can also enhance the activity of N_2O reductase by reducing O_2 availability and mitigate N_2O emissions resulting from denitrification. Therefore, while increasing cropping intensity increases both PNM and PDR, it also has the potential to reduce N_2O emissions within NT. In a multivariate analysis, the factors which best explain variation in PDR across the region include total N, POXC, one-day Cmin, and MAT (r^2 = 0.64), while a combination of factors did not improve the prediction of BDR beyond only MAT (r^2 = 0.12).

Initial extractable inorganic N was an important source of plant available N, indicated by its significant correlation with 24-hour (r = 0.83) and 28-day PRS^{TM}-probe NO_3^- (r = 0.42). Cropping intensification, however, also had a measurable positive impact on NO_3^- availability at both 24 hours and 28 days, and is representative of mineralization of SOM as an important source of plant available N. Greater NO_3^- availability was also associated with an increase in STIR, and this was attributed to either greater denitrification under NT earlier in the season under wetter conditions, greater plant N uptake under NT earlier in the season under improved

moisture conditions associated with NT, or mixing of leached NO_3^- back into surface soils associated with tillage. A multivariate analysis of 28-day PRS^{TM}-probe total N revealed a combination of 24-hour PRS^{TM}-probe total N, initial inorganic N, STIR, and cropping intensity explained 62% of the variation in 28-day total N across the four dryland sites in the study.

As with NO_3^-, leaching of S may also have contributed to greater S associated with an increase in STIR, where CT plots at Pendleton had greater 28-day S availability than NT plots. There were few observed differences in P availability and P variation was not significantly correlated with STIR or cropping intensity. Available P, however, and S displayed sensitivity to multiple soil C and N properties. After 28 days of incubation, P and S had a negative relationship with several soil C and N properties, indicating that under ideal conditions of enhanced microbial activity, gross immobilization of these macronutrients increases, and is possibly related to microbially mediated C/S and C/P ratios. Additionally, increased soil acidity associated with increased SOM would also limit P and S availability.

POXC was positively associated with Ca ($r = 0.32$), while multiple soil C and N properties exhibited a negative relationship with K and Mg. This was attributed to greater Ca activity inhibiting these other cations. Additionally, Ca and Mg were negatively associated with the water extractable portions of C and N, and considered indicative of the role of these nutrients in stabilization of SOM through cation bridging. At Kambitsch and Pendleton, an increase in STIR was associated with an increase in 28-day Ca availability. This greater Ca availability associated with CT was attributed to lower soil pH under NT, where increased Ca solubility under a decrease in pH may have resulted in enhanced Ca leaching, while tillage would result in mixing Ca back into the surface. Potassium exhibited a negative relationship with STIR and a

positive relationship with cropping intensity. An increase in MAP was associated with an increase in NO_3^- and Ca, while P and K were negatively associated with MAP. Sulfur, K, and Mg all increased across the study area as MAT increased.

Aside from Mn, micronutrients were poorly correlated with soil C and N properties and soil pH. The micronutrients Fe, Cu, and Mn increased with an increase in tillage intensity, as evidenced by 28-day results from Kambitsch, Pendleton, and Moro. Cropping intensification under NT, however, contributed to enhanced availability of these nutrients. Micronutrients displayed less sensitivity to MAP and MAT than macronutrients; however an increase in MAT is associated with an increase in Cu and Fe. Across the five sites, B and Zn at 24 hours adsorbed to PRS™ probes was below the detection limit, indicating the plant available levels of these micronutrients may be deficient within the study area.

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CHAPTER 4

SUMMARY AND CONCLUSIONS

Surface soils comprise a critical interface and have great potential to influence soil health through their influence on multiple soil processes and potential to mitigate soil erosion through proper management. The SOM status of these surface soils is of critical importance as SOM provides the energy source for microbes that in-turn drive soil processes such as nutrient mineralization and denitrification. SOM, however, is heterogeneous in nature and comprised of a continuum of C and N pools that necessitate multiple methodologies to capture and define various fractions of SOM which in-turn aid in a meaningful assessment of soil health.

In this study, the soil C and N properties of surface soils (0-10 cm) measured included SOC, total N, POXC, WEOC and WEON, and MBC and MBN, and provided the opportunity to assess the status of soil health within the inland PNW. Additionally, these soil C and N properties along with four soil processes - 1) C mineralization, 2) potential N mineralization, 3) potential and basal denitrification, and 4) nutrient supply rate – provided several important insights regarding soil health and the role of climate variables and management factors in influencing soil health.

Climate is the main driver of soil C and N properties within the inland PNW. An increase in MAP was associated with an increase in SOC and total N, while an increase in MAT was associated with a decrease in total N. Additionally, MAP explained 57% of SOC variability and 69% of total N variability across the four dryland sites comprising the study. When MAP was excluded from the analysis, MAT became the significant variable and explained 42% and 49%,

respectively, of SOC and total N variability. This result indicates that both MAP and MAT are critical variables driving soil C and N dynamics in the inland PNW. Furthermore, an assessment of the sensitivity of the hydrolyzable and non-hydrolyzable fractions of SOC indicated that both were equally sensitive to climate, revealing that pools with a longer turnover were as equally sensitive to a changing climate as pools with a shorter turnover time.

The influence of climate on N mineralization indices and denitrification was also evident. An increase in MAP is associated with an increase in PNM and 24-hour PRS™-probe NO_3^-, while an increase in MAT is associated with a decrease in both PNM and 24-hour PRS™-probe NO_3^-. The influence of MAP and MAT on denitrification was similar to the effect of these climate variables on N mineralization indices; an increase in MAP was associated with an increase in PDR, while an increase in MAT was associated with a decrease in both PDR and BDR. Moreover, these soil processes exhibited significant relationships with multiple soil C and N properties. This observation, along with the relationship between these soil processes and MAT and MAP suggests that N mineralization and denitrification may also be sensitive to a changing climate.

While MAP and MAT represent critical drivers of soil health within the inland PNW, the importance of tillage and cropping intensity to soil health were also evident in this study. POXC showed sensitivity to tillage and cropping intensity, and was also considered representative of stabilized SOM, a conclusion supported by its significant correlation with the hydrolyzable and non-hydrolyzable fractions of SOC and total N. Conversely, Cmin provided unique information about soil health not captured by POXC, particularly microbial activity, decomposition, and nutrient cycling.

An analysis of the influence of tillage and cropping intensity on POXC and Cmin, along with a comparative analysis of average values found in this study to reported values in the literature revealed important information regarding the influence of management on soil health within the region. The range of values reported in the literature for POXC indicates that soils within the inland PNW are below average in stabilized SOM. Results from other studies coupled with present findings suggest that cropping diversification along with NT is essential to building POXC. Cmin values, conversely, were within the range of values reported in the literature but nonetheless showed sensitivity to both tillage and cropping intensity. Likewise, results from the present study along with literature findings suggest that cropping intensification/diversification along with NT is also critical to enhancing Cmin.

Along with POXC and Cmin, the influence of management on N mineralization and denitrification was also evident. Both tillage and cropping intensification have significantly impacted PNM. At Pendleton, the influence of tillage was most notable, where NT plots had significantly greater PNM than CT pots. At Moro, cropping intensity has significantly influenced PNM, where annual cropping with a legume in rotation has resulted in significantly greater PNM than other NT rotations at Moro with a fallow year. Contrary to PNM, greater PRS™ -probe NO_3^- availability was associated with an increase in tillage; this was attributed to either greater denitrification under NT earlier in the season under wetter conditions, greater plant N uptake under NT earlier in the season under improved moisture conditions associated with NT, or tillage resulting in mixing of leached NO_3^- back into surface soils.

BDR did not differ significantly between treatments while PDR was significantly greater for crop rotations with a legume comprising at least half of the rotation. The influence of tillage

on PDR was not consistent across sites, and this was tied to variable soil C and N properties across sites with regard to tillage, particularly WEOC and MBC. While results suggest that increased cropping intensity is associated with an increase in PDR, this does not necessarily translate to an increase in N_2O emissions, as recent findings in the literature suggest cropping intensification under NT can enhance the activity of N_2O reductase by reducing O_2 availability and mitigate N_2O emissions resulting from denitrification. Therefore, while increasing cropping intensity may increase the potential for denitrification, it also has the potential to reduce N_2O emissions within NT.

Multivariate analyses were performed in an attempt to improve on the ability of single variable climate and management factors and soil C and N properties in explaining the observed variation in N mineralization and denitrification. A multivariate analysis of PNM with soil properties, climate and management factors indicated that easily measured POXC along with cropping intensity and MAT explain 71% of observed PNM variation across the four dryland sites in the study. A combination of total N, WEOC, and MAT, however, explain 81% of overall variation in PNM across the four dryland and represents an improvement in single factor prediction of PNM. Similarly, a combination of 24-hour PRS^{TM} total N, initial inorganic N, STIR and cropping intensity explained 62% of the observed variation in 28-day PRS^{TM} total N. And last, a multivariate analysis of denitrification revealed the factors which best explain variation in PDR across the region include total N, POXC, one-day Cmin, and MAT ($r^2 = 0.64$), while a combination of factors did not improve the prediction of BDR beyond only MAT ($r^2 = 0.12$).

Multiple studies have found that NO_3^- adsorbed to PRS^{TM} probes is related to plant N uptake. Regarding PNM, however, results within the literature vary regarding the relationship

of PNM to plant N uptake. In the present study, PNM was significantly correlated with 24-hour PRS^{TM}-probe NO_3^- but was not correlated with 28-day cumulative PRS^{TM}-probe NO_3^-. The fact that PNM from a longer incubation is not correlated with NO_3^- from an equally long PRS^{TM}-probe incubation suggests that PNM as measured in this study (28-day anaerobic incubation) is not related to plant N uptake. To be sure, however, PNM remains an important indicator of soil health as it represents the ability of microbes to decompose SOM and supply plant available nutrients.

Several PRS^{TM} nutrients also exhibited notable relationships with soil C and N properties and management variables. After 28 days of incubation, P and S had a negative relationship with several soil C and N properties, indicating that under ideal conditions of enhanced microbial activity, gross immobilization of these macronutrients increases, and is possibly related to microbially mediated C/S and C/P ratios. The ability of Ca activity to inhibit the activity of other cations was a possible explanation for the negative correlation of K and Mg with multiple soil C and N properties. Additionally, cation bridging and subsequent stabilization of SOM was attributed to the negative relationship between Ca and Mg and the water extractable portions of C and N. Aside from Mn, micronutrients were poorly correlated with soil C and N properties as well as with soil pH.

Leaching of S may have contributed to greater S associated with an increase in tillage intensity, where CT plots at Pendleton had greater 28-day S availability than NT plots. There were few observed differences in P availability and P variation was not significantly correlated with tillage or cropping intensity. At Kambitsch and Pendleton, an increase in tillage was associated with an increase in 28-day Ca availability. This greater Ca availability associated with

CT was attributed to lower soil pH under NT, where increased Ca solubility under a decrease in pH may have resulted in enhanced Ca leaching, while tillage would result in mixing Ca back into the surface. Potassium exhibited a negative relationship with tillage intensity and a positive relationship with cropping intensity. The micronutrients Fe, Cu, and Mn increased with an increase in tillage intensity, as evidenced by 28-day results from Kambitsch, Pendleton, and Moro. Cropping intensification under NT, however, contributed to enhanced availability of these nutrients. Across the five sites, 24-hour B and Zn adsorbed to PRS^{TM} probes was below the detection limit, indicating the plant available levels of these micronutrients may be deficient within the study area.

Last, evaluation of a soil health index which utilizes one-day Cmin, WEOC, and WEON revealed sensitivity of this index to both climate and management. Index' values for soils in the inland PNW range from 3.6 to 8.8, whereas 0 to 50 is the reported range of potential values; a range of 0-14, however, is more realistic for soils within the inland PNW.

The inland PNW is an important and unique ecoregions within the United States; it is a region dominated by WW-based agriculture, which not only forms the basis of the agrarian culture but also provides an important source of export grain for the commodity market and is subsequently a vital component of the region's economy. This study reveals that the region's soils are subject to the influence of climate but that conscientious management practices are integral to maintaining and improving soil health. Continued adoption of NT, along with crop diversification and intensification are necessary steps on the road to improved soil health and bolstering the region's important role in US agriculture.

APPENDIX A: Soil Tillage Intensity Rating (STIR) and Cropping Intensity for each study site

Kambitsch

Treatment†	Rotation Sequence	Operation	Operation STIR‡	Rotation STIR‡	Sequence Intensity§	Rotation Intensity€
WW-SC-SL (NT)	WW	Planting/ Double Opener w/ fertilizer application	13.81	14.36		
		Spray herbicide	0.15			
		Harvest	0.15		9	
	SC	Spray herbicide (2 times)	0.30			
		Planting/ Double Opener w/ fertilizer application	13.81			
		Spray Herbicide	0.15			
		Harvest	0.15		4	
	SL	Spray herbicide (2 times)	0.30			
		Planting/ Double Opener w/ fertilizer application	13.81			
		Spray herbicide	0.15			
		Harvest	0.15			
		Spray herbicide	0.15		4	**0.47**
WW-SC-SL (CT)	WW	Chisel Plow (Twisted Shovel)	45.50	88.3		
		Field Cultivator w/ 4" sweeps and spring tine harrow	28.44			
		Planting/ Double Opener w/ fertilizer application	13.81			
		Spray herbicide	0.15			
		Harvest	0.15		9	
	SC	Spray herbicide (2 times)	0.30			
		Chisel Plow (Twisted Shovel)	45.50			
		Field Cultivator w/ 4" sweeps and spring tine harrow	28.44			
		Planting/ Double Opener w/ fertilizer application	13.81			
		Spray herbicide	0.15			
		Harvest	0.15		4	
	SL	Spray herbicide (2 times)	0.30			
		Chisel Plow (Twisted Shovel)	45.50			
		Field Cultivator w/ 4" sweeps and spring tine harrow	28.44			
		Planting/ Double Opener w/ fertilizer application	13.81			
		Spray herbicide	0.15			
		Harvest	0.15			
		Spray herbicide	0.15		4	**0.47**

† WW = winter wheat; SC = spring cereal; SL = spring legume; NT = no-till; CT = conventional till.

ŧ Values for STIR from USDA-NRCS TN agronomy No. 50 (USDA-NRCS, 2006).

‡ Annualized STIR value based on summing operation STIR values and dividing by total years in rotation.

§ Based on the average number of months out of 12 months of growing plant cover.

€ Annualized cropping intensity based on sum of sequence intensities divided by total number of months in a complete crop rotation.

PCFS

Treatment†	Rotation Sequence	Operation	Operation STIR‡	Rotation STIR‡	Sequence Intensity§	Rotation Intensity€
Native Grass/CRP		Flail Mow	0.15	**0.15**	10	**0.83**
Perrenail Tall Wheat		Spray Herbicide (Spring/Fall)	0.30	**0.45**		
		Harvest	0.15		10	**0.83**
WW - SB - SW (NT)	WW	Spray herbicide	0.15	**6.3**		
		Plant/ Single operner with fertilizer application	5.69			
		Fertilizer Application/ Top Dress (broadcast?)	0.06			
		Spray herbicide	0.15			
		Harvest	0.15		9	
	SB	Spray herbicide (2 times)	0.30			
		Planting/Single opener with fertilizer application	5.69			
		Spray herbicide	0.15			
		Harvest	0.15		4	
	SW	Fertilizer Application/ Top Dress Broadcast	0.06			
		Spray herbicide(2 times)	0.30			
		Planting/Single opener with fertilizer application	5.69			
		Spray herbicide(2 times)	0.30			
		Harvest SW	0.15		4	**0.47**
WW-SL-SW (NT)	WW	Spray herbicide	0.15	**5.2**		
		Planting/Single opener with fertilizer application	5.69			
		Fertilizer Application/ Top Dress	0.06			
		Spray herbicide	0.15			
		Harvest	0.15		9	
	SL	Spray herbicide	0.15			
		Planting/Single Opener	2.44			
		Spray herbicide	0.15			
		Mower/Swath	0.15			
		Harvest	0.15		4	
	SW	Fertilizer/ Broadcast	0.06			
		Spray herbicide (Fall/Spring)	0.30			
		Planting/Single opener with fertilizer application	5.69			
		Spray herbicide (2 times)	0.30			
		Harvest	0.15		4	**0.47**
Alfalfa-SC-SL (NT/organic)	SW/cover crops (3 years)	Sweep Plow (20-40 in.)	9.75	**22.8**		
		Planting/Single Opener	2.44			
		Rotary Hoe (2 times)	33.15			
		Harvest	0.15		4	
	Alfalfa/Buckwheat (4 years)	Sweep Plow (20-40 In.)	9.75			
		Broadcast Alfalfa	0.15			
		Harvest	0.15		10	
	SW (2 years)	Sweep Plow Fall and Spring (20-40 in.)	19.50			
		Planting/Single Opener	2.44			
		Rotary Hoe	16.75			
		Harvest	0.15		8	
	Alffalfa (failed/ 3 years)	Sweep Plow (20-40 in)	9.75			
		Broadcast Alfalfa	0.15		4	
	SL (1 Year)	Sweep Plow (20-40 in.)	9.75			
		Plant/Single Opener	2.44			
		Harvest SL	0.15		4	**0.49**

† WW = winter wheat; SB = spring barley; SW = spring wheat; SL = spring legume; SC = spring cereal; NT = no-till; CT = conventional till.

ŧ Values for STIR from USDA-NRCS TN agronomy No. 50 (USDA-NRCS, 2006).

‡ Annualized STIR value based on summing operation STIR values and dividing by total years in rotation.

§ Based on the average number of months out of 12 months of growing plant cover.

€ Annualized cropping intensity based on sum of sequence intensities divided by total number of months in a complete crop rotation.

Pendleton

Treatment†	Rotation Sequence	Operation	Operation STIR‡	Rotation STIR‡	Sequence Intensity§	Rotation Intensity€
WW-Fallow (NT)	Fallow	Post-harvest fall spraying	0.15	12.9		
		Spray herbicide (spring)	0.15			
		Spray herbicide (summer/2 times)	0.30		0	
	WW	Planting/ Deep furrow drill with fertilizer application	24.70			
		Spray herbicide (2 times)	0.30			
		Harvest	0.15		9	0.38
WW-WP (NT)	WP	Planting/ Deep furrow drill with fertilizer application	24.70	25.2		
		Spray herbicide	0.15			
		Spray for crop kill	0.15		9	
	WW	Spray herbicide	0.15			
		Planting/ Deep furrow drill with fertilizer application	24.70			
		Spray herbicide (2 times)	0.30			
		Harvest	0.15		9	0.75
WW-Fallow (CT)	Fallow	Post-harvest fall spraying	0.15	88.2		
		Moldboard Plow - spring (9 in)	65.00			
		Harrow - Spring Tooth	15.60			
		Rod Weeding (4 times)	70.40		0	
	WW	Planting/ Deep furrow drill with fertilizer application	24.70			
		Spray herbicide	0.30			
		Harvest	0.15		9	0.38

† WW = winter wheat; WP = winter Pea; NT = no-till; CT = conventional till.

ŧ Values for STIR from USDA-NRCS TN agronomy No. 50 (USDA-NRCS, 2006).

‡ Annualized STIR value based on summing operation STIR values and dividing by total years in rotation.

§ Based on the average number of months out of 12 months of growing plant cover.

€ Annualized cropping intensity based on sum of sequence intensities divided by total number of months in a complete crop rotation.

Moro

Treatment†	Rotation Sequence	Operation	Operation STIR‡	Rotation STIR‡	Sequence Intensity§	Rotation Intensity€
WW-Fallow (CT)	Fallow	Post-harvest fall spraying	0.15	**70.9**		
		Spray herbicide (spring)	0.15			
		Flail Mow	0.15			
		Spring Primary Tillage - Chisel Plow w/ twisted points (15 cm)	52.65			
		Sweep Cultivation - 30 cm	9.75			
		Rod Weeding (3 times)	51.20		0	
	WW	Fertilize with Shank Applicators - August	6.50			
		Planting/ HZ openers	20.80			
		Spray herbicide (2 times)	0.30			
		Harvest	0.15		9	**0.38**
WW-Fallow (NT)	Fallow	Post-harvest fall spraying	0.15	**7.4**		
		Spray herbicide (3 times)	0.45		0	
	WW	Planting/ Double Opener with banded fertilizer	13.80			
		Spray herbicide	0.15			
		Harvest	0.15		9	**0.38**
WW-SB-Fallow (NT)	NT Fallow	Post-harvest fall spraying	0.15	**9.7**		
		Fallow Spraying (3 times)	0.45		0	
	WW	Planting/ Double Opener with banded fertilizer	13.80			
		Spray herbicide	0.15			
		Harvest	0.15		9	
	SB	Spray herbicide (2 times)	0.30			
		Planting/ Double Opener with banded fertilizer	13.80			
		Spray Herbicide	0.15			
		Harvest	0.15		4	**0.36**
WW-WP (NT)	WW	Spray herbicide	0.15	**14.4**		
		Planting/ Double Opener with banded fertilizer	13.80			
		Spray herbicide (2 times)	0.30			
		Harvest WW	0.15		9	
	WP	Spray herbicide	0.15			
		Planting/ Double Opener (Fertilizer applied at 7.5 cm)	13.81			
		Spray herbicide (2 times)	0.30			
		Harvest	0.15		9	**0.75**

† WW = winter wheat; SB = spring barley; WP = winter Pea; NT = no-till; CT = conventional till.

ŧ Values for STIR from USDA-NRCS TN agronomy No. 50 (USDA-NRCS, 2006).

‡ Annualized STIR value based on summing operation STIR values and dividing by total years in rotation.

§ Based on the average number of months out of 12 months of growing plant cover.

€ Annualized cropping intensity based on sum of sequence intensities divided by total number of months in a complete crop rotation.

Prosser

Treatment†	Rotation Sequence	Operation	Operation STIR‡	Rotation STIR‡	Sequence Intensity§	Rotation Intensity€
WW-Sw. Corn-Potatoe (NT)	WW	Disk and Packer	40.22	**68.6**	9	**0.54**
		Planting/Double Opener with fertilizer	13.81			
		Spray herbicide (2 times)	0.30			
		Harvest WW	0.15			
	Potatoe	Disk and packer	40.22		4	
		Planting Potatoe	28.67			
		Spray herbicide	0.15			
		Harvest Potatoe	13.75			
	Sw. Corn	Not yet planted in rotation				
WW-Sw. Corn-Potatoe (CT)	WW	Disk and Packer	40.22	**78.1**	9	**0.54**
		Planting/Double Opener with fertilizer	13.81			
		Spray (2 times)	0.30			
		Harvest WW	0.15			
	Potatoe	Disk ripper/roller	59.15		4	
		Planting Potatoe	28.67			
		Spray herbicide	0.15			
		Harvest Potatoe	13.75			
	Sw. Corn	Not yet planted in rotation				

† WW = winter wheat; Sw. Corn = sweet corn; NT = no-till; CT = conventional till.

ŧ Values for STIR from USDA-NRCS TN agronomy No. 50 (USDA-NRCS, 2006).

‡ Annualized STIR value based on summing operation STIR values and dividing by total years in rotation.

§ Based on the average number of months out of 12 months of growing plant cover.

€ Annualized cropping intensity based on sum of sequence intensities divided by total number of months in a complete crop rotation.

APPENDIX B: Mean annual temperature (MAT) and precipitation (MAP) for each study site between 1955 and 2012

Kambitsch

Weather Station†:
Moscow U of I, ID (COOP 106152)

Year	MAT (°C)	MAP (mm)
1955	7.3	583
1956	8.4	548
1957	8.6	515
1958	10.7	655
1959	8.5	573
1960	8.9	545
1961	9.2	608
1962	8.4	545
1963	9.1	516
1964	7.5	802
1965	8.8	423
1966	8.9	481
1967	9.2	527
1968	8.6	692
1969	7.9	513
1970	8.4	781
1971	7.9	770
1972	7.9	783
1973	8.5	700
1974	8.4	658
1975	7.4	840
1976	8.2	568
1977	8.5	581
1978	7.9	617
1979	8.3	644
1980	8.4	713
1981	8.7	732
1982	7.5	703
1983	8.3	810
1984	7.5	670
1985	6.4	471
1986	9.0	739
1987	9.6	509
1988	9.0	616
1989	8.4	681
1990	9.1	725
1991	9.0	621
1992	10.0	600
1993	7.9	601
1994	9.4	613
1995	9.1	886
1996	8.4	996
1997	9.1	827
1998	9.7	916
1999	9.0	689
2000	8.1	587
2001	8.8	585
2002	8.3	588
2003	9.7	756
2004	9.4	626
2005	9.0	631
2006	9.3	785
2007	8.6	626
2008	7.3	716
2009	6.8	739
2010	9.0	728
2011	8.0	732
2012	9.0	791
Mean	8.6	663

PCFS

Weather Station:
Pullman 2NW, WA (COOP 456789)

Year	MAT (°C)	MAP (mm)
1955	6.9	620
1956	8.3	551
1957	8.0	594
1958	10.3	758
1959	8.1	648
1960	8.3	674
1961	8.9	669
1962	8.2	543
1963	8.7	511
1964	7.6	691
1965	8.9	378
1966	8.8	475
1967	9.2	477
1968	8.7	573
1969	8.1	396
1970	8.4	558
1971	8.0	708
1972	8.2	543
1973	8.6	506
1974	7.6	510
1975	7.4	670
1976	7.9	400
1977	8.2	464
1978	7.6	463
1979	8.0	516
1980	8.1	585
1981	8.7	605
1982	7.6	648
1983	8.6	657
1984	8.0	608
1985	6.5	383
1986	8.9	518
1987	9.4	404
1988	9.0	488
1989	8.3	534
1990	8.9	586
1991	9.0	464
1992	9.9	447
1993	8.1	424
1994	9.4	474
1995	8.8	569
1996	8.4	727
1997	9.2	485
1998	9.7	571
1999	8.5	485
2000	7.5	455
2001	9.1	458
2002	8.5	393
2003	9.6	538
2004	9.4	484
2005	8.9	431
2006	9.4	551
2007	8.8	470
2008	8.5	477
2009	6.8	539
2010	9.1	552
2011	8.2	533
2012	9.2	524
Mean	8.4	533

Pendleton

Weather Station:
Pendleton BR Exp. Station, OR (COOP 356540)

Year	MAT (°C)	MAP (mm)
1955	-	-
1956	-	-
1957	9.8	461
1958	12.0	499
1959	10.1	396
1960	10.1	413
1961	11.3	397
1962	10.7	439
1963	10.4	352
1964	9.7	381
1965	10.5	345
1966	10.8	377
1967	11.1	293
1968	10.8	371
1969	9.7	339
1970	10.2	429
1971	10.1	536
1972	9.6	371
1973	10.4	200
1974	10.4	359
1975	9.6	451
1976	10.0	323
1977	9.9	386
1978	9.5	470
1979	9.8	407
1980	9.9	528
1981	10.6	529
1982	10.0	499
1983	10.4	594
1984	9.8	563
1985	8.2	363
1986	10.7	457
1987	10.7	303
1988	10.7	384
1989	9.9	420
1990	10.6	339
1991	10.5	461
1992	11.3	362
1993	9.0	464
1994	11.0	447
1995	10.7	526
1996	10.1	544
1997	10.7	418
1998	11.6	499
1999	11.0	377
2000	8.8	560
2001	9.0	355
2002	10.7	338
2003	11.6	433
2004	10.9	459
2005	10.4	328
2006	11.0	534
2007	10.3	354
2008	9.1	325
2009	10.4	284
2010	10.6	481
2011	-	-
2012	-	-
Mean	10.3	417

Moro

Weather Station:
Moro, OR (COOP 355734)

Year	MAT (°C)	MAP (mm)
1955	8.1	329
1956	9.1	307
1957	9.0	321
1958	11.0	357
1959	9.2	205
1960	9.1	276
1961	10.1	337
1962	9.5	297
1963	9.3	303
1964	8.6	304
1965	9.9	211
1966	9.7	292
1967	10.4	154
1968	8.6	279
1969	8.6	266
1970	9.2	290
1971	9.2	260
1972	9.0	268
1973	9.5	308
1974	9.5	212
1975	8.9	305
1976	9.6	178
1977	9.0	304
1978	8.8	277
1979	8.9	324
1980	8.6	403
1981	9.3	373
1982	8.5	312
1983	9.0	427
1984	5.8	394
1985	7.5	205
1986	9.7	276
1987	10.2	273
1988	9.8	259
1989	9.2	217
1990	10.1	251
1991	9.8	275
1992	10.7	279
1993	8.3	253
1994	10.4	248
1995	9.9	475
1996	9.4	442
1997	10.1	249
1998	10.4	347
1999	9.9	177
2000	8.8	224
2001	9.8	211
2002	9.5	183
2003	10.6	298
2004	10.2	279
2005	9.5	308
2006	10.0	407
2007	9.7	237
2008	9.2	174
2009	9.3	256
2010	9.4	462
2011	9.2	242
2012	9.7	288
Mean	9.4	288

Prosser

Weather Station:
Prosser, WA (COOP 456768)

Year	MAT (°C)	MAP (mm)
1955	9.2	210
1956	10.2	176
1957	10.0	282
1958	12.0	254
1959	10.0	150
1960	10.0	198
1961	11.3	299
1962	10.8	222
1963	10.8	198
1964	10.3	192
1965	11.3	121
1966	11.6	179
1967	12.1	111
1968	10.8	195
1969	9.7	184
1970	10.1	190
1971	10.2	209
1972	10.1	203
1973	10.6	246
1974	10.6	180
1975	9.8	217
1976	10.0	88
1977	10.4	195
1978	10.1	199
1979	10.1	187
1980	9.8	284
1981	10.8	198
1982	10.0	255
1983	10.6	342
1984	8.9	189
1985	9.3	154
1986	9.0	219
1987	12.4	163
1988	11.5	170
1989	9.9	161
1990	11.7	135
1991	9.7	175
1992	13.3	176
1993	9.9	134
1994	-	-
1995	-	-
1996	12.0	241
1997	11.9	226
1998	12.2	202
1999	12.2	155
2000	11.0	205
2001	11.3	186
2002	12.0	171
2003	13.1	225
2004	12.6	271
2005	12.0	238
2006	12.3	274
2007	11.9	188
2008	11.5	141
2009	12.8	84
2010	11.9	239
2011	-	-
2012	-	-
Mean	10.9	200

† From NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/)