CARBON STOCKS AND TILLAGE IN PALOUSE AGRICULTURAL SOILS

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Conservation tillage practices promote soil environmental conditions that may enhance carbon (C) sequestration in agricultural soils. However, the exact nature and magnitude of this effect is not fully understood. The goal of our study was to examine the ability of two forms of conservation tillage (no-till and chisel plow) to sequester C over a 12-year period. In addition, the relationship between soil organic C, root distribution and the general growing environment was determined in each tillage system. Greater root density and similar yields suggest that the measured increase in acidity is not having a negative impact on crop productivity or C inputs under NT. While there was a trend for greater C stocks under NT as opposed to CP, differences were not significant after 12 years. Greater C inputs under NT and similar C stocks suggest redistribution and greater loss of C as carbon dioxide and/or dissolved organic C under no-till as opposed to chisel plow. Carbon is highly variable on a field scale due to soil-landscape relationships and tillage influences. Variability of C presents challenges to obtaining representative samples to growers who are interested in measuring C stocks in their fields for either C credits or as means of assessing the impact of their management practices on soil quality. Growers interested in determining soil C stocks need to consider topographic variables such as aspect, slope percentage and landscape position.

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In the 21st century, global climate change has become a defining issue for the scientific community. The Intergovernmental Panel on Climate Change (IPCC) estimates that, due to the radiative forcing of greenhouse gases including carbon dioxide, nitrous oxides, and methane, global temperatures may rise between 1.4 and 5.2 degrees Celsius in the next century (Pachauri, 2014). Carbon dioxide, with an estimated 9.6 Pg of total emissions worldwide each year, is the largest of the greenhouse gases, in terms of the total volume of emissions (Batjes, 1996; Govaerts et al., 2009). This fact has made climate change mitigation through carbon sequestration one of the focal points of climate change research. Many scenarios for sequestering atmospheric carbon have been proposed including the oceans, biochar, and storage deep underground (Schellnhuber, 2011). However, the most promising option lies in soils. With 1500 Pg of carbon in the top 1 meter of soils worldwide, the terrestrial carbon pool is twice as large as that of the atmosphere. This pool of carbon is only surpassed by that contained in the oceans (Batjes, 1996; Baveye et al., 2011).

Climate change due to anthropogenic greenhouse gas emissions is one of the most pressing issues for science today. There are a myriad of possibilities that may help curb the expected changes in the Earth's climate. Due to the size of the terrestrial carbon pool, even small fluxes within it have significant implications for the global carbon pool. Thus, large agricultural areas like the Palouse region have enormous potential for terrestrial carbon sequestration.

Within the terrestrial carbon pool, agricultural lands offer a distinct opportunity for carbon sequestration. Agricultural lands are heavily managed and, in many cases around the world, are large net sources of carbon, both indirectly and directly (Lal, 2003). Given the size of the terrestrial carbon pool, even small changes in the agricultural carbon pool can have large implications to the global carbon cycle (Kirschbaum, 2000). Marland et al. (2003) described the four main sources of carbon emissions in agriculture as: (a) plant respiration; (b) the oxidation of organic carbon in soils and crop residues; (c) the use of fossil fuels in agricultural machinery and (d) the use of fossil fuels in the production of agricultural inputs such as pesticides and fertilizers. Of these four sources, controlling the oxidation of crop residues and resulting flux of carbon dioxide has the most potential as both a carbon sink and soil quality improvement mechanism (Gebhardt et al., 1985; Lal, 2003).

Tillage accelerates the oxidation of organic carbon and plant residues that releases carbon dioxide, especially close to the soil surface. Tillage is broadly defined as the mechanical mixing of surface soils before or after planting in agricultural fields. Tillage is used to create a fine seedbed that ensures good soil-to-seed contact, incorporate residues and soil amendments, and reduce competition from weeds (Gebhardt et al., 1985). Tillage operations consist of a wide spectrum of practices that vary in the amount of soil disturbance and crop residues left on the surface of the field. Conventional tillage practices completely overturn the soil column down a specified depth, usually 20-30 cm, with a moldboard plow. Reduced tillage consists of a tillage operation that leaves at least 30% of crop residues on the soil surface. No-tillage systems are systems that only disturb the soil to create a space for seeds, usually with a seed drill or similar mechanism (Gebhardt et al., 1985).

The crop residues that are left behind in reduced tillage and no-tillage systems promote carbon sequestration in a number of ways. Crop residues cover and insulate the soil surface, which reduces thermal amplitude and stress in relation to soils fully exposed to sunlight. Warmer soil temperatures tend to promote increased rates of microbial metabolism and subsequent respiration of CO_2 (Bono et al., 2008). In contrast to being incorporated into the soil all at once as in conventional tillage, the crop residues left on the surface in reduced tillage are slowly incorporated into the soil over the course of a season (Alvarez and Alvarez, 2001). Crop residues also protect the soil surface from wind and water erosion that can carry away particulate carbon and disrupt soil aggregates.

In addition to the potential positive effects that reduced tillage can have on carbon dynamics in agriculture, reduced and no-tillage systems also help promote other beneficial soil properties to agricultural systems. Ancillary benefits of reduced tillage include better water relationships, increased water-stable aggregation, enhanced nutrient cycling, and increased earthworm activity (Drees, Karathanasis et al. 1994; Karlen, Lal et al. 2009; Stone and Schlegel 2010).

While it is generally believed that reduced tillage promotes carbon sequestration, recent studies have reported mixed results (Wander, Bidart, and Aref, 1998; Yang and Wander 1999; Blanco-Canqui and Lal, 2008; Christopher, 2009; D'Haene et al., 2009; Sleutel et al., 2006; Plaza-Bonilla et al., 2010). The inconsistency stems from a wide variety of factors. One of the most significant factors in the variability in carbon measurements is the maximum sampling depth. Specifically, there are many questions about whether the primary carbon dynamics responsible for sequestration occur within the plow layer or if the entire soil profile must be considered. Studies that only sample the plow layer (e.g. McConkey et al., 2003; Ernst and Siri-Prieto, 2009; Messiga et al., 2011) consistently show net sequestration in reduced tillage soils.

Several authors (Ellert and Bettany, 1995; Wander, Bidart, and Aref, 1998; Gal et al., 2007; Lee et al., 2009) have addressed the necessity of an appropriate methodology for calculating carbon values in soils, especially when sampling in contrasting tillage systems. Ellert (1995) recognized the implications of different bulk densities present in reduced tillage and conventional tillage systems. The decreased disturbance in reduced tillage means that bulk density is higher near the surface relative to conventional tillage. If this difference is not taken into account when calculating soil carbon values, an overestimation can occur. Equivalent soil mass compares soil organic carbon based on equal masses, thereby accounting for differences in bulk density (Ellert and Bettany 1995).

Although tillage affects organic carbon in soils, there are numerous other factors that are important in carbon storage, both in terms of direction and magnitude. Deen (2003) emphasized the separation of an agricultural soil profile into two distinct sections: the plow layer and the soil below the plow layer. The carbon storage in these layers is controlled by highly contrasting forces. Carbon storage in the plow layer is primarily controlled by tillage, climate, topography, and short term crop rotations. Carbon storage in deeper soil layers below the plow layer is controlled by long term cropping history of the field and climate (Chatterjee and Lal, 2009).

It is the carbon dynamics in deeper soil layers that has become an important question in relation to agricultural soils. Deeper soil layers are characterized by much lower levels of soil organic carbon, but with a much higher variability than surface layers due to pedogenic factors and the lack of homogenization that tillage provides (Syswerda et al. 2011). The loss of carbon below 30 cm in reduced and no-tillage systems is often large enough to offset the surface gains in comparison to conventional tillage (Wallace and Wallace, 1990; Blanco-Canqui, 2008). This underscores the importance of understanding tillage effects on the distribution of carbon, and often the redistribution, which occur within a particular soil or region.

Plant roots are one of the main drivers in carbon sequestration (Kell, 2011). Roots are the transfer mechanism of carbon from recent photosynthesis to the soil. This transfer of carbon to the soil is typically facilitated by carbon-based root exudates that can adsorb to soil particles. This link between roots and carbon sequestration helps to explain the variability of carbon, especially in the vertical dimension, within a soil profile. This link is especially important when dealing with plants with especially deep rooting depths, such as wheat. This link means that significant importance must be placed on root architecture and distribution of roots within a soil profile, especially in relation to carbon distribution within the same profile.

The amount of carbon stored in agricultural soils is highly variable. This is due to the numerous factors controlling carbon storage. The amount of carbon stored in the surface layers of agricultural fields is primarily controlled by crop rotations, crop selection, and tillage regime. These two factors dictate the above-ground biomass, root density, the amount of soil disturbance, and the amount of biomass incorporated into the soil. Reduced tillage managed fields that leave at least 30% of crop residues on the soil surface act to sequester carbon by controlling the soil temperature and allowing the carbon to slowly enter the soil over the course of a season (Gebhardt et al., 1985). This is in contrast to conventionally tilled fields which incorporate organic matter all at once and leave the soil surface bare for much of the year.

There are still many uncertainties relating to carbon storage in agricultural soils. Although up to 90% of the original carbon can be lost in the subsequent years after initial cultivation (Knops and Tilman, 2000), it is not clear as to how much carbon can then be “put back” into the soil with reduced tillage agriculture. Early research (e.g. Bauer and Black, 1981) showed that carbon levels in a conventionally tilled field reach a steady state after about 40 years of continuous management. The length of time after reduced tillage management is instituted needed for carbon to reach a new steady state is unclear at this point as well as what the magnitude of soil organic carbon would be at this new steady state (Karlen et al., 2009; Sundermeier et al., 2011).

An understanding of the carbon dynamics at depth in both conventionally tilled and reduced tillage systems is critical to understanding tillage effects on carbon sequestration in agricultural soils. These dynamics are highly variable and dictated by the long-term cropping history of the field and the climate of the region in question. It is clear that considering the entire soil profile is crucial to understanding the potential of an agricultural field to store carbon (VandenBygaart et al., 2002; Yang et al., 2008). It is clear that the tillage effects on carbon sequestration in agricultural soils are highly variable and often site-specific. This underlines the necessity of regional-based research on carbon sequestration before conclusions are made about the potential of a soil to store carbon.

The Palouse region of northern Idaho and eastern Washington is characterized by undulating topography and loess-derived, deep soils. Wheat, peas, lentils, and oil seeds are the primary crops of the region. The annual wheat crop, on a yield per acre basis, makes the Palouse one of the largest agricultural areas in the world, in terms of per-acre productivity. The annual agricultural production of the Palouse along with the large aboveground and belowground biomass of wheat grants it tremendous potential for agricultural carbon sequestration. The highly erodible loessial soils and the steep slopes (8-30%) create a complicated soil-landscape relationship. The complex nature of the Palouse soil landscape reinforces the highly site-specific nature of carbon sequestration and the need to study it on a regional basis.

Study Objectives

The primary objective of this study is to compare carbon stocks in reduced tillage agricultural soils of different ages. Specifically, we will:

1) Determine if differences in rooting depths in the two tillage treatments are related to the measured patterns of carbon with depth.

2) Create an extension-oriented, conceptual guide to sampling and measuring soil carbon in the Palouse region for growers who are interested in carbon credits or measuring the impact of management on the soil quality in their fields.

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CHAPTER TWO: CONSERVATION TILLAGE INFLUENCES ON ROOT DISTRIUBTION AND SOIL CARBON SEQUESTRATION

ABSTRACT

Conservation tillage practices promote soil environmental conditions that may enhance carbon (C) sequestration in agricultural soils. However, the exact nature and magnitude of this effect is not fully understood. The goal of our study was to examine the ability of two forms of conservation tillage (no-till and chisel plow) to sequester carbon over a 12-year period. In addition, the relationship between soil organic C and root distribution was determined in each tillage system. Carbon and root biomass were sampled in 2012 down to 90 cm in four replicated, paired no-till/chisel plow plots. A fixed effects model utilizing a randomized complete block design with repeated measures was used to analyze carbon stock and root biomass responses to depth, tillage, and tillage/depth interaction. Tillage significantly influenced root biomass for the whole profile ($P=0.01$) and NT had a significantly larger root biomass than CP in the 0- to 10-cm ($P=0.0008$) and 10- to 20-cm depths ($P=0.0005$). No significant differences were found for C stocks between the treatments ($P=0.99$), although there was a non-significant trend of greater C storage in NT. Soil pH was significantly lower in NT in the 0- to 10-cm depth ($P=0.0001$). Greater root density and similar yields suggest that increased acidity is not having a negative impact on crop productivity or C inputs under NT. Greater C inputs under NT and similar C stocks suggest redistribution and greater loss of C as carbon dioxide and/or dissolved organic C under no-till as opposed to chisel plow.

INTRODUCTION

Human activities account for an estimated 9.6 Pg of annual carbon (C) emissions and the effects of these emissions on global climate has become a defining scientific and policy issue in the 21st century (Pachauri, 2014). There is an estimated 1500 Pg C stored in top one meter of soils worldwide (second only to oceans) and this pool has historically been a net source of C emissions due to practices such as high disturbance agricultural management (Govaerts, 2009). The sensitivity of this C pool to agricultural management presents the potential that changes in management could reverse C losses, potentially converting agricultural lands into net C sinks. Carbon storage in agricultural soils is determined by the balance between C inputs from crop residues and organic amendments and C losses from decomposition and erosion (Bronick, 2005). Tillage management influences C storage through its effect on disturbance and the retention of crop residues on the soil surface.

Tillage methods that retain greater than 30% of crop residues on the soil surface are defined as conservation tillage (Gebhardt, 1985). No-till (NT) utilizes the minimum disturbance needed to inject seeds through the residue cover into the soil and generally retains greater than 90% of residues. Although it is a form of non-inversion tillage, chisel plowing (CP), results in greater soil disturbance than NT and can lead to 15-65% less residue retention than that found in NT systems (Karlen, 2009). Reduced disturbance and increased surface residue retention associated with conservation tillage have been shown to improve soil structure, increase soil water holding capacity, enhance soil biodiversity, and increase organic matter additions to the soil (Gal, 2007). While it is widely accepted that conservation tillage improves overall soil quality, the magnitude and direction of its effect on soil C storage is not well understood (Van Eerd et al., 2014).

Some studies have shown that conservation tillage practices lead to net storage of C in relation to conventional tillage (CT) management. In a 20-year comparison between CT and NT, Fuentes et al. (2012) reported significant C gains in the 0- to 10-cm depth for NT. The gains in NT were attributed to significantly higher soil aggregation that protected organic matter from microbial degradation, as well as enhanced C enrichment of the aggregates in NT. Surface residue retention also decreased erosion-related breakdown of large aggregates near the soil surface. Bono et al. (2008) found positive effects on C storage by NT after three years in the 0- to 20-cm depth. This effect was attributed to increased productivity and yield in NT due to greater soil moisture retention that resulted from surface residue retention.

In general, studies comparing conservation and conventional tillage effects that only consider near-surface soil (0- to 30-cm) generally report significant gains in C with conservation practices (Yang and Wander 1999; Plaza-Bonilla, 2010). Results of studies that consider the entire soil profile are often more varied and have even shown C losses in conservation tillage in relation to conventional tillage. After 17 years of conventional tillage and NT in a wheat-barley rotation, Plaza-Bonilla (2010) found surface gains in C stocks in NT, but no significant differences in C stocks to the 50-cm depth. The lack of difference when deeper depths were considered was attributed to the incorporation of crop residues deeper into the soil profile under conventional tillage practices.

Previous results strongly suggest that tillage practices change the physical and biochemical properties of soil with depth and that only regarding surface C stocks may lead to overestimation of the impact of conservation tillage practices on C sequestration (Blanco-Canqui et al., 2011). The underlying processes responsible for differential impacts of tillage on C storage with depth have not been fully studied and are ultimately determined by the effect of individual practices on C inputs and losses throughout the soil profile.

Inputs of C through crop residues vary in differently managed agricultural systems. In NT, surface residue remains at the surface where it is slowly incorporated by soil organisms (Fuentes et al., 2012). Plant residues mixed into near-surface soil are largely responsible for reported increases in soil C stocks within the 0-to 30-cm depth of conservation tillage systems. Carbon deeper in these same soils, however, may slowly decrease due to the lack of tillage which physically incorporates crop residues to depths of 15-30 cm (Olson and Al-Kaisi, 2015).

Rooting systems can be extensive, extending below two meters in cereals and 20-30% of C assimilated by the plant is allocated below ground in roots. and can also be a significant C input to soils (Kuzyakov, 2000; Qin et al., 2004). A significant portion of this material is root exudates composed of labile organic compounds. Additionally, the high chemical recalcitrance of root material in cereal crops combined with the conditions in subsurface soils being less conducive to decomposition means that root material may be preferentially preserved. Preservation mechanisms and exudates can result in roots being a significant source of C in soils (Rasse, 2005; Barbera, 2012). It is possible that conservation tillage methods may promote soil environmental conditions, especially relating to surficial soil moisture retention, which may promote enhanced root growth (Vakali et al., 2011; Guan et al., 2015).

Carbon inputs from root turnover, root exudates and surface residues may be influenced by tillage practice directly due to processes such as residue placement, and indirectly through modification of the soil. For example, increases in compaction associated with NT practices in some soils may reduce root density, above and belowground biomass production and C inputs (Munkholm, 2008). In addition, tillage-associated changes in pH may negatively impact the growing environment potentially reducing germination and biomass production. In the cereal production region of the Inland Pacific Northwest, significant declines in soil pH in the 0-30 cm depth of soil have been noted in conservation tillage systems (Mahler and McDole, 1987). Declines in pH are associated with the lack of mixing and acidity generated by the use of ammonium-containing fertilizers. Studies comparing soil pH in conservation and conventional tillage systems suggest the danger of aluminum toxicity and are often below the optimal values for wheat production (Brown et al., 2008). These changes in the soil solution chemistry can cause significant decreases in aboveground and belowground productivity and impact C returns to the soil as a result (Kemmitt et al., 2006).

In the Palouse region of northern Idaho, there is relatively little research on C dynamics in subsurface soils, and of the studies that exist, many are confounded by long-term influences of erosion and inconsistent sampling protocols (Brown and Huggins, 2012). In addition, many studies focus on comparing NT and conventional tillage, despite the fact that many forms and degrees of conservation tillage are utilized and conventional tillage is no longer the dominant practice (Kok et al., 2009). We suspect that different tillage methods within the conservation tillage spectrum may lead to differences in the growing environment and root distribution and therefore have significant ramifications for C storage under these treatments. The primary objective of this study is to measure differences in the distribution of C with depth and whole-profile C stocks in CP and NT treatments of a long-term tillage plot experiment in the Palouse region. Root density under both tillage treatments was measured to determine the input of C within each treatment and pH and bulk density were measured to assess differences in the general growing environment.

MATERIALS AND METHODS

Study Site

This study was conducted at the University of Idaho's Kambitsch Research Farm located near Genesee, ID. The region experiences a Mediterranean-like climate that is characterized by warm, dry summers and cool, moist winters. The mean annual temperature is 8.3 °C and the average annual precipitation is 605 mm (Western Regional Climate Center, 2015). The dominant soil type within the soil mapping unit at the research farm is Palouse silt-loam (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls), but the site also has close geographical associations with Latah silt-loam (fine, mixed, superactive, mesic Xeric Argialbolls) and Latahco silt-loam (fine-silty, superactive, frigid Argiaquic Xeric Argialbolls) (Soil Survey Staff, 2013). These soils range from well-drained to somewhat poorly drained and have textures ranging from silt loam at the surface to silty clay loam in the subsoil (Soil Survey Staff, 2013). The research plot itself is situated on a south-facing aspect with slopes ranging from 11-17%.

Prior to 2000, the site was managed under conventional tillage. Starting in 2000, chisel plow (CP) and no-till (NT) treatments were applied to study the influence of conservation tillage on crop performance, soil properties, and soil organisms (Johnson-Maynard et al. 2007). The experimental design consisted of three crops-spring and winter wheat (*Triticum aestivum*) and spring pea (*Pisum* *sativum*)- planted and rotated annually through three strips, each measuring 88 m x 20 m, in a north-south orientation parallel to the slope. Each strip was paired with treatments of CP and NT across the slope, perpendicular to the cropping strips. The current experimental design used for this study was started in 2010. This design consists of 4 CP-NT treatment plot pairs with each tillage plot measuring 20 m x 80 m, oriented in an east-west direction. Each tillage plot contains 3 crop strips each measuring 7 m x 80 m planted and rotated annually through spring pea (*Pisum sativum*), winter wheat (*Triticum aestivum*), and spring barley (*Hordeum vulgare*). The placement of CP and NT treatments remains the same as the previous experimental design (Fig 2.1), resulting in the tillage practices being in place for a 12-year period.

During fall, CP treatments are tilled to a depth of 20 cm with a chisel and two cultivations are done just prior to planting in spring. The chisel plow uses a 4-m-wide Glencoe Soil Save with a row of straight coulter disks in front and behind a row of 7-cm-wide shanks with 10-cm-wide twisted shovels spaced 30-cm apart. An 11-m-wide Wil-Rich 2500 cultivator is used with 1-cm-wide shanks spaced 18-cm apart with attached tines spaced 8-cm apart. Depth of cultivation is 8-10 cm. In NT treatments, the plots are left undisturbed with the exception of the planting operations. The NT plots are planted with a FlexiCoil drill with Barton II disk-type openers (Robertson, 2010). Fertilizer rates are based on spring soil test results and established University of Idaho fertilizer recommendations.

Root Biomass

Root biomass methods were adapted from Bolinder et al. (1997). Roots were collected in October 2012 (2 weeks following harvest) down to 90-cm in 10-cm increments in 10 soil pits split evenly between CP and NT treatments. Roots were only collected from the winter wheat strips in each treatment. Three replicate soil cores 7.9-cm in height and 5.4-cm in diameter (180 cm^3) were taken from each depth with a slide-hammer driven soil coring probe. Samples were taken from between rows, so the roots collected were predominantly fine roots (<2 mm). Sampling placement and depth can have significant ramifications when measuring absolute amounts of root biomass. Bolinder et al. (1997) found that sampling between crop rows yielded 35% of the root density that was measured in samples taken from the crop row, primarily due to influence of coarse roots found close to the plant base. The difference based on sampling position in respect to crop row was not present below 30-cm because it is estimated that over 65% of root biomass is present above that point in the soil profile for cereal crops (Qin, 2004). After collection, root cores were frozen at -20 °C until processing. Roots were separated from soil using a hydropneumatic elutriation system from Gillison's Variety Fabrication (Benzonia, Michigan). This system utilizes water pressure and compressed air to separate root and plant residues from soil samples (Bolinder et al., 1997). Following the washing procedure, visible plant residues were separated from the roots and the root samples were dried at 50 °C for 12 hours and weighed. No distinction was made between living and dead roots in these measurements. The ash-free, dry weight was calculated for each root sample after placing the sample into a muffle furnace at 650 °C for 6 hours. Total C concentration of root samples for each depth was determined by dry combustion (Nelson and Sommers 1996) using a CNS analyzer (Vario Max CNS from Elementar Analysensysteme, Germany).

Soil and Growing Environment Characterization

Soil cores were taken in October 2012 down to 1.5 m with two replicates in each crop strip in both tillage treatments using a hydraulic-driven soil probe from Giddings Machine Company (Windsor, CO). After collection, soil cores were stored in a cooler at 4 ˚C until processing. The cores were cut into depth sections (0-10, 10-20, 20-30, 30-60, 60-90, 90-120, 120-150 cm). Depth sections were subsampled, weighed and oven-dried for bulk density calculations. The remaining parts of each depth section were air-dried and ground to pass a 2-mm sieve. The ground samples were further subsampled and ground to pass a 250-µm sieve. Less than 2-mm samples were used to measure soil pH on a 1:1 basis with triple-distilled water. Samples ground and sieved to 250-µm were used to measure total C concentration in the CNS analyzer. Means of total organic C and total C on samples with a soil pH greater than 6.5 were analyzed using a 2-sample t-test at $\alpha=0.15$ and were found to not be significantly different ($p=0.66$), therefore contributions from carbonates into total C were considered to be negligible.

Data Analysis

The data was analyzed with a randomized complete block design with repeated measures using a fixed effects model with the significance level set at $\alpha=0.05$. Tillage treatment, depth and tillage-depth interaction were used as the fixed effects and root biomass, bulk density and soil pH were the response variables. Means of C stocks down to 150 cm across the tillage treatments were compared used a 2-sample t-test with the significance level set at $\alpha=0.05$. All statistical analyses were performed using SAS® Version 9.2 statistical software (SAS Institute Inc., 2009).

RESULTS

Characterization of the Growing Environment

Soil pH and bulk density were selected to assess the impact of tillage on the growing environment because they both impact plant growth and are known to be sensitive to tillage management (Mahler and McDole 1987; Fabrizzi et al., 2005; Chatterjee, 2009). Soil pH values in both treatments ranged from 5.6 at the surface (0-10 cm) to 7.5 at depth (120- to 150-cm) and both treatments showed sharp increases with depth down to 40-cm and a much more gradual increase from 40- to 150-cm (Fig 2.2). In general, pH values in NT were lower than in CP until the 80-cm depth, after which CP was slightly lower. For the whole profile, the mean pH value for NT (6.6) was significantly lower than for CP (6.8) (P=0.0005). There was a significant (P=<0.0001) interaction between tillage and depth. Given this, it was possible to make same-depth comparisons across the tillage treatments. However, only the treatment difference in the 0- to 10-cm depth was significant (P=<0.0001) where the pH in NT was 5.5 and 5.8 in CP.

Bulk density values were not different between NT and CP in terms of the whole profile mean (P=0.81) and the interaction between tillage and depth was not significant (P=0.63), so same-depth comparisons were not made. Values ranged from 1.41 to 1.45 g cm^{-3} at the surface and 1.66 to 1.71 g cm^{-3} in the 120- to 150-cm depth (Fig 2.3).

Root Biomass

Mean root biomass across the whole profile (0-90 cm) was greater in NT with 0.25 mg roots cm^{-3} and 0.19 mg roots cm^{-3} in CP (P=0.01). This difference reflects the significantly greater root biomass values in the top 20-cm of the NT treatment (Fig 2.6). In the 0-to 10-cm depth, root biomass under NT was 0.44 mg roots cm^{-3} compared to 0.22 mg roots cm^{-3} in CP (P=0.0008). Root biomass was also significantly greater in the 10- to 20-cm depth under NT with 0.55 mg roots cm^{-3} compared to 0.34 mg roots cm^{-3} in CP (P=0.0005). Below the 20-cm depth, root biomass was not significantly different between the two treatments. Roots were only measured to 90 cm due to physical limitations in digging the soil pits below that depth.

Percent Carbon and Carbon Stocks

Percent C values across both tillage treatments ranged from 1.75% at the surface to 0.17% at depth (Fig 2.4). There was a non-significant trend (P=0.10) of greater total C concentration in NT with a value of 0.80%, compared to 0.73% in CP. The larger whole-profile mean value in NT, as compared to CP, largely reflects a trend of greater values in the first 60 cm of soil. After 60 cm, percent C values are even more similar. Percent nitrogen values ranged from 0.12% at the surface to 0.01% at depth for both tillage treatments, following the same general trends as soil C (data not shown). The interaction between tillage and depth was not significant (P=0.99), so same-depth comparisons were not made. The mean C stock to the 150-cm depth tended to be greater in NT (122 Mg C ha^{-1}) than in CP (117 Mg C ha^{-1}). However, these mean values for C stocks were not significantly different (P=0.66). Just under half (47%) of the C stocks for both treatments were stored within the top 30-cm, 58 Mg C ha^{-1} in NT and 56 Mg C ha^{-1}. Carbon stocks for the 30-to 60-cm depth were 30 Mg C ha^{-1} in NT and 27 Mg C ha^{-1} for CP. Within the 60-to 150-cm depth, values were 34 Mg C ha^{-1} in NT and 35 Mg C ha^{-1} in CP (Figure 2.5).

DISCUSSION

Characterization of the Growing Environment

There were no significant differences in bulk density between NT and CP treatments which is most likely attributable to advances in modern NT technology which result in a much lower degree of soil compaction (Fabrizzi et al. 2005) with the use of NT drills. Bulk density data taken in 2002 from the same site as this study showed values ranging from 1.16 g cm^{-3} at the surface to 1.36 g cm^{-3} at the 20- to 30-cm depth and no significant differences between NT and CP (Johnson-Maynard et al., 2007). Measurements taken in 2006 and 2009 showed no difference between NT and CP and values ranged from 1.16 g cm^{-3} at the surface to 1.34 g cm^{-3} at the 30- to 60-cm depth (Unpublished data).

Despite some variability in the bulk density values from year to year, there values in NT and CP have never differed. Natural changes in bulk density over the course of a season and changes over time due to water content, depth of freezing, and root growth makes it difficult to interpret and compare repeated bulk density measurements over a period of years in one system (Logsdon and Cambardella, 2000). It is also possible that differences in sampling timing and methodology affected the bulk density values. Several studies have shown that any effect that tillage has on bulk density is inconsistent and it is likely that soil type is a more dominant factor in determining bulk density differences (Ismail et al. 1994; Chatterjee, 2009; Christopher, 2009). Bulk density is an important ecosystem property and is a significant control on water and gas movement within the profile and root penetration, as well as crop productivity and yield (Bronick, 2005). We do not expect that surficial bulk density values will effect wheat root growth as root impedance generally rises with values higher than 1.6 g cm^{-3} (Fabrizzi et al., 2005).

Significant differences in soil pH between NT and CP were only found in the surface 10-cm of the profile. This difference is likely the result of the contrasting levels of disturbance in NT and CP. The lack of mixing of the surface soil in NT results in the concentration of acidic ions from the nitrification of surface-applied nitrogen fertilizers and consequently, lower soil pH values than those typically found in CP and conventional tillage treatments (Ismail et al. 1994; Umiker et al. 2009; Chatterjee, 2009). A lesser contribution to soil acidity in NT comes from the mineralization of nitrogen in the abundant crop residues on the soil surface. Mineralization leads to the production of acidic ions (Thomas, 2007). The disturbance of surface soil in CP treatments results in the mixing of nitrogen fertilizers and surface residues which counters the acidifying effects that can be found in NT, in addition to the mixing of higher pH subsoil (Olson and Al-Kaisi, 2015).

Soil pH changes following conversion from more conventional tillage methods to no-tillage has been shown to be inconsistent and highly dependent on soil type and the application of additives such as fertilizers and liming agents. These effects are typically confined to the top 10-cm of the profile. Hussain (1999) found differences in pH in the 0- to 5-cm range in an 8 year study contrasting NT and CP and found NT had a significantly higher pH than did CP. The lack of mixing in NT led to surface-applied lime being concentrated at the soil surface and a higher pH than in CP, where the mixing spread the lime into a larger section of the profile. Other authors have found a difference in the surface 10-cm of the profile, but found NT to have a lower pH than CP due to acidification from nitrification of fertilizer- N (Rhoton, 2000), however this effect was not present below 10-cm in depth. In contrast, Dick (1983) found after 19 years under NT management, an Alfisol had lower pH than under reduced or conventional tillage within the 0-to 30-cm depth. The difference in pH, however, was more pronounced within the top 10 cm of soil. These results show that changes in soil pH can occur in surface soil following changes in tillage; however the effect can be site-specific, and this emphasizes the importance of long-term monitoring. Soils in the Palouse region, where the use of agricultural lime as a soil amendment is rare, have been shown to experience a decline in pH in near surface soils with conservation tillage methods (Brown et al., 2008).

Acidification of surface soils in NT can lead to reduced rates of germination and reduced early season growth; although growth in the later season is often not affected as root systems extend well below acidified surface soils. However, low surface pH values in NT can affect crop yields

(Kemmitt et al., 2006). For the 2012 growing year at this study site, overall winter wheat yields at the study site were lower in NT (2.1 t) than in CP (2.3 t) (unpublished data). Wheat generally has a higher tolerance for lower pH values and yields aren't significantly affected until pH values drop below 5.1 (Mahler and McDole, 1987). It is possible that lower surficial pH values in NT resulted in lower yields in relation to CP, however the difference in yield between NT and CP is relatively small (0.2 t), and the surface pH measurements fall close to the optimum pH for wheat growth of 5.4 (Brown et al., 2008). Average values for harvest index (the ratio of grain mass and aboveground residues) as measured in 2013 and 2014 in these same plots was 0.98 for both treatments (data not shown). Harvest index data, therefore, suggests that the proportion of total biomass to seed yield is similar between the treatments.. Therefore, it is unlikely that soil pH values at the surface are affecting wheat yields and C inputs at this time. However the apparent divergence in pH in the 0- to 10-cm depth between NT and CP (Figure 2.2) could represent a concern to crop yields in the future and warrants future monitoring.

Root Biomass

Measured root density was approximately twice as high in NT relative to CP in the top 20-cm of the soil profile, despite significantly lower pH values in the surface of NT. This difference is likely due to a number of factors relating to the effects that the lack of disturbance in NT has on soil structure, nutrient status, and soil moisture and temperature. In comparing conventional tillage and NT influences on winter wheat root density and bulk density each year for five years, Qin et al. (2004) found greater root densities in the surface (0-10 cm) of NT soils and that the depth to which NT increased root density increased over time. The larger root densities were attributed to more favorable soil structure in NT for root growth. Bulk density did not differ between treatments in our study, but the lack of disturbance in NT can lead to soil structure changes over time. This can come in the form of greater numbers of large macropores relative to more intense tillage regimes (not measured in our study) due to the preservation of earthworm burrows and former root channels (Drees et al. 1994). Johnson-Maynard et al. (2007) found significantly greater densities of earthworms in NT as compared to CP at this same research site. This network of biopores and macropores provides existing pathways for new roots to grow (Chirinda et al., 2012; Jemai et al., 2012).

The lack of disturbance in NT has variable effects on nutrient status. For more mobile nutrients, the increased volume of large macropores in NT, may promote increased infiltration and translocation deeper into the profile than in CP (Thomas, 2007). However, the lack of disturbance can lead to stratification near the surface of less soluble nutrients like calcium, phosphorus, zinc, and magnesium; although this concentration is likely favorable to surficial root growth in NT relative to CP (Ismail et al. 1994; Rhoton, 2000).

The concentration of crop residues on the soil surface protects the soil from temperature extremes and makes the surface soil less subject to thermal stress that could decrease root density. This protection also facilitates more efficient conservation and usage of soil water (Merrill et al. 1996; Fabrizzi et al. 2005). These factors can have a significant effect on earlier stage root growth and moderate soil condition extremes longer into the growing season leading to higher root biomass near the surface and higher C inputs for NT (Qin et al. 2004).

The chemical nature of roots and their physiochemical role in soils means that root material can be preferentially preserved in soils, relative to aboveground shoot material. Mechanisms for preferential preservation of root material are significant as root-derived C has been shown to be an important for C storage in cropland soils (Flessa, 2000). Rasse (2005) described three primary mechanisms that could lead to preservation of root material. In terms of chemical composition, root material in cereal crops has high proportions of recalcitrant compounds such as tannins and lignins that are highly resistant to microbial degradation (Barbera, 2012). Roots can physically link soil particles into soil aggregates, and in doing so, lead to physical protection from microbial decomposition. Root exudates, in the form of labile organic compounds, can also act as glue-like agents to form soil aggregates. Due to the close proximity with the soil mineral matrix in the rhizosphere, exudates and decomposition products from roots are often bound up by mineral surfaces, leading to protection from further degradation.

Live root material, through exudation, sloughing off of fine roots, root hairs, and high activity of fine roots, can have a significant effect on the soil environment (Chirinda, 2012). Bolinder et al. (1997) estimated that, for cereals, 20-30% of C assimilated by the plant is allocated below ground in root material. Root exudates, in the form of labile organic compounds, may represent up to 50% of this allocation. Root exudates have been shown to be able to act as priming agents that can speed up decomposition or act as preservation agents that slow down or prevent decomposition (Rasse et al. 2005). Differential root densities based on tillage in near-surface soils could make a priming effect conferred by root exudates a significant consideration in tillage influences on C dynamics.

Percent Carbon and Carbon Stocks

For the whole profile (0-150 cm), there were no significant differences in C concentration or C stocks between the two treatments. This could be attributable to the relatively small contrast in terms of tillage intensity between the two treatments. Although not statistically significant, there was a trend of higher C storage in NT at the 0- to 30-cm and 30- to 60-cm depths. Previous work conducted on this same site suggests gains in C for NT, especially in the 30- to 60-cm depth over the first eight years of the experiment. Percent C and bulk density were measured from 0-60 cm in three NT and three CP plots in 2001 and 2009 using the same methods as described for this study. Carbon stocks for the 0- to 60-cm depth in 2001 averaged 105 Mg C ha^{-1} in NT and 102 Mg C ha^{-1} in CP. Carbon stocks as measured in 2009 were 116 Mg C ha^{-1} in NT and 100 Mg C ha^{-1} in CP. There was an increase in C stocks between 2001 and 2009 in NT, and the change occurred primarily in the 30- to 60-cm depth, with an average C stock in 2001 of 40 Mg C ha^{-1} and 47 Mg C ha^{-1}. Small increases in average C stocks were measured in the 0- to 30-cm depth as well. Past studies in the Palouse comparing primarily conventional tillage with NT have found trends of surficial (0-30 cm) C accumulation in NT treatments (Kennedy and Schillinger 2006; Purakayastha et al. 2008; Umiker et al. 2009; Brown and Huggins 2012). After 12 years, trends of higher C storage in NT may yet lead to significant differences in the future at this site. Carbon stock increases following conversion to NT management have been shown to peak after 10 years and slowly decrease to zero in the subsequent 10 years (Huggins et al., 1998; Govaerts et al., 2009).

While site-specific differences between studies makes C stock comparisons unreliable, it is possible to make broad comparisons. Recent studies have measured C stocks that are close to values measured in our study. After 50 years in a silt loam soil in a corn/soybean rotation comparing NT, CP and CT treatments, Kumar et al. (2012) found that NT stored significantly more C in the 0- to 10-cm depth (21 Mg C ha^{-1}) than either CP (17 Mg C ha^{-1}) or CT (17 Mg C ha^{-1}). Although not significant, NT also stored more C in the 0- to 30-cm depth (47 Mg C ha^{-1}) than CP (44 Mg C ha^{-1}). After 13 years comparing NT, CP, and CT treatments under continuous barley in a sandy silt soil, Morell et al. (2011) found similar C storage gains in the 0- to 30-cm depth for NT (50 Mg C ha^{-1}) over CP and CT (46 Mg C ha^{-1}).

There were no significant differences between NT and CP treatments in C concentrations or stocks in our study at any depth. This was not expected given the fact that root biomass, and therefore, root-C inputs were significantly greater under NT as compared to CP. Due to the sampling and processing procedures employed in this study (i.e. sampling in the inter-row), it is likely that the figures for root biomass are conservative, especially closer to the soil surface. Bolinder et al. (1997) found in reduced tillage that the amount of roots for cereal crops taken from 0- to 15-cm in the inter-row was 35% of the amount found in the same depth in within the row. The authors attributed the difference to the larger presence of coarse roots near the surface, as differences between sampling points were not significant in the 15- to 30-cm range. Even with conservative estimates in this study, the root biomass in the top 20-cm and the differences between the treatments is a significant C pool. Taking into account soil bulk density and C concentration of the root material itself, the root biomass collected from the top 20-cm represents approximately 0.40 Mg C ha^{-1} in NT and 0.22 Mg C ha^{-1} in CP for the 2012 growing season alone.

The fate of this portion of the C pool is critical to understanding tillage-related effects on agricultural systems. There are several mechanisms, although not measured in this study, which could explain why almost double the root C inputs in the top 20 cm of NT soil have not resulted in significantly greater C stocks. These include: 1) earthworm activity 2) biologically-driven changes in microbial decomposition rates due to priming agents, and 3) loss of C in the upper profile as DOC and translocation downward in profile facilitated by structural characteristics of NT soils. It is also necessary to consider the fact that the increased root biomass in NT isn't expressed in the carbon stock measurements due simply to the amount of total organic carbon already in the 0- to 20-cm depth. Even correcting for the conservative nature of the root biomass measurement, bringing the raw C input from roots in NT to around 1.2 Mg C ha^{-1} yr^{-1}, this amount is still only 3% of the total carbon stock of 45 Mg C ha^{-1} in the 0- to 20-cm depth.

The lack of disturbance in NT has been positively correlated with higher earthworm and burrow densities (Tomlin, 1995; Birkás et al. 2004). Studies within the Palouse region specifically focusing on tillage effects on earthworms have found trends of greater earthworm densities in conservation tillage fields compared to conventional tillage fields (Umiker et al. 2009). Results from the same research plot as this study found higher earthworm densities in NT and that earthworm populations responded quickly to the elimination of tillage (Johnson-Maynard et al. 2007). The larger earthworm populations found in NT are likely due to the lack of direct mortality from tillage operations and more favorable soil moisture and temperature conditions due to soil surface cover by crop residues. Earthworms can contribute to C cycling in soils through direct translocation of organic matter downward in the soil profile and can contribute to the DOC pool in soil through C-rich compounds left behind on the walls of burrows (Tomlin, 1995). However, through processing and interactions with gut biota, earthworm casts can influence microbial communities and activities, resulting in increased decomposition rates (Lubbers et al., 2013; Aira and Domínguez, 2014).

A priming effect refers to a large change in turnover of soil organic matter due to a relatively moderate addition of a C source to the soil. Priming effects can lead to large amounts of C and nitrogen being either immobilized (sequestered) or released into the soil through decomposition (Kuzyakov and Domanski 2000). In the case of our study, it is plausible that root exudates are acting as a priming agent to the soil microbial biomass and leading to increased mineralization rates due to preferential decomposition of the labile exudate material and organic matter. This priming effect would be more significant in NT where there is a higher concentration of root exudates and organic matter near the surface, relative to CP. However, due to the higher amount of C inputs, NT still has a trend for higher C stocks (Bailey et al. 2002).

The lack of disturbance in NT soils has been shown to lead to an increase in soil microbial biomass, relative to more conventional tillage regimes (Guggenberger,1999; Bailey, 2002; Li, 2012). This effect is likely confined to the top 20- to 30-cm of the soil column. The increase in soil microbial biomass is most likely attributable to the overall higher level of substrate in the form of crop residues and root material in NT soils, and the amelioration of soil temperature and moisture extremes by the crop residue cover (Frey, 1999). It is also possible that the large bio- and macro-pore network in NT soils facilitates superior gas, water, and nutrient movement within the soil column. Comparing NT and CT treatments in a silty clay loam soil after ten years, Martino and Shaykewich (1994) found that NT had more abundant and evenly distributed macropores likely preserved from old root growth. The priming effect speeding up microbial activity conferred by abundant root exudates that could be promoted by higher root densities in NT soils would speed up degradation of organic matter and production of dissolved organic carbon (DOC) compounds by the larger microbial biomass that conditions in NT can promote.

Dissolved organic carbon is an important C pool in soils due to its sorption activities with nutrients and the soil mineral matrix, as well as being an energy source for soil microorganisms and could be a significant factor in our study (Jiménez, 2006). Dissolved organic C is linked to the quantity and placement of plant residues and is affected by tillage intensity. The labile nature of DOC makes tracking its movement through the soil ecosystem difficult and this has limited our understanding of the role that DOC has in C sequestration (Grandy, 2009). Due to enhanced residue retention on the surface, DOC levels are generally greater in NT at the surface while more intense tillage regimes can have higher DOC enrichment at depth; however, the concentration of residues generally results in NT having higher overall levels of DOC than do tilled soils (Wright, 2007; Dou, 2008; Sun et al. 2011). Other than dissolution of organic matter, other major sources of DOC include soil microorganisms and root activity.

Translocation of DOC from these sources downward in the soil profile has been suggested as a significant means of C cycling in deeper soil layers (Lorenz, 2005). While there was no significant difference in bulk density between the NT and CP treatments in our study, there may be important differences in terms of soil structure and pore networks. Drees et al. (1994) showed through micromorphological analysis that, although conventionally tilled soils can have a higher total pore area than NT soils, average pore size was greater in NT. This difference in average pore size may be significant as a few large pores (occupying less than 30% of the total pore area) may account for greater than 70% of water flux through the soil column (Dunn and Phillips, 1991). Earthworm burrows are particularly applicable in this case due to their size, depth, and interconnectivity (Tomlin, 1995).

The environment in NT can promote greater amounts of DOC, relative to higher intensity tillage methods, by supporting a higher amount of root biomass, soil microbial biomass, and earthworm density (Govaerts et al., 2009). Additionally, it is possible that the microbial biomass is primed by root exudates, leading to higher degradation rates of the abundant organic matter in the surface layers of NT. Greater root and earthworm density under NT may be leading to increased macroporosity and the soil's ability to leach DOC to greater depths in the soil profile. In this study, there were no significant differences in C concentration or stocks in the surface soil layers. However, the whole profile for NT has a higher C stock (~5 Mg C ha^{-1}) than did CP, and 70% of this difference is accounted for in the 30- to 60-cm soil layer in NT (Figure 2.7). At the study site and in Palouse soils generally, there is a slight increase in clay content between 30 cm and 60 cm (Robertson, 2010). It is therefore plausible that the higher production of DOC and subsequent translocation of it downward in the profile is leading to C being sequestered by the soil mineral matrix. Conditions in subsurface soil layers are typically more conducive to C sequestration due to lower microbial activities and less available oxygen and can lead to subsurface soil being a significant C pool. The effects of tillage regime on subsurface conditions and C storage are not well understood and this data reinforces the need for C sequestration studies to focus on the whole soil profile.

CONCLUSION

Results from this study showed that there are no significant differences in C concentration or C stocks at any depth between NT and CP after 12 years. However, when calculated for the whole profile, there is a non-significant trend of higher C stocks for NT and this is in agreement with other studies on the same site. The difference in C stocks between NT and CP was roughly 5 Mg C ha^{-1} and approximately 70% of this difference was accounted for in subsurface soil layers well below the area physically effect by tillage. This coincides with a significant measurement of nearly twice the fine root biomass in surface soil (top 20-cm) in NT. It is likely that the dynamics observed in our study are the result of a complex interaction of tillage-induced differences in microbial biology, soil structure, and biochemistry. It is possible that the lack of disturbance in NT promotes an environment conducive to greater levels of DOC from rhizodeposition and microbial biomass, and that greater macroporosity and earthworm activity in NT may promote vertical translocation of C as DOC lower in the profile to be immobilized in the soil mineral matrix.

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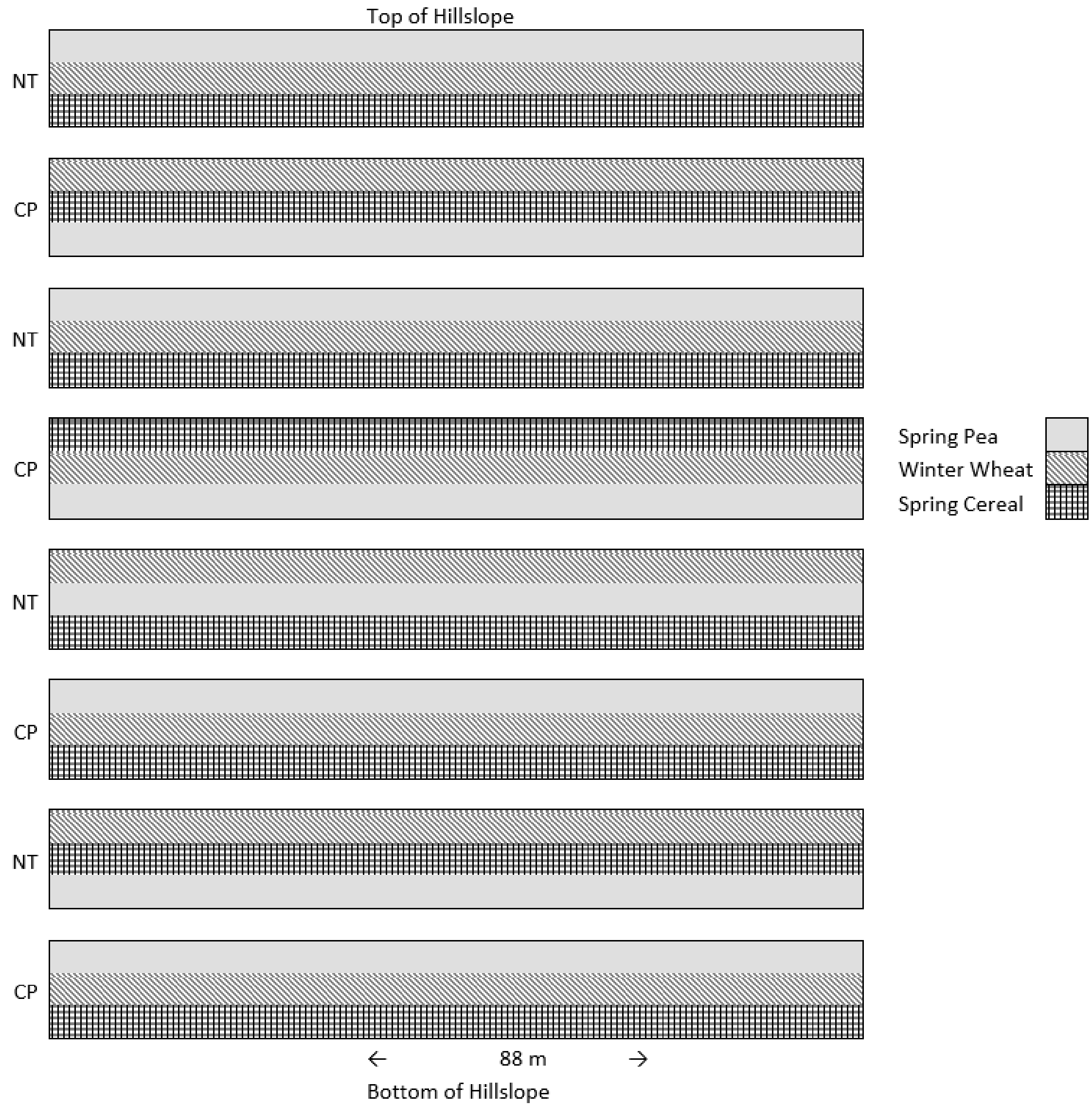

Figure 2.1 – Schematic of Kambitsch Farm site in 2012. Tillage plots are 88 m x 20 m. Crop sub-plots are 88 m x 7 m. Tillage plots are separated by a 1.5 m alley. Not to scale.

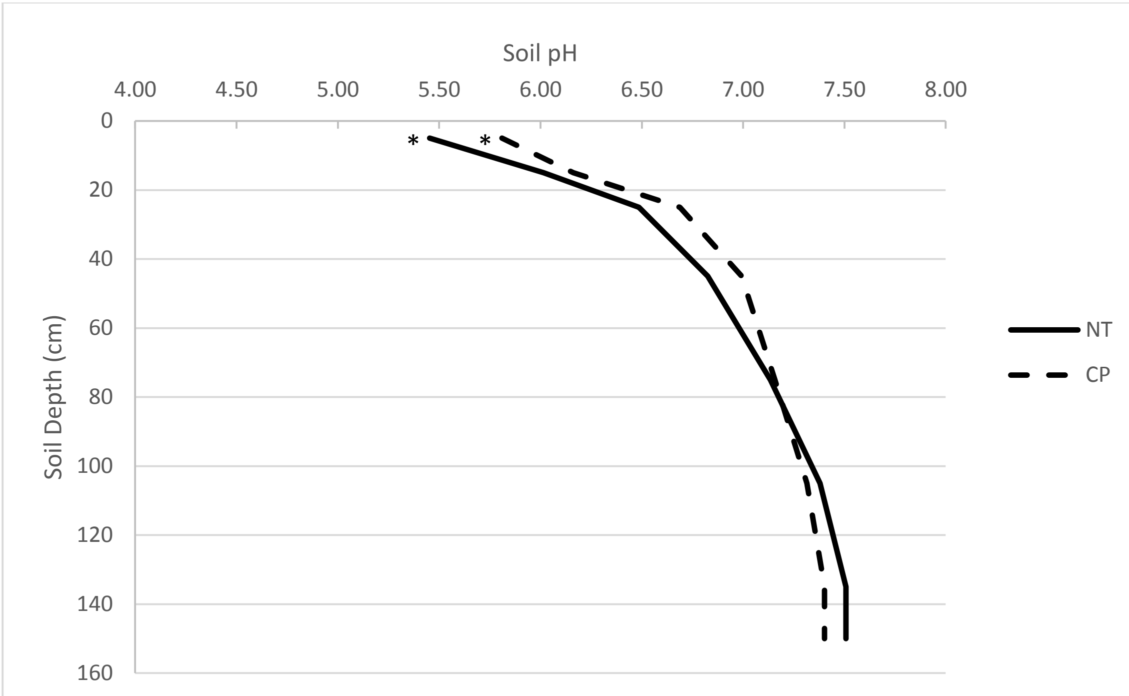

Figure 2.2 – Soil pH (1:1 with water) for NT and CP treatments in October 2012 at Kambitsch Research Farm, Genesee, ID. An asterisk (*) denotes significant difference (P=0.05) within a depth.

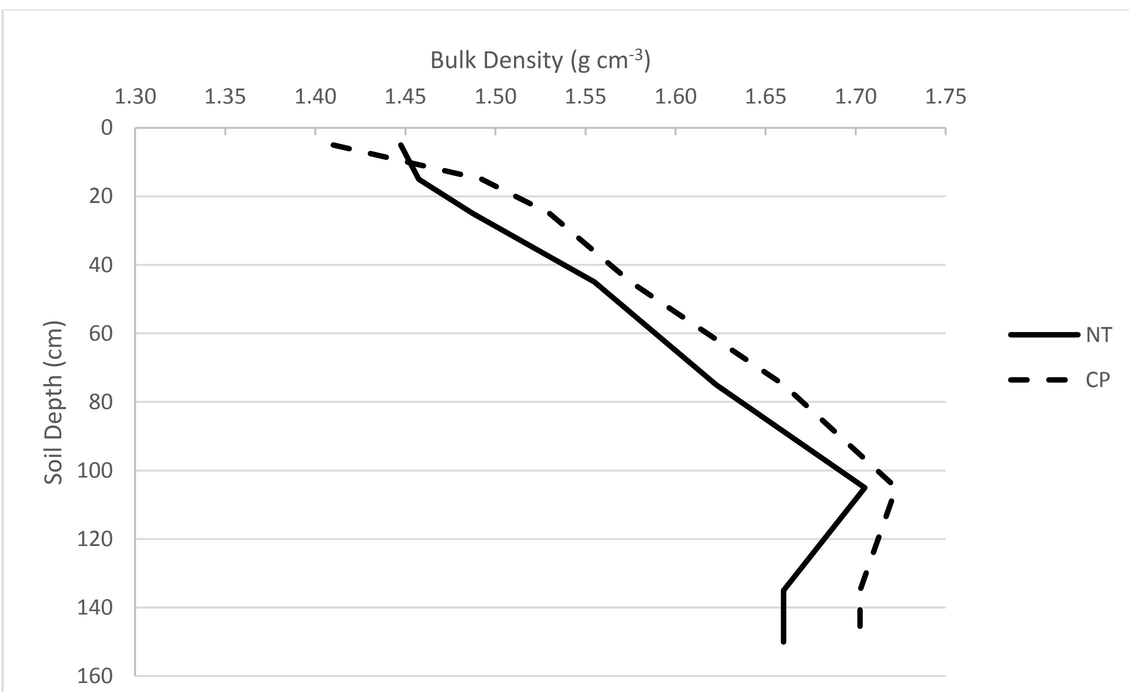

Figure 2.3 – Bulk density for NT and CP treatments in October 2012 at Kambitsch Research Farm, Genesee, ID

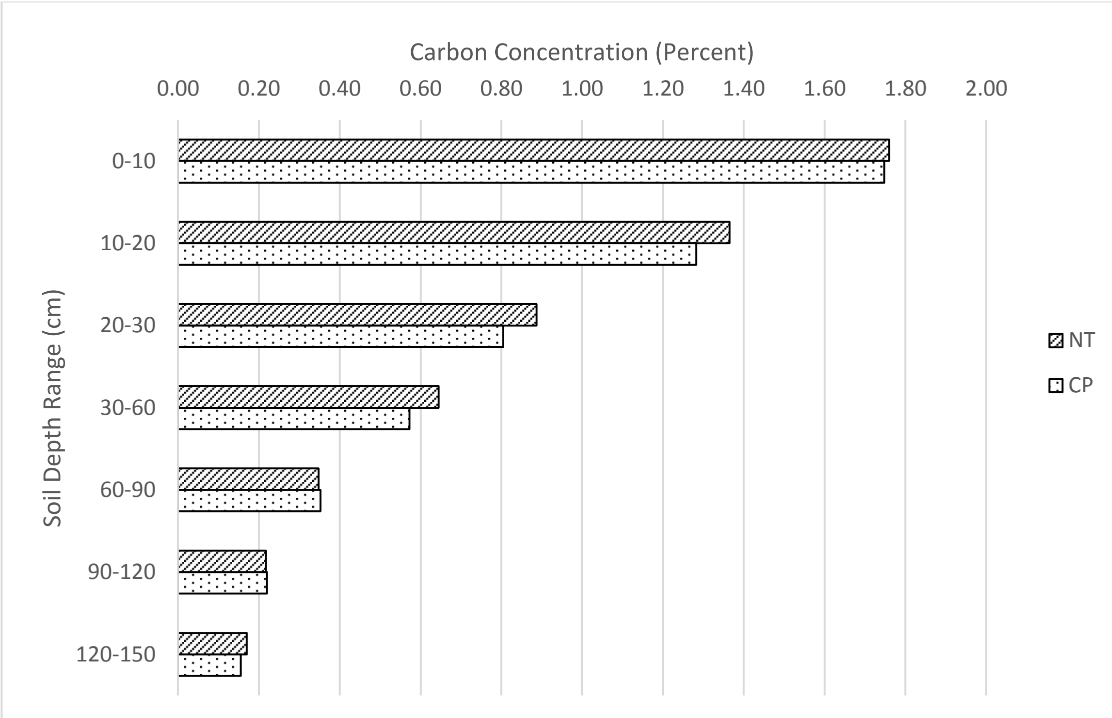

Figure 2.4 – Percent carbon values for NT and CP treatments in October 2012 at Kambitsch Research Farm, Genesee, ID

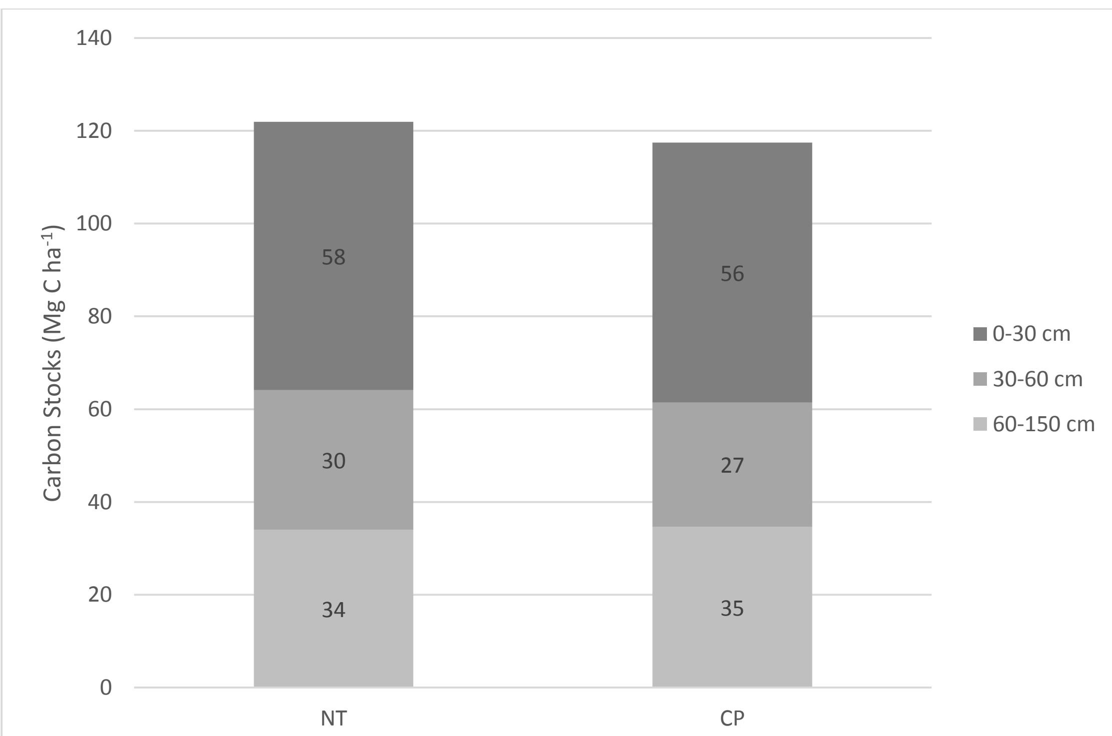

Figure 2.5 – Carbon stocks to 150 cm, separated into different profile sections, for NT and CP treatments in October 2012 at Kambitsch Research Farm, Genesee, ID

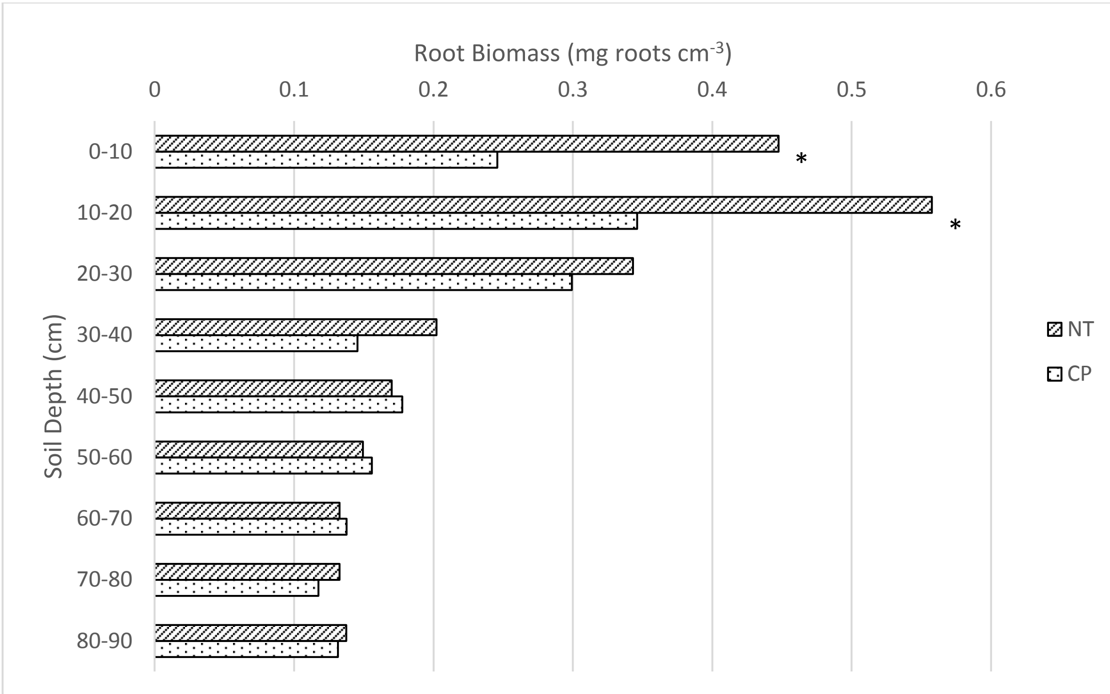

Figure 2.6 – Fine root biomass measurements for NT and CP treatments taken post-harvest in October 2012 at Kambitsch Research Farm, Genesee, ID. An asterisk (*) denotes a significant difference within a depth.

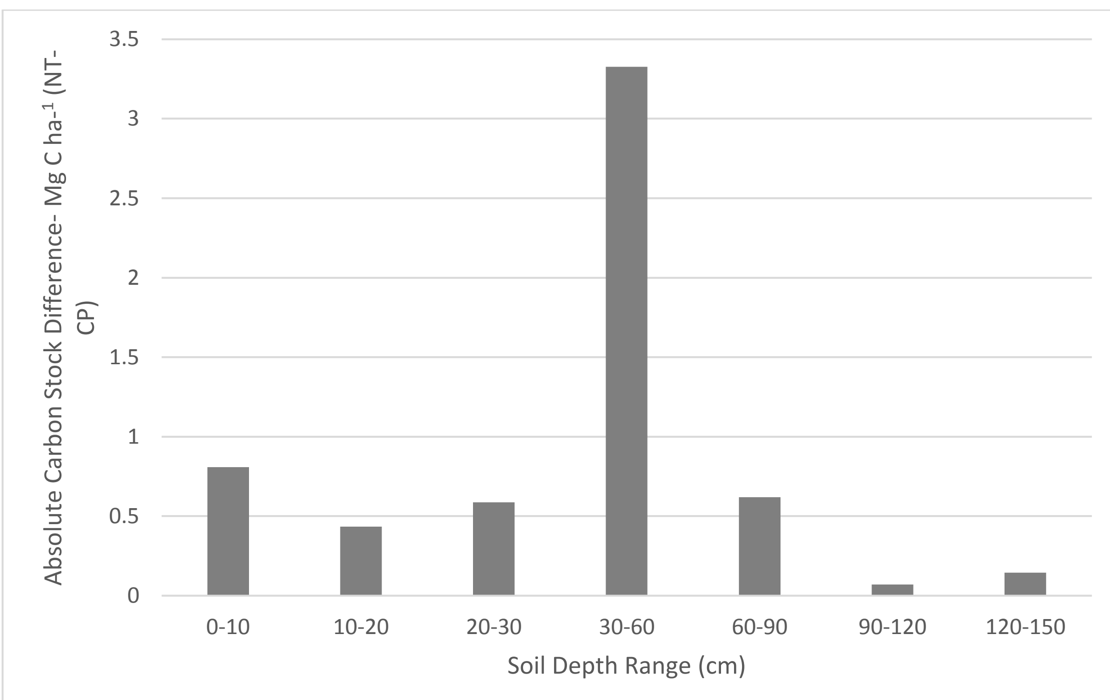

Figure 2.7 – Absolute carbon stock differences between treatments (NT minus CP) for each depth range taken post-harvest in October 2012 at Kambitsch Research Farm, Genesee, ID

CHAPTER THREE: CARBON STOCKS AND TILLAGE IN PALOUSE AGRICULTURAL SOILS

ABSTRACT

Human-related activities result in the emission in over two trillion pounds of heat-trapping carbon dioxide annually and it is estimated that this may result in global mean temperatures rising between 4 and 11 degrees Fahrenheit. Carbon sequestration, the process of fixation and long-term storage of atmospheric carbon dioxide, has become one of the defining issues of the world scientific community in the 21st century and is looked at as a way to manage atmospheric CO_2 concentrations. There is significant potential for carbon storage in the terrestrial carbon pool and particularly in agricultural soils due their sensitivity to land use changes like tillage. Tillage is the mechanical disturbance of soil that is utilized to prepare a suitable seedbed and reduce competition from weeds. Tillage can affect soil carbon input through influences on plant growth and returns to the soil and carbon losses through influences on the decomposition rates of micro-organisms, the balance of which determines whether net carbon storage occurs. Carbon is often highly variable on a field-scale due to relationships with the landscape and carbon sampling requires accounting for this variability to obtain samples that are representative of the area being studied. Carbon measurements are typically reported as percent of the sample (concentration) and this measurement is limited in its usefulness in comparing values to other studies. Bulk density is used to express carbon concentration as a mass of carbon, which has considerable utility in comparing to reported values from different soil types and climate zones.

Introduction

The Palouse region of eastern Washington and northern Idaho covers over two million acres and comprises one of the most productive wheat (*Triticum aestivum* L.) producing agricultural areas in the United States. Over one million acres of the Palouse region is cropland where the principle crop, wheat, is grown in rotation with, barley, peas, lentils, and canola. Underlying this highly productive cropland are deep, fine-textured soils derived from wind-blown silt material (loess) and formed under native grassland vegetation. The Palouse region is characterized by complex and steep topography; over 80% of the cropland in the Palouse has a slope between 8 and 30 percent, and some slopes up to 45% are farmed (Hall, 1999). Historically, the prevalence of high intensity tillage methods, combined with the steep topography, resulted in soil erosion rates that exceeded 25 t ac^{-1} yr^{-1} (0.125 in yr^{-1}). However, in response to the widespread environmental impacts of soil erosion, lower intensity tillage methods that reduced soil erosion began to be adopted in the 1970's. Conservation tillage methods are now dominant in the region (Kok et al., 2009).

Global climate change has become a defining issue for the world scientific community in the 21^{st} century. It is estimated by the Intergovernmental Panel on Climate Change that emissions of heat-trapping greenhouse gases due to human activities (e.g. burning of fossil fuels) may result in global mean temperatures rising between 4 and 11 degrees Fahrenheit in the next century (Pachauri, 2014). In terms of total emissions, carbon dioxide is the largest of the greenhouse gases, with human activities resulting in over two trillion pounds of emissions annually (Govaerts et al. 2009). Carbon sequestration, the process of fixation and long-term storage of atmospheric carbon, has become one of the focal points of climate change research. Storage of carbon in the terrestrial carbon pool-primarily comprised of plant biomass, soils, and microbial communities-presents a practical option to enhance carbon sequestration. The top three feet of soil worldwide stores over 3000 trillion pounds of carbon, more than twice the storage in the atmosphere and is only surpassed by the oceans (West and Post, 2002).

In contrast to the carbon stored in the oceans or atmosphere, the terrestrial carbon pool is predominantly made up of organic carbon derived from living things and is able to be actively managed through land use techniques. Carbon levels in soils are determined by the balance between carbon inputs from plant biomass and organic amendments and carbon losses from decomposition and erosion (Olson and Al-Kaisi, 2015). Carbon inputs into the soil include the process of photosynthesis by plants, incorporation of crop residues into the soil, and root exudates and turnover belowground. Carbon losses from the soil include decomposition and plant respiration as well as erosion and leaching losses from the profile (Figure 3.1). It follows that to store carbon in soils, the inputs must exceed the losses. In this sense, large agricultural areas like the Palouse present a significant opportunity for carbon sequestration. Agriculture management methods can have effects on the inputs and outputs of carbon and therefore have significant ramifications as to whether a particular system is a net store or net sink for soil carbon. The size of the terrestrial carbon pool is such that even small changes, such as those possible in agricultural management, can have significant effects on the global system (Kirschbaum, 2000).

A major element of agriculture management is tillage. Tillage is broadly defined as the mechanical mixing of surface soil to varying depths that serves to create a suitable seed bed, incorporate residues and amendments, and reduce competition from weeds (Gebhardt, 1985). Tillage management is the primary control on the amount and placement of crop residues in the soil profile. Tillage methods that retain 30% or greater of crop resides on the soil surface are defined as conservation tillage (CT), which can also be referred to as reduced tillage, and tillage methods that retain greater than 90% of residues on the soil surface are defined as no-till (NT). No-till is considered part of the conservation tillage spectrum. Conventional or moldboard plow tillage (PT) typically overturns soils to a certain depth, incorporating most residues into the soil profile and leaving only sparse residue cover on the surface.

Marland et al. (2003) categorized four sources of carbon losses through emissions in agricultural systems: 1) plant respiration; 2) the decomposition of organic carbon in soils and crop residues; 3) the use of fossil fuels in agricultural machinery; and 4) the use of fossil fuels in the production of inputs such as fertilizers. Tillage influences factors within the soil environment that largely determine the decomposition rate carried out by soil micro-organisms and the availability of crop residues to these organisms: residue placement, soil structure, and soil moisture and temperature (Syswerda et al., 2011). Tillage can also influence soil carbon inputs to the soil through effects on the production of aboveground shoot material and belowground root material (Qin et al. 2004; De Vita et al. 2007). In this sense, CT methods may promote soil environmental conditions that reduce decomposition rates and carbon losses from the soil as well as increase carbon inputs, leading to net carbon storage. However, the full nature and magnitude of this effect is not fully understood (Van Eerd et al. 2014).

Tillage Influences on Carbon Storage

Bulk density, the mass of soil per unit area, is a reflection of the amount of soil pore space and is therefore a significant control on water, gas, and root movement within the soil. Bulk density is considered to be an indicator of soil quality, as it increases due to compaction. Tillage can influence bulk density through the mechanical disturbance and loosening of near-surface soils that rearranges soil particles, however, it has been shown that soil type may be a more significant factor in bulk density (Christopher, 2009). Historically, it has been found that NT can lead to varying degrees of soil compaction due to the lack of soil disturbance, but this effect is restricted to surface soils and the difference is small in relation to PT and CT (Gal, 2007). The increased values in NT are typically not past the threshold that would impede root growth (greater than 0.60 lbs in^{-3} or 1.70 g cm^{-3}) in silt-loam textured soils found in the Palouse (Fabrizzi, 2005). Additionally, conditions in NT can promote larger amounts and preservation of macro-pores from former root channels and soil fauna that can mediate elevated bulk density and soil compaction by providing preferential channels for water movement and new root growth (Drees et al. 1994). This can lead to increased plant productivity and carbon returns to the soil as well as the downward transport and storage of carbon deeper in the profile (Chirinda et al. 2012).

Tillage serves to incorporate amendments such as fertilizers and liming agents, so the amount and placement of amendments and nutrients within the soil profile is often dependent on the intensity and depth of tillage. Crop residues under NT management are not incorporated into the soil profile causing nutrients and amendments to become concentrated in surficial soils (Doran, 1980). Negative impacts of the stratification of nutrients are sometimes apparent in Palouse soils when nitrogen fertilizers are applied in NT systems. As bacteria oxidize ammonium (NH_4^+) they produce hydrogen ions which lower pH (increase acidity) in the near-surface soil (Hussain et al. 1999). This effect does generally not occur in higher disturbance tillage systems since near-surface soil is mixed with higher pH subsoil during tillage operations (Dikgwatlhe et al. 2014). The lack of incorporation in NT is significant for less mobile nutrients (e.g. phosphorus), and these nutrients may be stratified in near-surface soils. Greater soil pore connectivity and preservation of larger soil pores in CT systems may allow the transport of more mobile nutrients (e.g. nitrogen and potassium) deeper into the soil profile (Bronick and Lal, 2005). Soil pH and nutrient status differences due to tillage can alter carbon inputs into the soil by influencing crop productivity and carbon returns to the soil.

Soil moisture and temperature are strongly correlated to each other, largely due to the specific heat of water regulating temperature fluctuations in soil (i.e. dry soil heats up faster than wet soil). Tillage can directly influence soil moisture content and temperature by affecting soil structure characteristics and by controlling residue retention that affects rates of surface runoff, water infiltration and thermal stress on the soil through the growing season (Abid, 2009). Residue retention in NT provides the soil surface with insulation from solar radiation. Residues can keep soils colder and inhibit germination and crop growth early in the season and the same residues can reduce thermal stress during the warmest periods of the growing season (Fabrizzi, 2005). Stress on plants related to moisture and temperature, either too much or too little, can result in impacts on plant productivity and carbon returns to the soil. Moisture and temperature conditions also significantly influence carbon losses through decomposition by soil micro-organisms.

The production of aboveground shoot material and the degree to which it is returned to the soil is often the primary factor addressed when considering the effect of tillage management on carbon storage. However, root material in cereals can account for 20-30% of carbon assimilated by the plant through photosynthesis (Kuzyakov and Domanski, 2000). Root distribution is a reflection of a plant's ability to access nutrients and water, as well as structural factors that influence how easily roots can move through the soil. No-till can promote favorable conditions in near-surface soils, especially in terms of moisture and nutrient content, which can lead to superior root growth compared to CT and PT (Vakali et al. 2011). Additionally, the lack of disturbance in NT can preserve preferential channels in the form of large, connected soil pores for new root growth (Munoz-Romero, 2010; Chirinda, 2012). Roots are a significant source of carbon in soils due to chemical characteristics that make roots more resistant to decomposition and the release of carbon compounds into the soil by live roots (Rasse et al. 2005). These mechanisms for preferential preservation result in the proportion of root material represented in relatively stable, long-term pools of carbon being as much as 2.3 times as much as shoot material (Katterer et al., 2011).

Estimates of Carbon Stocks

Several studies within the Palouse region have measured carbon stocks and contrasted carbon storage between tillage methods. Comparing 24 fields to a depth of 50 cm, split evenly between PT and CT, Umiker et al. (2009) found that NT increased carbon concentration in near-surface soils. Site differences in erosion, productivity, and decomposition rates due to the complex topography of the Palouse likely hindered the ability to detect significant tillage effects. Robertson (2010) examined CT and NT treatments to a depth of 60 cm on a single hillslope and found that NT had a larger net gain in carbon storage than RT in the eight years the treatments were in place. Purakayastha et al. (2008) examined carbon storage in the 0- to 20-cm depth in a wide range of tillage management regimes including native grassland, PT, and fields managed by NT practices for both 4- and 28-year periods. Carbon stocks under PT were significantly lower than those measured under the other treatments while both short and long term NT showed significant carbon storage gains in the 0- to 5-cm depth.

More recent studies have compared carbon stocks between tillage treatments. After 50 years in a silt loam soil in a corn/soybean rotation comparing NT, CP and CT treatments, Kumar et al. (2012) found that NT stored significantly more carbon in the 0- to 10-cm depth (9 t C ac^{-1}) than either CT or PT (8 t C ac^{-1}). NT also stored more carbon in the 0- to 30-cm depth (21 t C ac^{-1}) than CT (20 t C ac^{-1}). After 13 years comparing NT, CT, and PT treatments under continuous barley in a sandy loam soil, Morell et al. (2011) found similar carbon storage gains in the 0- to 30-cm depth for NT (22 t C ac^{-1}) over CT and PT (21 t C ac^{-1}).

Sources of Variability

The determination of net carbon stock changes following a change in tillage management is complicated by the effects of tillage on a wide array of soil physical and biological characteristics, each with its own implications for crop productivity, return of carbon to the soil, and therefore the overall carbon balance. Measurements of carbon storage can be highly variable spatially and based on the depth range sampled as well as the amount of time the tillage treatment has been in place. Additionally, the potential of CT methods to sequester carbon can be highly variable due to complex, site-specific interactions of management with climate, soil type, erosion, and crop rotation (Blanco-Canqui et al. 2011).

Net carbon storage typically occurs in zones where crop residues are incorporated (Dikgwatlhe et al. 2014). As a result, the depth of sampling often has a significant effect on whether a difference in carbon storage is found between two tillage methods. Studies that only examine near-surface soil (0- to 20-cm) typically find that NT soils are enriched in carbon in relation to tilled soils of the same type (Franzluebbers, 1994; Alvarez, 1995). This pattern is attributed to the surface concentration of residues resulting in less contact between the soil and the residues, as well as soil moisture and temperature conditions in NT soils that often lead to slower decomposition rates (Fuentes, 2012).

Studies comparing NT and PT that examine larger portions of the profile typically find surficial carbon enrichment in NT, but have also found carbon enrichment in deeper soil layers in PT, resulting in small or no net carbon storage for NT (Jemai et al. 2012). Enrichment of deeper soil layers in PT coincides with the depth of tillage, where most of the surface residues are deposited. This is due to increased contact of residues with subsoil materials that generally promote low decomposition rates due reduced microbial activity and increased clay content. Clay can bind with organic material, making it unavailable to micro-organisms carrying out decomposition (Olson and Al-Kaisi, 2015).

The period of time that a tillage treatment has been in place also makes a significant difference in detecting carbon stock changes. Conversion of native grassland to agricultural production can reduce the annual return of plant biomass to the soil by up to 80%, leading to a 20-30% overall loss of carbon stocks (West and Post, 2002). This loss is primarily due to significantly lower root biomass and overall productivity of annual crops in relation to native grasslands, as well as tillage effects on soil moisture and temperature (Janzen, 1998). In terms of physical properties and carbon storage, soil ecosystems typically respond quickly to changes in tillage management. A majority of the initial carbon stock losses upon the cultivation of a native grassland may happen within three to five years, after which the losses level off until a new carbon balance between inputs and outputs is reached (Govaerts et al. 2009). Carbon stocks can be slow to change when tillage management changes to NT. The rate of carbon gains generally increase slowly in the first five years, peak between five and ten years, and decrease to near-zero between 15 and 20 years as the system reaches a new balance between carbon inputs and losses (Huggins et al., 1998).

Two samples taken from the same depth, but from different parts of a field are likely to contain different amounts of carbon. Additionally, changes in soil carbon content as a result of changes in tillage management or any other land-use change will occur in a non-uniform pattern across a field (Conant, 2011). Field-scale differences in carbon content are largely driven by topography, especially in highly variable, complex landscapes like the Palouse region. Topography refers to the physical configuration of the land surface with respect to elevation and slope (Buol et al. 2011). In particular, slope steepness as well as the compass direction the slope is oriented toward (aspect) can be sources of field-variability in carbon content due to the influences of slope on water movement, erosion, soil moisture and temperature, and soil formation (Govaerts et al. 2009).

The consideration of aspect in carbon sampling is especially important in complex landscapes like the Palouse where steep slopes up to 45% may be farmed (Kok et al. 2009). Aspect influences the amount of sunlight a slope receives and the steepness of the slope can intensify the impact of aspect. The effect of aspect is significant when considering north/east and west/south-facing slopes: north/east-facing slopes tend to receive less sunlight and south/west-facing slopes tend to receive more intense sunlight. This can result in north/east-facing slopes being cooler and wetter than south/west-facing slopes (Egli et al. 2006). In Mediterranean climate areas such as the Palouse where the summer months are often very dry, cooler and wetter soils can result in increased plant productivity and also favors conditions that promote slower decomposition rates (Buol et al. 2011). Increased carbon returns to the soil due to higher productivity and decreased losses from decomposition can lead to north-facing slopes generally having higher carbon stocks. This difference is highlighted in two profiles taken from the same CT field in the Palouse where the profile measured on the north-facing slope has 24 tons of carbon per acre more than the south-facing slope, although this effect is not always as pronounced (Figure 3.2).

Sampling and Measuring Soil Carbon

Accounting for these factors of variability requires a careful and methodical sampling plan. The process of sampling and measuring soil carbon is generally split into obtaining the samples and analyzing the samples in a laboratory. Carbon sampling can be approached as a single “point in time” measurement; however it is more common for a sequence of samples to be taken over a specified period of time to establish the magnitude of carbon storage as well as the rate of any change that is taking place. The absolute amount carbon in soil may vary by climate, soil type, and crop rotation and this often makes comparing soil carbon measurements unreliable. However, by taking samples over a period of years, more reliable comparisons may be made. This sort of monitoring may be started at the onset of a change in land use, such as an alteration in tillage management. It is important to have clear objectives, both in terms of the geographic area being studied and of what is trying to be accomplished through the sampling. The size of the area and the overall objectives will largely dictate the location and number of samples needed.

Soil carbon is most often measured directly from soil samples that are analyzed in a laboratory. There are emerging technologies that may be able to measure soil carbon non-destructively and *in situ* (i.e. in the field without disturbing the soil for a sample), however, these methods are still being developed and refined (Conant, 2011). The most common method for gathering soil samples for analysis utilizes a soil coring device. These devices come in a myriad of forms ranging from simple T-shaped probes that are either pushed or hammered into the soil to hydraulically-drive probes that must be mounted on tractor or other vehicle. The type of probe used for sampling depends upon soil conditions and the depth range being sampled; shallower sampling or moist soil may be collected easily with a push probe while deep sampling or hard, dry soils may require heavy equipment. Soils with a high content of stones, gravel or coarse fragments may necessitate the digging of a soil pit where samples are taken from individual depths one at a time with a handheld probe. In terms of timing, if carbon sampling of an area is being undertaken in response to a change in land management (i.e. tillage), an initial round of sampling should take place before or very close to that change to establish a starting point in terms of the carbon in the soil. By establishing a baseline, future carbon measurements can be compared to determine the effect of the management on the soil.

In many cases, it may be useful to break the sampling area into subsections based on landscape qualities (e.g. steep slope, gentle slope, flat area). Mahler and Tindall (1997) describe this process at length as part of overall nutrient sampling. In the process of developing these subsections it is also important to note areas where sampling should not take place such as along fence lines, very shallow soils, or depressed areas that tend to collect washed-out soil and water (Mahler, 1997).

Within each subsection, several full-profile samples should be taken. The sampling locations within each section can be made semi-random by sampling in a zig-zag pattern. Once the samples in each section have been taken, samples from the same depth can be mixed together into a composite. This composite will be sub-sampled for analysis. Sampling sites can be marked with a GPS unit for future reference.

Once the samples have been obtained, they are typically stored in a cooler at around 38 degrees Fahrenheit until processing begins to decrease the activity of micro-organisms in the samples. If samples were taken as intact soil cores, the cores are cut into specified depth sections and air-dried. Air-drying is an important process because microbial decomposition will continue to occur in field moist soil and oven drying may result in the burning off of carbon from the samples. Once dry, samples may be sieved to remove rocks and gravel as it is often impractical to grind these rocks for analysis and the carbon content from rocks in the soil is typically not included in soil carbon measurements. The soil samples are then ground either by hand (i.e. with a mortar and pestle) or with an electric soil grinder to break down soil fragments into soil particles. After grinding, the soil samples are sieved again to remove organic matter such as crop material and roots that are most often excluded from soil carbon measurements.

Each ground sample is thoroughly mixed and a sub-sample is taken from it for carbon analysis. The most common method for soil carbon measurement is dry combustion and this method generally requires less than 0.03 oz (1 gram) of soil per sample. Typically, the soil is weighed into porcelain crucibles that are then placed by a machine into a furnace heated to 1650 degrees Fahrenheit. The temperature of the furnace is hot enough that all of the carbon in the soil sample undergoes complete combustion and is released as carbon dioxide that is collected and measured by the analyzer.

When soil carbon is measured, it is generally necessary to consider the presence of inorganic carbon sources such as soil carbonates. General carbon analysis by dry combustion will not make a distinction between the types of carbon in a sample. While inorganic carbon is part of the overall carbon cycle, it is not subject to consumption by soil micro-organisms and changes on different timescales than organic carbon sources and it is therefore not always included in soil carbon calculations. Carbonates are transported in the soil profile easily by water, so carbonates are generally washed out of the soil profile in higher precipitation areas. However, steeper or dryer slopes may have carbonates present within the measured soil profile. Carbonates are sensitive to soil pH (i.e. they dissolve in acid) and so carbonates are only considered a concern in soils with a pH higher than 6.8.

The results from carbon analysis are usually reported as the percentage of carbon in the sample (carbon concentration). This measurement is limited in its usefulness because it isn't expressed as a weight of carbon in the sample (i.e. pounds of carbon) and it doesn't incorporate the volume of the soil being measured. However, carbon concentration can be used to show trends in soil carbon in a particular field or area over time. Reliable comparison of carbon measurements requires converting carbon concentration into the mass of carbon (carbon stocks) using a measurement of bulk density.

Bulk density is the dry mass of soil per unit volume and is typically sampled using a push- or hammer-driven soil core that has a cylinder secured inside to hold the soil sample (Blake and Hartge, 1986). To avoid compaction within the soil core, it should be driven far enough into the soil to gather the sample from the required depth, but not compressed beyond that point. Ideally, bulk density measurements should be taken in late spring once the soil has dried out enough to walk on. Bulk density varies due to moisture content in soil, and therefore is somewhat variable over the season. Soil that is too wet is subject to compaction and also may not stay in the sampler while soil that is too dry typically has elevated bulk density and the sampling process can lead to cracking and rearrangement in the sample that can distort the measurement. Bulk density is measured by determining the difference in mass between the moist soil sample and the same sample after it has been oven-dried. The volume of the soil sample is obtained by calculated the volume of the soil core.

Carbon stocks are calculated by multiplying the carbon concentration by the bulk density of the soil and the depth of soil in question (i.e. 12 inches of soil). After accounting for unit conversions in the calculation, carbon stocks are expressed as a mass of carbon per unit area for a specified depth range (i.e. tons of carbon per acre for the 0- to 12-inch depth). Calculating carbon stocks for an entire measured soil profile requires calculating and adding the stocks from all of the depth ranges that were measured. An example calculation for carbon stock is shown below for a sample from the 0- to 12-inch depth with a bulk density of 0.05 lbs in^{-3} (1.25 g cm^{-3}) that was analyzed and measured at 2.5% carbon:

$$0.025 \times \frac{0.05\ lbs}{1\ in^3} \times 12\ in = \ 0.015\ lbs\ C\ in^{-2} \times 3135 = 47\ t\ C\ ac^{-1}$$

In the above calculation, 2.5% has been divided by 100 and 3135 represents the unit conversion from lbs in^{-2} to t ac^{-1}.

The use of bulk density is important as measured values can be highly variable, both spatially and with depth. Profiles that may otherwise look identical if just concentration were considered can become contrasting when bulk density values are incorporated and carbon stocks are calculated. A measurement of carbon concentration in two profiles from the same CT field in the Palouse region shows two nearly identical profiles; both with average concentrations of 1.4% for the 60 inch profiles that were measured (Figure 3.3). However, the bulk density measurements of the same profiles were different, especially near the surface where the average bulk density values for the 0- to 12-in depth range was 0.043 lbs in^{-3} (1.17 g cm^{-3}) in Profile 1 and 0.05 lbs in^{-3} (1.38 g cm^{-3}) in Profile 2. When carbon stocks are calculated, this difference results in five more tons per acre of carbon in Profile 2 in the 0- to 12-in depth (Figure 3.4). Further variability in the bulk density profiles result in differences in carbon stocks at depth as well.

Recommendations for the Palouse Region

The complex, variable landscape of the Palouse region leads to high field-scale variability in carbon stocks. Additionally, the most common crops grown in the region are cereal crops, which have rooting depths that can extend below five feet in the soil profile. These factors can present challenges to obtaining representative samples as the variability can require more intensive sampling and the rooting zone of cereals necessitates deeper sampling. As demonstrated by measured profiles from the Palouse region, over 60% of carbon can occur below one foot and half of that can be found between two and five feet belowground (Figure 3.4). Grid sampling should be used when possible, however, the sampling method that breaks fields into subsections that is described above (Mahler, 1997) may be appropriate in accounting for this variability. The subsections should split the study area into distinct landscape sections, focusing on representing both cooler, wetter north/east aspects and warmer, dryer south/west aspects. Although sampling to five feet may not be practical for all situations depending upon soil conditions and available equipment, samples should be obtained from as deep as possible.

Conclusion

Field-scale variability, especially in a complex landscape like the Palouse can present significant challenges to measuring soil carbon in a manner that is representative of the area being sampled. However, by understanding the effects on field-scale variability due to natural soil processes and tillage, sampling plans can be developed that best account for the variability and allow for long-term monitoring of soil carbon conditions. The monitoring of soil carbon in agricultural settings, especially following changes in tillage management, will be significant to understanding landscape-scale carbon cycling and the ability of agricultural lands to store atmospheric carbon. Understanding the sensitivity of carbon stocks in agricultural soils to small changes is significant to the future of carbon sequestration research aimed at mitigating human-related carbon emissions and consequences of climate change.

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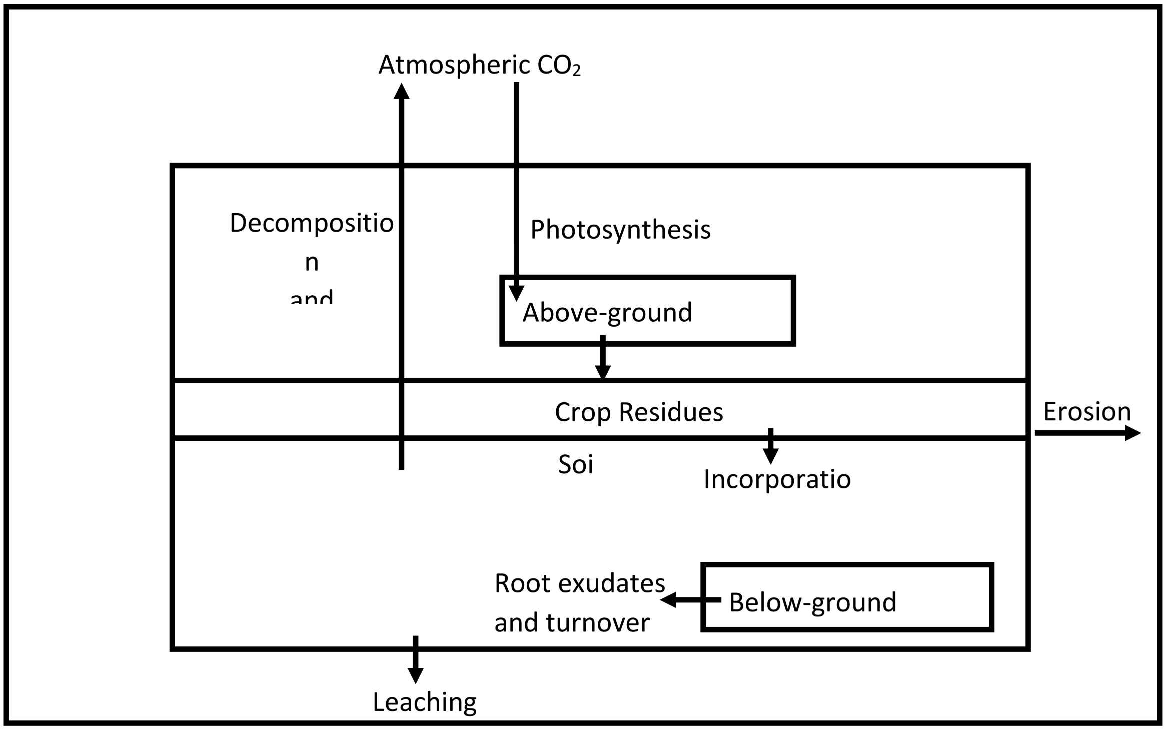

Figure 3.1 – Simplified diagram of carbon cycling in agricultural systems

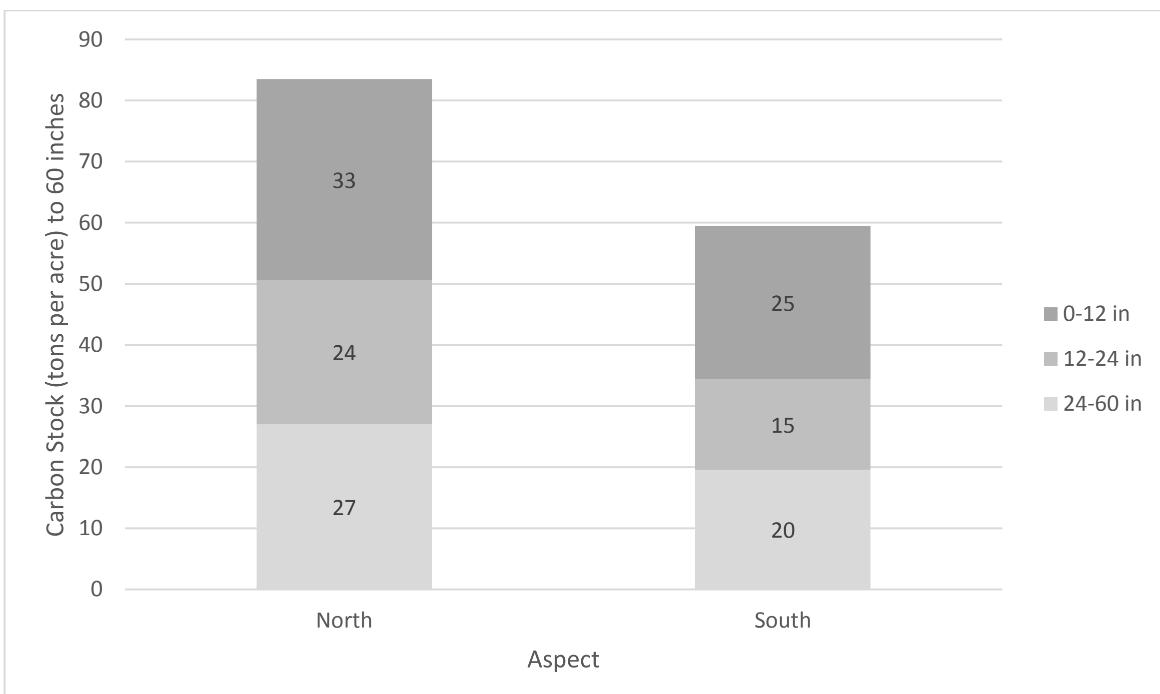

Figure 3.2 – Comparisons of carbon stocks from contrasting aspects from two on-farm soil profiles

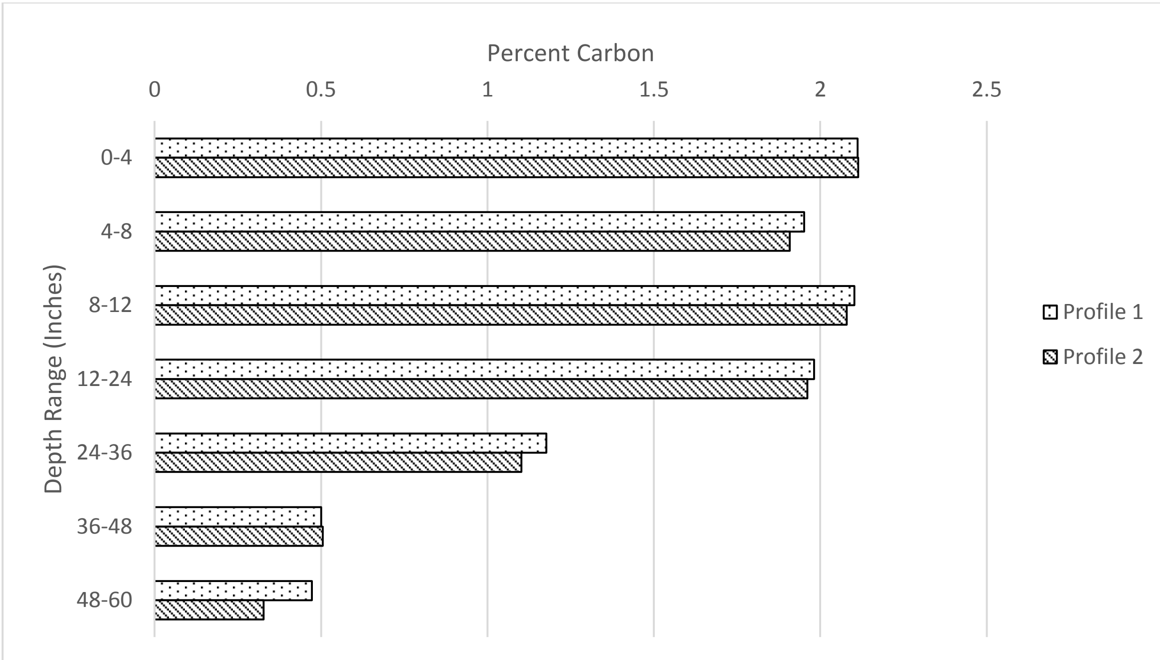

Figure 3.3 – Comparisons of percent carbon by depth in two on-farm soil profiles from the same field

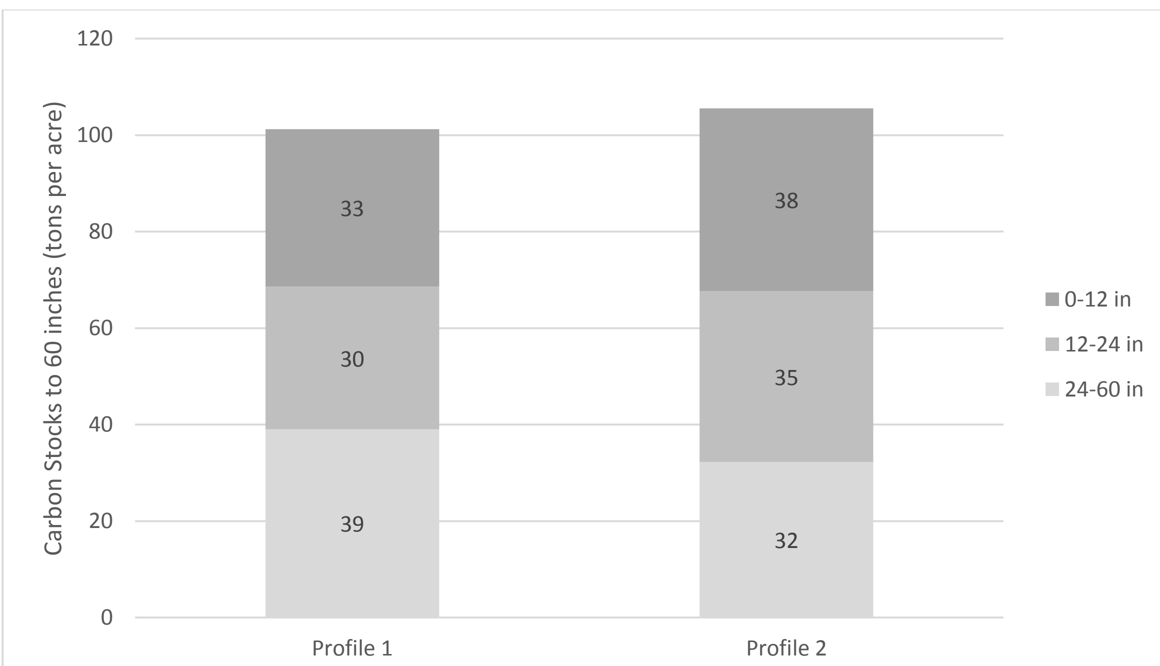

Figure 3.4 – Comparison of the two on-farm profiles from Figure 3.3 with bulk density used to calculate carbon stocks