Digging deeper: Surface and subsoil carbon as affected by N fertilizer and tillage in continuous corn

by

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Abstract

Agricultural practices such as added C inputs and adoption of no-till are known to increase soil organic C (SOC) near the soil surface; however, it is unclear if these effects persist at depth. A long-term experiment compared the effects of two tillage systems (no-till (NT) and conventional till (CT)) and N source on SOC in Mollisol planted with continuous corn (*Zea mays* L.) in central Kansas. The N sources included composted organic waste (OrgF), urea (MinF), and no N fertilizer addition (Ctrl). The soil profile to a depth of 120 cm was measured for soil organic C (SOC) and N, bulk density, dissolved organic C (DOC), and $\delta^{13}C$ and $\delta^{15}N$. Soil organic C in the soil profile was expressed as equivalent soil mass. Soil organic C and N were higher in the surface 5 cm in NT compared to CT, but the reverse was true within the 5-15 cm soil layer. Dissolved organic carbon (DOC) and the $\delta^{13}C$ and $\delta^{15}N$ signatures reflected the effects of OrgF addition to a depth of 45 cm; however, effects on soil organic C stocks were only apparent in the surface 15 cm. Twenty-two years of OrgF increased SOC stocks in the 0-15 cm layer by 18.2 Mg C ha^{-1} over Ctrl (-1.22 Mg C ha^{-1}) and MinF (2.24 Mg C ha^{-1}). In the profile (0-60 cm), all treatments lost SOC from the 1992 baseline except for NT OrgF (0.66 Mg C ha^{-1}). Conventionally tilled OrgF lost 7.49 Mg C ha^{-1} suggesting that NT conserved the additional C inputs more than CT. Most of the losses were in the 30 to 60 cm layers where there was a buried A horizon. Within the 30-45 cm depth, NT OrgF decreased losses of SOC (-3.80 Mg C ha^{-1}) compared to CT OrgF (-12.9 Mg C ha^{-1}). In summary, surface management effects on soil C sequestration were confined to the surface 15 cm even with additional C inputs. Although DOC and $\delta^{13}C$ was elevated with OrgF in the 15-45 cm depths, this did not result in sequestered C. In these annual cropping systems, considerations need to made for deep-rooted crops and rotations

to deliver C inputs into the subsoil; however, this must include no-tillage as tillage loses the benefits of additional C inputs.

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Dedication

This work is dedicated to my family. I would especially like to honor the memory of Harry and Valerie Watts, Gerald Rogers, Myrtle Warner, Nicole Watts, Ryan Kilgore, Gustav Åhr and Heather Heyer. To all people working for liberation: We have a world to win.

Chapter 1 - Introduction

Climate change is a threat to the interconnected global food, energy, and economic systems due to rising temperatures and more extreme and variable precipitation (Lal, 2016). The increased concentration of greenhouse gases in the atmosphere has increased global mean annual temperature since the pre-industrial era and is projected to continue (IPCC, 2018). Efforts to reduce greenhouse gas emissions and concentration in the atmosphere are required to mitigate these effects, and storing C in the soil is one way of doing so. The largest terrestrial pool of C is the soil with approximately 1550 Pg C in the upper 1 m of soil and up to 2400 Pg C, considering soil to 2 m in depth (Smith et al., 2007; Batjes, 2014). Soil has a large potential to store C with soil C sequestration which occurs when C replenishment is greater than C loss (Lal, 2016).

Conservation agriculture is a proposed method of both mitigating and adapting to global climate change by increasing soil organic C (SOC) stocks (Lal, 2016). This directly mitigates greenhouse gas emissions from soil and it is tied closely with adaptation to climate change because increased SOC generally makes soil more resilient to climate variability (Lal, 2016). One of the largest drivers of soil C emissions is land-use change, especially when converted from a native system into a managed system (Lal, 2011; Sanderman et al., 2017). Practices such as tillage, nutrient addition, and crop rotation are some of the main drivers of SOC dynamics in agricultural soils (Lal, 2011).

Historically, research has focused on the upper 20-30 cm of soil globally (Rumpel and Kögel-Knabner, 2011); however, more researchers are interested in deep soil C. In soils >1 m deep, over 50% of C in the soil profile is located between 25-100 cm (Batjes, 2014). In 2 m deep soils, 80% of C is located below the upper 30 cm, globally (Batjes, 2014). It has been shown that C can persist in the deep soil in an undisturbed environment for over 100 years (Torn et al., 2008). However, many studies show management practices such as tillage, cover crops, and the addition of manure or compost have differing effects on surface and subsoil C (Angers and Eriksen-Hamel, 2008; Maillard and Angers, 2014; Tautges et al., 2019). This study builds on this research and specifically focuses on the relationship between management practices and deep soil carbon. Moving forward, the focus will be directed to understanding the environmental and microbial controls on degradation and formation of SOC and management effects on C in the surface and subsoil.

Soil organic carbon sequestration

Soil carbon sequestration is a key strategy to mitigate greenhouse gas production. The soil carbon pool is in constant flux as soil microbes are drivers in both decomposition and stabilization of SOC (Liang et al., 2017). Carbon sequestration occurs when C replenishment is greater than C loss. Practices such as no-till, application of animal manure or compost, and cover crop rotation generally have great potential to store C in many cropping systems (Lal, 2011).

Soil organic carbon – modern and historical conceptions

Soil organic matter (SOM) must be considered in the context of global climate change. This is because climate and other ecosystem properties, like vegetation, affect the formation and decomposition of SOM (Schmidt et al., 2011). These properties directly influence SOC because of their influence on soil microbes which drive C cycling (Keiluweit et al., 2017). Soil microbes play a dual role in the release of SOC as carbon dioxide and methane and the stabilization of SOC (Schimel et al., 2011; Liang et al., 2017). This understanding of SOC cycling as dependent on ecosystem properties is relatively recent, and it is critical to explore the current paradigm of SOC research in this context (Schmidt et al., 2011; Kleber and Johnson, 2010).

Traditionally, SOC has been thought to become stabilized when it has been thoroughly processed into chemically recalcitrant macromolecules, which can no longer be consumed by microbes (Schaeffer et al., 2015). This is known as the humic substance model (Kuzyakov, 2010). Through a series of biotic and abiotic condensation reactions, it was believed that SOC could become resistant to degradation based on its molecular structure (Marschner et al., 2008; Kleber, 2010). However, recent research contradicts the humic substance model. For instance, compounds once thought stable, such as lignins and plant lipids, can turn over much faster than previously thought (Kleber and Johnson, 2010; Amelung et al., 2008). In addition to this, compounds that were once thought very labile, such as sugars, can become integrated into SOC efficiently (Voroney et al., 1989; Sokol et al., 2019) and stabilized for several decades (Marschner et al., 2008). Also, the abiotic condensation reactions of SOM to stabilized molecules, critical to the humic substance framework, are minor (Kleber and Johnson, 2010). Most stabilized SOC is processed by microbes to varying degrees (Miltner et al., 2012). This has led to the modern understanding of SOC processing by microbes as continuous, gradual, and dependent on environmental conditions (Liang et al., 2017; Cotrufo et al., 2013; Schmer et al., 2014).

The current understanding of SOC that replaces the humic substance model relies on a clearer understanding of the microbial processes regulating SOC dynamics (Liang et al., 2017). This ecosystem understanding focuses on how changes in the environment affect microbial communities and their ability to release or stabilize SOC (Jastrow et al., 2007; Schmidt et al., 2011; Liang et al., 2017). Major environmental controls identified on the soil microbial community include, but are not limited to: temperature, water content, oxygen content, nutrient availability, pH, organic carbon content, and size of particles and pores (Lehmann and Kleber, 2015; Hansel et al., 2008; Kirschbaum et al., 2004). Soil microbial biomass decreases exponentially with depth while more specialized communities develop in deep soil due to these environmental limitations (Kramer and Gleixner, 2008). It is important to review how each of these affects the microclimate within the soil, which controls microbial activity, and thus influence SOC dynamics.

Origin of soil organic carbon

There are believed to be two major pathways to SOC stabilization (Cotrufo et al., 2015). The first occurs over time; microbes consume labile C and transform it into a soluble form, as dissolved organic matter (DOM), which readily bind to mineral sites in the soil subsurface and become physiochemically protected (Kaiser and Kalbitz, 2012). This bonded material is referred to as mineral associated organic matter (MAOM). As time passes, conversion from DOM to MAOM slows and greater amounts of particulate organic matter (POM) increases, which is primarily made up of partially decomposed plant structural compounds (Cotrufo et al., 2015). The MAOM is naturally resistant to microbial decomposition by its physical and chemical bonds to soil mineral surfaces and is thought to be a pool that drives SOC sequestration (Cotrufo et al., 2013). A recent survey of over 8,000 European forest soils determined that the MAOM pool saturates while POM did not (Robertson et al., 2019). This suggests that MAOM is a major pathway in SOC stabilization (Robertson et al., 2019).

Most stabilized SOC is processed by microbes at some point (Grandy et al., 2008), and most soil C is derived from roots (Rasse et al., 2005; Sokol et al., 2019). One of the early changes in plant C is its aerobic decomposition and transformation into DOC (Cotrufo et al., 2015). Dissolved organic carbon is adsorbed strongly in the upper soil surface, close to where it was formed (Fröberg et al., 2007; Kaiser and Kalbitz, 2012). Dissolved organic carbon is measured from C content in dissolved organic matter (DOM). Dissolved organic matter can move through the soil by way of hydraulic flow and becomes tightly adsorbed to silt or clay mineral surfaces (Kaiser and Kalbitz, 2012). After being adsorbed, it can now be considered MAOM. This MAOM is physically and chemically protected from oxidation by microbial decomposition due to the anaerobic conditions at the mineral binding sites (Keiluweit et al., 2017). Over time, as more complex molecules are generally broken down into simpler compounds, the insoluble decomposition products can become part of the particulate organic matter (POM) pool. The POM fraction is generally compounds >2000 μm in size and turns over more slowly than DOC (Cotrufo et al., 2013). Simpler compounds and monomers became mineral-associated more efficiently than larger compounds (Liang et al., 2017; Sokol et al., 2019). The large and small biopolymers which form from decomposition byproducts are generally found in lower proportions in MAOM than monomers (Lehmann and Kleber, 2015). These decomposition processes gradually continue and process C in the soil, with DOM being more bioavailable to microbes than POM, while MAOM is strongly protected (Kaiser and Kalbitz, 2012). However, when environmental conditions allow, MAOM can also be consumed and returned to the DOM pool (Kaiser and Kalbitz, 2012; Liang, et al., 2017).

With MAOM being a key mechanism in SOC stabilization, it is important to consider recent evidence that SOC is stabilized within anaerobic microsites (Keiluweit et al., 2017). These microsites can be related to SOC occlusion (MAOM) in soil peds or aggregates as Sexstone et al. (1985) showed greatly depleted oxygen profiles and higher rates of anaerobic activity approaching the center of some soil aggregates. This concept of specialized sites of SOC stabilization is driving the current understanding of SOC dynamics, where it has been proposed that the SOC dynamics of litter decomposition in the bulk soil differs from that in the rhizosphere (Sokol et al., 2019). The rhizosphere contains an active and diverse microbial community compared to the bulk soil (Sokol et al., 2019). As the complexity of C increases, microbes in the rhizosphere convert that C into CO_2 at a much higher rate than litter-derived C (Sokol et al., 2019). Thus, litter-derived C leaches into the subsoil at a greater rate than C leaches from the rhizosphere (Sokol et al., 2019). The ability of microbes to transform C inputs into stabilized SOC is referred to as the entombing effect (Liang et al., 2017). This is in contrast to the priming effect in which nutrient addition can spur microbial decomposition and thus increase SOC loss (Jenkinson et al., 1985).

The priming effect has drawn attention as a proposed mechanism driving SOC loss from disturbance (Jenkinson et al., 1985; Kuzyakov, 2010). When C and N sources are added to soil, they can quickly become consumed and mineralized into CO_2 by microbes (Zhu and Cheng, 2011; Nottingham et al., 2009). One recent study found intensive fertilization (N, P, K, Ca, and S) decreases organic matter decomposition while low fertilization resulted in increased organic matter decomposition (Liu et al., 2018). These processes were termed positive and negative priming, in their respective role in priming SOC for microbial decomposition (Liu et al., 2018). The negative priming effect is similar to the entombing effect proposed by Liang et al. (2017) in which microbes are drivers of SOC stabilization in their conversion of fresh C into SOC. This process of "entombing" C generally takes place over a longer period than positive priming which results in rapid C mineralization (Liang et al., 2017; Liu et al., 2018).

The differing effects of nutrient availability on SOC suggest nutrient limitation, in which O, N, and P act as controls on microbial SOC stabilization (La Rowe et al., 2011). Thermodynamic analysis of C in soil has shown that protected SOC is generally more reduced and subject to rapid loss when oxidized (La Rowe et al., 2011). The presence of thermodynamically unstable forms of C in soil indicates energy potential alone does not drive SOC protection but depends on other environmental conditions (La Rowe et al., 2011; Schmidt et al., 2011; Keiluweit et al., 2017). From an agricultural and climate perspective, this means careful attention must be paid to the nutrient balances to minimize emissions and promote SOC sequestration.

There is much debate on the concept of SOC saturation (Six et al., 2002; Stewart et al., 2008; Castellano, 2015). This concept describes the ability of soil in forming stabilized SOC related to its current level of C saturation. Soils with low C saturation are generally expected to have a higher rate of SOC stabilization than soils closer to C saturation (Stewart et al., 2008). When new litter enters the soil, it can replace older compounds previously adsorbed to mineral binding sites which can then be transported to deeper soil layers where adsorption sites are less saturated (Bingham and Cotrufo, 2016). This may be a way in which the C saturation status of the soil surface could facilitate downward translocation of C into subsoil layers as in Nicoloso et al. (2015). In addition to this, Castellano et al. (2015) found that SOC stabilization rate was determined by the soil's level of C saturation rather than C input quality. Thus, other nutrients and conditions for microbes on a microclimate scale may be limiting and thus vital to SOC sequestration (Sokol et al., 2019; La Rowe et al., 2011). This is likely the cause for the spatial variability of C distribution and microbial specialization with depth (Kramer and Gleixner, 2008).

It is estimated that soils globally store at least three times as much C in the upper 1 m of soil as found in plants or the atmosphere (Batjes, 2014). The natural source of SOC is from plants, primarily roots, root exudates and, to a lesser degree, plant and animal litter (Rasse et al., 2005; Sokol et al., 2019). The SOC pool is closely linked with the active microbial community through the soil profile (Kramer and Gleixner, 2008). Considering the modern understanding of SOC cycling, the focus is directed to understanding effects on soil environmental conditions with agricultural management.

Management effects on deep soil organic carbon

Conversion of natural ecosystems to agricultural production has a profound impact on nutrient cycling and ecosystem services. It is estimated that 110 Pg of SOC has been lost with anthropogenic land use, with over 65% of SOC loss occurring since recent industrialization and intensification of land use in the past 250 years (Sanderman et al., 2017). This loss of SOC is driven by practices that are general disturbances to natural cycles such as nutrient addition and tillage (Sanerman et al., 2017). Globally, approximately 50% of SOC stocks in the upper meter of soil lie below 30 cm (Batjes, 2014). Some studies show deep soil C loss, up to 450% more than surface soils when exposed to disturbance (Fierer et al., 2003). Thus, agricultural impact on SOC stocks must be considered to sufficient depth to understand the true nature of C sequestration.

Conservation agriculture is one way to improve soil quality and protect SOC (Lal, 2016). These practices include reduced soil disturbance, increased C inputs (manure, compost, and biomass addition), permanent soil cover, crop rotation, and reduced soil erosion (Lal, 2016). Moving forward with an ecosystem perspective, the focus will be directed toward understanding how the practices of tillage and type of fertilizer addition influence microbial conditions and, thus, the distribution of SOC within the soil profile (Schmidt et al., 2011).

Effect of manure and compost addition on soil organic carbon

Field application of high C inputs, such as manure or compost, returns C to the soil and is one way to address the widespread loss of C since the conversion of native to agricultural lands (Lal, 1999). Manure (dairy, swine, or poultry) applications can significantly reduce lifetime emissions from these products compared to long-term storage and housing (SOCCR2, 2018).

Long-term manure application has been known to increase SOC (Lynch et al., 2006). Stewart et al. (2015) found that dairy manure addition increased SOC stocks in the upper 30 cm of a rainfed NT continuous corn system. In a recent meta-analysis, cattle manure addition increased SOC stocks over the control by approximately 8 to 17 Mg C ha^{-1} in the upper 20-30 cm (Maillard and Angers, 2014). This increase in SOC stocks was also observed over mineral fertilizer additions by approximately 4 to 10 Mg C ha^{-1} (Maillard and Angers, 2014). The addition of poultry manure was much more variable, ranging from loss of 3 Mg C ha^{-1} to gain of 20 Mg C ha^{-1} versus control and loss of 3 Mg C ha^{-1} to gain of 10 Mg C ha^{-1} over mineral fertilizers (Maillard and Angers, 2014).

The conversion of manure into stabilized C over mineral N sources suggests other properties of the manure may influence microbial functions stabilizing SOC, such as P or Fe biosolid content (Lynch et al., 2006; La Rowe et al., 2011). Manure is generally characterized by increased C:N and P (Lynch et al., 2006). Isotopic signature is another way to trace manure-derived C and N dynamics within the soil. The $\delta^{13}C$ signature of manure is reflective of the animal's feed source, generally C3 or C4 plants (Lynch et al., 2006). Some selective C cycling by microbes also decreases $\delta^{13}C$ signature, though this process generally accounts for minor changes to the plant source C signature (Lynch et al., 2006). The $\delta^{15}N$ signature is a measure of microbial processing since microbes preferentially consume lighter N^{14} before N^{15} (Lim et al., 2010). Thus, thorough processing of N in the gut of animals, especially ruminants, produce manure with enriched N^{15} signatures that can be traced into the soil (Lynch et al., 2006).

Compost is another common fertilizer with high C concentration. Lynch et al. (2006) characterized C3 and C4 composts and reported changes in soil C, N, $\delta^{13}C$, and $\delta^{15}N$. Similar to manure, compost also has a distinct C and N isotopic signature. The composting process itself can lead to isotopic shifts in C and N through microbial processing. Composting depleted the $\delta^{13}C$ signature from the source material (-1.6 ‰) and N was significantly enriched to 7.9 ‰ (Lynch et al., 2006). One year after compost application, up to 95% of compost C was retained in soil (Lynch et al., 2006).

Similar results were found by Feng et al. (2014), where high C inputs were retained in the soil. Accrual of SOC occurred within soil macroaggregates with high C inputs (Mikha et al., 2015; Fonte et al., 2009). Cover crops are another way to add C to the soil. Despite SOC gains detected in the surface with high C input, deeper soil layers can still lose SOC (Tautges et al., 2019). Cover crops increased SOC in the upper 30 cm, but overall losses were recorded from the throughout the soil profile (0-200 cm) after 19 years (Tautges et al., 2019). These deep soil studies which present profile SOC loss represent a potential opportunity for SOC sequestration as well as reveal the importance of proper deep soil sampling and analysis.

Tillage effect on soil organic carbon

Tillage strongly influences SOC dynamics and is a major choice producers make. Since cultivation, it is estimated that intensively tilled soils have lost up to 75% of SOC in the upper 1 m of soil, globally (Lal, 2011; Sanderman et al., 2017). Plowing breaks up soil aggregates which are the main sites of SOC sequestration in temperate soils, exposing protected SOC to oxidation and mineralization (Mikha and Rice, 2004; Mikha et al., 2015; Keiluweit et al., 2017). No-till is one strategy to increase SOC globally (Lal, 2004). In a meta-analysis of 67 experiments, West and Post (2002) reported that conversion of CT to NT generally increases SOC stabilization and reverses SOC loss from cultivation. Approximately 85 % and 15 % of SOC sequestration with NT occurred in the 0-7 cm layer and 7-15 cm layer, respectively, while no changes in SOC were found in the 15-30 cm depth (West and Post, 2002). These surface effects are supported by another meta-analysis that found NT increased SOC in the surface 10 cm while CT and NT recorded overall losses from 20-40 cm (Luo et al., 2010). However, the impact of tillage on deep SOC dynamics has shown differing responses to tillage in surface and subsoil.

A meta-analysis of 69 experiments, studies that sampled below 40 cm showed no difference of NT or CT with full profile analysis (Luo et al., 2010). In addition to this, climate, temperature, and N fertilization were found to have no effect on SOC stocks between CT and NT (Luo et al., 2010). A meta-analysis of NT versus full-inversion tillage found that NT generally stored more SOC in the upper 0-10 cm while inversion of surface residue increased deeper SOC (20-35 cm) (Angers and Eriksen-Hamel, 2008). This is likely due to an increase in mineral stabilization of C when residue was brought into contact with soil particles (Angers and Eriksen-Hamel, 2008). Soil C stabilization increased and oxidative consumption of this SOC decreased when plant material was incorporated into the subsoil (Angers and Eriksen-Hamel, 2008).

Tillage and N fertilizer practices can enhance SOC sequestration efforts. One review of tillage and N application, it was noted that SOC accumulation was possible with reduced tillage and N application regardless of the cropping system, soil type, or climate (Alvarez, 2005). Along these lines, NT and C input increased SOC stocks in the upper soil surface through an increase in macroaggregates (Mikha and Rice, 2004; Nicoloso et al., 2018). This effect was also found by Khalona et al. (2013) where 22 years of tillage and mulching increased surface SOC through improved aggregation. These surface effects of management on SOC are well known, but interest in deep soil C has increased.

Deep soil sampling

Although surface gains in SOC occur with minimal soil disturbance and increased C inputs, profile assessments of SOC have revealed mixed results. In one whole-profile assessment to 120 cm, no differences in SOC stocks were detected between strip tillage and NT (Stewart et al., 2018). Follett et al. (2013) found no effect from N fertilization rates, but that NT reduced profile SOC loss (0-120 cm) compared to conventional tillage in an irrigated corn system.

One difficulty in measuring nutrient stock differences over decades is changes in bulk density due to different management practices. To account for this, soil mass must be standardized before comparing nutrient concentrations. This is known as equivalent soil mass (ESM) (Ellert and Bettany, 1995). Considering up to 50% of SOC is below 30 cm depth (Batjes, 2014), studies should strive to compare SOC in deeper layers and by ESM (VandenBygaart and Angers, 2006). Another difficulty in deep SOC stock assessment is the variability of SOC at depth. In a review of Swyserda et al. (2011), Kravchenko and Robertson (2011) found over 80% of the variability in whole-profile C stocks was from 30-100 cm depth. Thus, it is recommended that deep SOC stocks are best compared for differences within respective soil layers (Kravchenko and Robertson, 2011). In addition to C stocks, C dynamics at depth can be traced by more detailed analysis of the soil SOC pool such as DOC or isotope fractions of ^{13}C and ^{15}N.

Chapter 2 - Materials and Methods

This study was designed to evaluate the effects of tillage systems (no-till, NT and conventional till, CT) and N management (control, Ctrl; compost, OrgF; and urea, MinF) on profile SOC dynamics in a temperate, rainfed, continuous corn (*Zea mays* L.) system after 22 years. This was assessed through comparing SOC stocks by equivalent soil mass (ESM) and measurement of soil C/N, dissolved organic carbon (DOC) and natural C/N isotope abundance ($\delta^{13}C$, $\delta^{15}N$). Based on previous studies, it is hypothesized that NT coupled with OrgF will promote most SOC stabilization.

Site and experimental design

The experimental site was located at Kansas State University's North Farm in Manhattan, KS (39° 12' 42"N, 96° 35' 39"W; elevation 310 m). Annual mean precipitation was 800 mm and mean annual temperature was 11.4° C. The soil was a moderately well-drained Kennebec silt loam (fine-silty, mixed, superactive mesic Cumulic Hapludoll) which was described at the start of the experiment in 1991 and in 1999 by Soil Survey staff (Harris, 1993; App. A.1-2). The soil contains a buried palesol encountered at 41cm depth (abrupt wavy boundary) (App. A.1). The younger parent material was post-settlement alluvium which was likely deposited in the late 19th century after previous cultivation of the surrounding landscape (Harris, 1993). The younger alluvium overlies a paleosol which was older alluvial material. The 1999 pedon description found the Ab horizon of this soil at 29-66 cm depth (App. A.2). This fits well with the 1991 horizonation description and shows the variability of the subsoil at this site. The buried A horizon also contains a texture change with a clay increase from the overlying horizon from 21%

to 24%. The B horizons below this depth were classified as argillic horizons (Bt) in 1991 and as rather undeveloped (Bw) in 1999 (App. A.1-2).

Prior to cropping, the site was a tallgrass prairie, native to the area. The site was cultivated at least 60 years prior to the establishment of this experiment in 1990. It was intensively tilled throughout this time as well. This experiment was a long-term tillage and N source study described in detail in Harris (1993). Plots were established in 1990 as split-plot randomized block design with four replications under continuous corn (*Zea mays* L.). Tillage systems were the main plots and N source was the subplot. Subplots were 7.5 m x 6 m. Tillage systems were conventional tillage (CT) and no-till (NT). Corn was planted through the previous crops' standing residue in the NT plots with minimal soil disturbance. Weeds were chemically controlled with broadcast herbicide following planting (Harris, 1993). The CT operations consisted of preplant offset disk set to 10 cm depth and postharvest chisel plow to 15 cm (Harris, 1993).

Fertilizer source was the subplot treatment. Fertilizer was applied at a rate of 168 kg N ha^{-1}. Mineral fertilizer (MinF) was applied as broadcast urea. The second N treatment was sourced from various types of organic sources high in C. The original organic fertilizer (OrgF) treatment was fresh cattle manure from Kansas State University's Beef Unit (Harris, 1993). Each year, the manure was analyzed for total N, $NH_4^{+,}$ and NO_3^- and application rates were calculated assuming 100% of NH_4^+ and NO_3^- and 35% of organic N was available (Harris, 1993). Since 2001, mixed source compost (food waste, hay waste, and cattle manure) has been applied (Nicoloso et al., 2018). Food waste was sourced from KSU dining halls and the compost windrows were manged by KSU Department of Agronomy. Prior to application each year, compost was analyzed for total N, organic N, NH_4^+, and NO_3^- (App. A.5) Compost application rate was then calculated assuming 50% of organic N and 100% of mineral N was available during the growing season. A control (Ctrl) treatment consisted of no N application (0 kg N ha^{-1}).

Soil sampling

Soil cores were collected in fall 2012 with a Giddings Soil Exploration probe (Windsor, CO) to a depth of 120 cm (5 cm diameter). Five cores were collected per plot. Three cores were collected from each plot for lab analyses. Two additional 120 cm cores were collected for bulk density analysis. All undisturbed soil cores were separated into layers 0-5 cm, 5-15 cm, 15-30 cm, 30-45 cm, 45-60 cm, 60-75 cm, 75-90 cm, 90-105 cm, 105-120 cm in field and stored in bags. Bulk density samples were bagged individually and bulk analysis cores were composited by layer. Care was taken to avoid compaction in the field and to ensure accurate separation into layers. Samples were placed in a cooler with ice packs and transported to cold storage (4 °C) from the field.

Evaluation of SOC stocks

Soil bulk density was determined by gravimetric moisture analysis. The bulk density samples were dried at 105 °C (at least 24 h) then weighed and calculated. The bulk density measurements were averaged by depth for each plot. For analysis of SOC, a subsample was taken from the composited cores and air-dried for 48-72 h. Visible roots were removed from the sample and discarded. The soil was then passed through a 2 mm sieve and finely ground with a mortar and pestle.

Soil samples were analyzed for total soil carbon and N by dry combustion with a C and N elemental analyzer (Flash EA 1112 Series, ThermoScientific, Waltham, MA). Previously published data (Harris, 1993) was compiled for a baseline reading of bulk density and SOC. This analysis used the same baseline data as Nicoloso et al. (2018) in which SOC data is from the treatments two years into the study and the bulk density data was from the main tillage treatments only. Soil organic carbon stocks were determined on equivalent soil (ESM) basis to account for soil differences across a landscape or soil bulk density changes induced by management (Ellert and Bettany 1995). The ESM-C was calculated as follows:

$$Mass_C\ (Mg\ ha^{-1}) = conc. \times P_b \times T \times 10{,}000\ m^2\ ha^{-1} \times 0.001\ Mg\ kg^{-1}$$

Where:

$Mass_C$	=	C mass by unit area ($Mg\ C\ ha^{-1}$)
conc.	=	C concentration ($kg\ C\ Mg^{-1}$)
P_b	=	bulk density of layer ($Mg\ m^{-3}$)
T	=	thickness of soil layer (m)

The thickness of soil added from the layer below is calculated as follows:

$$T_{add} = \frac{(M_{soil,\ equiv} - M_{soil,\ surf}) \cdot 0.0001\ ha\ m^{-2}}{P_{b\ subsurface}}$$

where:

T_{add}	= additional thickness of subsurface layer required to attain the equivalent soil mass (m)
$M_{soil,\ equiv}$	= equivalent soil mass = mass of horizon with greatest bulk density ($Mg\ ha^{-1}$)
$M_{soil,\ surf}$	= sum of soil mass in surface layer(s) ($Mg\ ha^{-1}$)
$P_{b\ subsurface}$	= bulk density of subsurface layer ($Mg\ m^{-3}$)

The reference for each cumulative soil layer was based on the plot with the highest bulk density. This calculation was completed for each depth of soil within each plot. The soil mass was calculated to the sampled depth, then some mass of soil from the layer below was added to soil mass to equal the standardized soil mass at that layer. For example, this means that when comparing 0-5 cm layers, some soil was added from the 5-15 cm depth. Soil samples were taken to a depth of 90 cm in 1990. Therefore, since some soil from the 60-90 cm depth was added to for the equation, the calculation can only determine ESM up to the 60 cm depth. It is recommended to choose the standardized core based on the highest bulk density (Ellert and Bettany, 1995). In theory, the standardized soil mass could be the lightest mass or other soil mass, but this can complicate the calculation, either subtracting soil from each layer or a combination of addition and subtraction depending on plot and layer of soil calculated. To calculate the ESM by layer, the calculated ESM from the overlying cumulative layers was subtracted from the cumulative layer to that depth. For example, the 45-60 cm ESM by layer was determined by subtracting the 0-45 cm layer from the 0-60 cm layer for that plot.

As in Nicoloso et al. (2018), the 1992 ESM was calculated using the 1990 bulk density data and C and N data from 1992 from the N treatments.

Stable isotope analysis

Sieved, dried and ground soil samples were weighed in tin capsules (11.0 – 12.0 mg) on a microbalance in preparation for analysis of ^{13}C and ^{15}N ($\delta^{13}C$ and $\delta^{15}N$) at KSU Stable Isotope Mass Spectrometry Laboratory (SIMSL). Analysis was done with a ThermoFinnigan Con Flo III interface and ThermoFinnigan Delta-plus Continuous Flow Stable Isotope Ratio Mass

Spectrometer (ThermoFisher Scientific, Waltham, MA). The expressed $\delta^{13}C$ and $\delta^{15}N$ values were measured in parts per-mill (‰) as follows:

$$\delta^{13}C = [(R_{sample} - R_{standard}) / R_{standard}] \times 10^3$$

$$\delta^{15}N = [(R_{sample} / R_{standard}) - 1] \times 10^3$$

where, R is the ratio of ^{13}C:^{12}C in the sample and in the Pee Dee Belemnite (PDB) standard from the Pee Dee River Formation (Hemingway, SC) and the ratio for ^{15}N:^{14}N in the sample and in atmospheric N_2 ($R_{standard}$ = 0.003676), respectively.

Dissolved Organic Carbon (DOC)

The DOC was extracted using a 0.5 *M* potassium sulfate (K_2SO_4) solution (Vance et al., 1987) at 1:5 weight to volume ratio (Jones and Willett, 2006). The samples were shaken for 30 min on an orbital shaker and filtered through Whatman No. 42 filters into an acid-washed glass vial. Extracted samples were stored at -10 °C until analysis with a TOC Shimadzu analyzer (Shimadzu Corporation, Japan).

Statistical analysis

The main effects of tillage and N management on ΔSOC (1992-2012) were assessed using a repeated measures analysis of SOC stocks with tillage and N management as main effects with plot as a repeated unit.

An analysis of variance (ANOVA) was performed, data were checked for normality and transformed as necessary with just the ESM-C and ESM-N layer analysis log-transformed. Outliers beyond two standard deviations from the mean within depth and treatment were removed from the data set. Except in the case of calculating average bulk density for 2012, outliers were replaced with the average value within depth and treatment to ensure consistent sample sizes in statistical analysis. Where bulk density for a soil layer was outside an expected range (0.8 - 1.8 g/cm^3), that layer of the core was excluded. In these cases, the core was excluded from the bulk density average and just one core was used to calculate average bulk density. Some $\delta^{13}C$ were more depleted than expected C3-sourced C should be (-26 to -23 ‰). These outliers occurred at lower depths (60+ cm) and were minimal. The change in equivalent soil mass C and N per layer was log-transformed due to non-normal distribution. An ANOVA was used to assess the main treatment effects of tillage and N management and interaction between tillage and N management. Statistics were analyzed on all response variables measuring SOC change and stocks (ΔSOC by slice and cumulative layers, bulk density, C and N concentration, $\delta^{13}C$, $\delta^{15}N$, and DOC by using SAS PROC MIXED; SAS 9.4). Differences were run with Bonferroni's adjustment and are reported with letters to denote significance. Results were considered statistically significant at $P < 0.10$.

Chapter 3 - Results

Bulk Density

Soil bulk density data was collected in 1990 (Table 1) and 2012 (Table 2). The ANOVA of bulk density change between 1990 and 2012 is provided in Table 3. Tillage and N source affected bulk density over time. It is important to note these significant effects occurred throughout the soil profile (0-60 cm), including a three-way interaction between Year × Tillage × N source in the 0-5 cm and 5-15 cm depths.

Soil C and N concentration

No-till increased the soil C concentration (24.9 g C kg^{-1}) compared to CT (20.9 g C kg^{-1}) in the surface 5 cm depth only ($P = 0.062$; Table 4, 5). At this depth, N concentration was also increased with NT (3.06 g N kg^{-1}) over CT (2.05 g C kg^{-1}; $P = 0.087$). Conventional tillage increased C concentration (16.7 g C kg^{-1}) compared to NT (14.8 g C kg^{-1}) in the 5-15 cm layer ($P = 0.028$).

Fertilizer source significantly affected soil C and N concentration in the 0-5 cm and 5-15 cm layers ($P <0.001$) and only N concentration in the 105-120 cm layer ($P < 0.001$; Table 4, 5). Compost application resulted in significantly increased C and N concentration in the 0-5 cm, 5-15 cm, and 105-120 cm layers. The control (Ctrl) and mineral fertilizer (MinF) treatments were not significantly different in C or N concentrations within any layer. In the 0-5 cm depth, OrgF treatments averaged 33.8 g C kg^{-1} compared to the Ctrl and MinF ($P < 0.001$) 15.8 and 19.1 g C kg^{-1}, respectively. The OrgF treatment continued to have higher C concentration in the 5-15 cm depth with 19.1 g C kg^{-1} while the Ctrl and MinF was 14.2 and 13.9 g C kg^{-1}, respectively ($P < 0.001$). The N concentration within these layers was also increased by OrgF application. In the surface, 0-5 cm, OrgF addition resulted in N concentration of 4.89 g N kg^{-1}, over 300% of Ctrl and MinF treatments ($P < 0.001$). This trend continued in the 5-15 cm subsurface depth with OrgF treatment measuring 2.50 g N kg^{-1}, 225% percent higher than both Ctrl and MinF treatments ($P = 0.006$). For the remainder of the soil profile, no significant effects of N source were found on soil N concentration within the profile until the final depth, 105-120 cm ($P = 0.005$), where OrgF averaged 0.71 g N kg^{-1} with Ctrl and MinF averaged 0.31 and 0.41 g N kg^{-1} respectively.

The carbon to nitrogen ratio (C:N) was significantly lower in the upper 15 cm with the application of OrgF ($P < 0.001$; Table 6). The Ctrl and MinF treatments were not significantly different. In the surface layer, 0-5 cm, OrgF averaged 7.87. For the remainder of the soil profile, the C:N with OrgF increased slightly in the 5-15 cm layer to 9.34. The Ctrl and MinF remained undifferentiated. No significant differences were found within profile C:N with regard to tillage, nor was there a significant interaction between tillage and N source.

Soil C and N isotope analysis

For the N source with OrgF, the C3-C source, resulted in depleted $\delta^{13}C$ in the 0-5 cm, 5-15 cm, 30-45 cm and 105-120 cm depths (Table 7). The Ctrl and MinF treatments were not significantly different within these layers. The OrgF was depleted in $\delta^{13}C$ in the 0-5 cm layer, -20.7 ‰ ($P < 0.001$). The Ctrl and MinF averaged -17.1 and -17.6 ‰, respectively in this layer. In the next layer, OrgF had a significantly depleted $\delta^{13}C$ value of -18.7 ‰ ($P = 0.043$). The Ctrl and MinF treatments were more enriched in $\delta^{13}C$, averaging -17.1 and -17.4 ‰, respectively. Neither N source or tillage significantly changed $\delta^{13}C$ in the 15-30 cm depth. In the 30-45 cm depth, OrgF was again significantly depleted in $\delta^{13}C$ from Ctrl and Min F ($P = 0.013$) averaging -16.2

‰. The Ctrl and MinF treatments were not different, with values of -14.8 and -14.9 ‰, respectively Tillage had a significant influence in the 30-45 cm layer ($P = 0.026$). No-till was slightly more depleted (-15.8 ‰) than CT (-14.8 ‰). At the 120 cm depth, OrgF averaged -20.0 ‰ ($P = 0.059$) where Ctrl and MinF were -16.2 ‰ and -15.9 ‰, respectively.

No-till had significantly depleted $\delta^{13}C$ values at the 30-45 cm depth to -15.8 ‰. This was more depleted than CT, which averaged -14.9 ‰ ($P = 0.025$).

Similar to $\delta^{13}C$, N source with OrgF had significantly higher $\delta^{15}N$ in the 0-5 and 5-15 cm layers as well as the deepest layer sampled, 105-120 cm ($P < 0.001$, $P < 0.001$, $P = 0.009$; Table 8). In the 0-5 cm depth, OrgF enriched $\delta^{15}N$ to 10.0 ‰ compared to the Ctrl and MinF (6.52 and 6.80 ‰, respectively). The Control and MinF were not statistically different with respect to $\delta^{15}N$ throughout the soil profile. Organic fertilizer significantly increased the $\delta^{15}N$ in the 5-15 cm layer ($P < 0.001$) to 8.54 ‰ $\delta^{15}N$. At the 60-75 cm depth, an enriched $\delta^{15}N$ signature was apparent in the OrgF plots at 6.74 ‰ ($P = 0.070$) compared with the Ctrl and MinF, 5.18 ‰ and 5.62‰, respectively. At 105-120 cm, OrgF had a higher in $\delta^{15}N$ content, averaging 5.81 ‰ $\delta^{15}N$.

A significant tillage effect was noted at the 30-45 cm depth for $\delta^{15}N$. No-till had enriched $\delta^{15}N$ of 7.11 ‰ ($P = 0.052$), which was higher than CT of 6.17 ‰. No significant interaction between N source and tillage was found to influence the $\delta^{15}N$ content (Table 8).

Dissolved organic carbon

Nitrogen source with OrgF significantly increased dissolved organic carbon (DOC) from the surface layer through the 45 cm depth ($P < 0.001$; Table 9). Application of OrgF also increased DOC within the lowest layer sampled, 105-120 cm ($P = 0.039$). The Ctrl and MinF were not significantly different at any depth with regard to DOC. Dissolved organic carbon in

OrgF in the 0-5 and 5-15 cm layers averaged 155 and 107 mg C kg^{-1}, respectively. The DOC in OrgF was double that of the Ctrl and MinF treatments within these depths. At deeper layers, OrgF had higher DOC to a depth of 45 cm. At the 15-30 cm depth, DOC was 57.3 mg C kg^{-1} in OrgF while Ctrl and MinF measured 35.0 and 37.7, respectively. Dissolved C in OrgF in the 30-45 cm layer was 44.6 mg C kg^{-1}. The Ctrl and MinF treatments measured 32.9 and 32.7 mg C kg^{-1}. No other differences in DOC were detected until the final depth where OrgF averaged 38.1 mg C kg^{-1} and Ctrl and MinF treatments averaged 29.6 and 31.5 mg C kg^{-1}, respectively. Tillage affected soil DOC at the 45-60 cm depth where NT had significantly less DOC at 34.6 mg C kg^{-1} ($P = 0.083$) than CT at 43.6 g C kg^{-1}. There was no interaction between tillage and N source on soil DOC.

Soil organic carbon change (1992-2012)

The OrgF significantly increased SOC stocks in the 0-5 and 5-15 layers (Table 10). Here, OrgF increased SOC by 9.77 and 8.41 Mg C ha^{-1}, respectively. Soil organic C in the Ctrl and MinF treatments were relatively unchanged and were not significantly different in this layer. In the 15-30 cm depth, no significant differences were detected among N source or tillage. In the 30-60 cm layers, all treatments lost SOC. At the 30-45 cm depth, the Ctrl fertilizer treatment lost the least amount of C, approximately -2.54 Mg C ha^{-1}. The OrgF and MinF lost similar amounts of C, 8.33 Mg C ha^{-1} and 9.06 Mg C ha^{-1}, respectively. In the 45-60 cm layer, MinF lost the greatest amount of C at -21.0 Mg C ha^{-1} where OrgF lost 12.2 Mg C ha^{-1}. The Ctrl treatment was statistically similar to both the OrgF and MinF treatments, losing 15.2 Mg C ha^{-1}.

The adoption of NT increased SOC in the surface 0-5 cm by 5.06 Mg C ha^{-1} above the baseline ($P = 0.052$, Table 10). This was nearly twice as much SOC as CT in the surface, which only accumulated 2.67 Mg C ha^{-1}. In CT, SOC increased by 4.01 Mg C ha^{-1} in the 5-15 cm layer ($P = 0.061$). An interaction between tillage and N management occurred at the 15-30 cm depth, but results were inconclusive after Bonferroni's adjustment. A significant interaction occurred at 30-45 cm. In general, NT MinF and CT OrgF lost the most C within this layer, -11.0 and -12.9 Mg C ha^{-1}, respectively ($P < 0.001$, Table 11). The NT Ctrl and OrgF and CT Ctrl and MinF were statistically similar, varying between -7.14 Mg C ha^{-1} and 0.58 Mg C ha^{-1}.

After 20 years of management, all treatments lost SOC but added C from OrgF significantly reduced SOC losses throughout the soil profile (0-60 cm) ($P < 0.001$, Table 12). The Ctrl and MinF treatments were undifferentiated throughout the profile from 0-45 cm, but MinF lost significantly more SOC (-31.0 Mg C ha^{-1}) compared to Ctrl (-18.2 Mg C ha^{-1}) in the full profile (0-60 cm). There was an interaction between tillage and N source for 0-45 cm and 0-60 cm (Table 13). For 0-45 cm, the gain in SOC for the NT OrgF was 14.4 Mg C ha^{-1} while for CT OrgF the gain was only 3.16 Mg C ha^{-1} which was statistically similar. However, NT MinF lost 14.2 Mg C ha^{-1} and CT MinF lost 5.97 Mg C ha^{-1}. Soil profile analysis from 0-60 showed NT OrgF increased SOC stocks by 0.66 Mg C ha^{-1} ($P = 0.084$, Table 13). This result was similar to CT OrgF and CT Ctrl which lost 7.49 and 10.8 Mg C ha^{-1}, respectively (Table 13). Conventionally tilled OrgF and Ctrl were similar to all other treatments (Table 13). Substantial loss of SOC occurred with NT Ctrl (-25.6 Mg C ha^{-1}), NT MinF (-33.8 Mg C ha^{-1}), and CT MinF (-28.3 Mg C ha^{-1}; Table 13).

Soil nitrogen

In the 0-5 layer, NT increased N by 1.88 Mg N ha^{-1} while CT increased N by 2.26 Mg N ha^{-1} ($P = 0.054$, Table 14). In the 5-15 cm layer, CT increased N by 2.30 Mg N ha^{-1} while NT lost 0.34 Mg N ha^{-1} (P = 0.063, Table 14). No other tillage effects on soil N were found for the remaining profile depths (15-60 cm).

Changes in ESM-N were significant for the 0-5 cm, 5-15 cm, 30-45 cm, and 45-60 cm layers. Application of OrgF increased soil N by 5.50 Mg N ha^{-1} in the 0-5 cm layer over Ctrl and MinF, which changed N by -0.01 and 0.71 Mg N ha^{-1}, respectively ($P < 0.001$, Table 14). In the 5-15 cm layer, OrgF increased soil N by 4.56 while Ctrl and MinF lost 0.94 Mg N ha^{-1} and 0.68 Mg N ha^{-1}, respectively ($P < 0.001$). No significant differences were detected in the 15-30 cm depth. All N source treatments lost soil N from 30-60 cm depth. The interaction between tillage and N source was not significant at any depths.

The tillage effect was significant on the cumulative soil N for 0-15 cm, 0-30 cm, 0-45 cm, and 0-60 cm depths (Table 15). Conventional tillage had higher soil N in the 0-15 cm (P = 0.089) compared to No-till (1.53 Mg N ha^{-1}). In 0-30 cm, soil N stocks were higher with CT than with NT (P = 0.084). Conventional tillage retained 1.95 Mg N ha^{-1} within 0-45 cm while NT lost 6.01 Mg N ha^{-1} (P = 0.026). From 0-60 cm, NT and CT changed soil N by -13.0 Mg N ha^{-1} and -0.82 Mg N ha^{-1} (P = 0.013).

Fertilization with OrgF significantly increased profile N from 0-60 cm (Table 15). The Ctrl and MinF were similar throughout and less than OrgF at every depth. Soil N increased in the 0-5 cm depth by 5.50 Mg N ha^{-1} with OrgF, while Ctrl lost 0.01 Mg N ha^{-1} and MinF gained 0.71 Mg N ha^{-1} ($P < 0.001$). In the 0-15 cm depth, OrgF increased soil N by 10.1 Mg N ha^{-1} ($P < 0.001$). The Ctrl and MinF treatments changed by -0.95 and 0.21 Mg N ha^{-1}, respectively. The OrgF increased soil N within 0-30 cm by 9.12 Mg N ha^{-1} ($P <0.001$). The Ctrl and MinF lost 4.15 Mg N ha^{-1} and 3.12 Mg N ha^{-1}, respectively. From 0-45 cm, OrgF increased soil N by 6.57 Mg N ha^{-1} while Ctrl and MinF lost 6.09 and 6.59 Mg N ha^{-1}, respectively (P = 0.006). The OrgF increased soil N by 0.38 Mg N ha^{-1} ($P = 0.088$). No fertilization (Ctrl) and MinF decreased soil N.

Chapter 4 - Discussion

No-till over 20 years increased SOC in the surface 0-5 cm by 5.06 Mg ha^{-1} while CT only increased surface SOC by 2.67 Mg ha^{-1} (Table 12). On the other hand, CT significantly increased SOC within the 5-15 cm layer so that cumulative SOC from 0-15 cm was not different between tillage systems. This redistribution of SOC via inversion by tillage has been reported by others (Angers and Eriksen-Hamel, 2008; Gregorich et al., 2009). The addition of OrgF was primarily confined to the surface 15 cm for SOC. While DOC was elevated in the OrgF treatment to a depth of 45 cm, the elevated DOC did not result in greater SOC. Nicoloso et al. (2018) reported that SOC in the NT with OrgF had saturated in the 0-5 cm layer with subsequent translocation in the underlying 5-15 cm layer. They also found no accumulation of SOC below 15 cm with either tillage system. Dissolved organic carbon is adsorbed strongly in the upper soil surface, close to where it was formed (Fröberg et al., 2007; Kaiser and Kalbitz, 2012). The soluble C pool is most easily consumed by microbes, thus if it does not become minerally-associated, it is likely to be respired as CO_2 (Robertson et al., 2019; Cotrufo et al., 2013; Kaiser and Kalbitz, 2012; Fröberg et al., 2007). In another study, Hsaio (2019) found higher enzyme activity and microbial biomass in the 30-45 cm layer of the OrgF treatment suggesting that higher microbial activity was respiring the DOC. The high concentration of DOC near the soil surface and the sharp decline in subsequent depths is similar to Fröberg et al. (2007) where strong retention of DOC in the surface depths was restricted to surface layers. By the 15-30 depth, DOC concentration for OrgF had decreased to 57.3 mg kg^{-1} and was roughly one-third of the surface concentration of DOC. By contrast, the Ctrl and MinF treatments had DOC concentrations of 32.9 and 32.7 mg kg^{-1} less than half the surface concentration of DOC. As the saturation model predicts, the sorption rate of DOC seems dependent on its concentration in the soil (Tipping et al., 2012; Stewart et al., 2008).

The $\delta^{13}C$ confirms the stabilization of the OrgF in the 0-15 cm layer. There was a slight difference in $\delta^{13}C$ in the 30-45 cm but no change in SOC was observed at this layer. It appears labile DOC may not contribute significantly to stabilized SOC.

Cumulative depths of SOC revealed that NT OrgF conserved the additional C inputs more than the CT OrgF. For 0-60 cm, NT OrgF had a net increase of 0.66 Mg C ha^{-1} while tillage resulted in a net loss of 7.49 Mg C ha^{-1}. While these differences were not significant, the trend was NT was more conservative than CT. Differences in SOC stocks are difficult to determine in these deeper layers due to increased spatial variability in SOC with depth (Tautges et al., 2019). This suggests that with sustainable intensification, NT could be an essential component for conserving C from compost (Nicoloso et al., 2018; Luo et al., 2010).

In the upper 60 cm, all treatments lost SOC. The losses of SOC for OrgF in the lower 15-60 cm were substantial (-21.6 Mg C ha^{-1}) and completely offset the surface gain of 18.2 Mg C ha^{-1} in the upper 15 cm. The MinF and Ctrl lost 31.0 and 18.2 Mg C ha^{-1}, respectively. In the MinF and Ctrl treatments, both tillage systems had no change in SOC in the upper 30 cm; however, all treatments lost SOC in the 45-60 cm layer regardless of N source including the OrgF. This layer was within the buried Ab horizon which varied from 41-59 cm (App. A.1). This is similar to another maize tillage and N rate study where NT and N application maintained SOC in the surface but lost SOC below 30 cm (Stewart et al., 2017). It appears in these annual cropping systems, plant C either through roots or surface decomposition of plant residue is not impacting SOC at this depth. Microbial activity at this depth is resulting in a net loss of SOC in the buried A horizon.

The change in soil N mass follows SOC accumulation in the surface with OrgF increasing soil N in the 0-5 cm and 5-15 cm layers by 5.50 Mg N ha^{-1} and 4.56 Mg N ha^{-1}. No change in N was detected with fertilization in the 15-30 cm depths. While OrgF reduced SOC losses in the 45-60 cm layer, OrgF lost the most soil N in this depth. With regard to tillage, NT lost more soil N than CT especially in the deeper portions of the soil profile where the buried A horizon resides. The decoupling of C and N and enhanced microbial productivity with OrgF, also evidenced by the increased C:N with depth, has been shown with N fertilizer addition as microbes preferentially consume N from soil organic matter and become more specialized with depth (Ehtesham and Bengtson, 2017).

In another study at this site enzyme activity and microbial activity were measured throughout the soil profile (Hsiao, 2019). They found enhanced bG and NAG activity in the buried A horizon. Supporting the theory that microbial activity in the buried A horizon is causing a loss of soil C and N without the replenishment by plant material in annual cropping systems. Thus agricultural systems need to consider deeper inputs of C through crop selection and rotations.

Chapter 5 - Summary

Organic fertilizer (OrgF) addition over 22 years increased SOC stocks in the upper 15 cm by 18.2 Mg C ha^{-1} in contrast to Ctrl and MinF which gained 0.12 Mg C ha^{-1} and 2.24 Mg C ha^{-1} respectively. However, profile SOC (0-60 cm) decreased across all N treatments (0-60 cm). Addition of OrgF reduced profile SOC loss (0-60 cm). No-till with OrgF shows promise in reducing SOC losses in deeper soil layers below 30 cm. Nitrogen source had no effect on SOC change in the 30-60 cm layers where all treatments lost approximately 18 Mg C ha^{-1}. No-till slightly increased SOC in the upper 5 cm by 5.06 Mg C ha^{-1} over CT which gained 2.67 Mg C ha^{-1}. Conventional tillage had more SOC in the 5-15 cm layer due to soil inversion.

The addition of OrgF increased dissolved organic carbon (DOC) and C3-C up to 45 cm; however, this did not result in SOC gain within this depth. Microbial activity is driving SOC loss at this depth. Thus to prevent profile C loss, deeper C inputs must be considered for this system. Also, soil must be sampled to sufficient depth and analyzed by bulk density to understand the effects of tillage and N treatments on SOC stocks. Sampling too shallow (<30 cm) severely underestimates SOC stocks and affects conclusions drawn about tillage and fertilization practices on SOC dynamics. This has major implications for modeling and climate change in which accurate knowledge of these practices is necessary to mitigate climate change.

Chapter 6 - References

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List of Tables

Table 1. Bulk density (1990).

Bulk density (g cm^{-3})					
	depth (cm)				
Year	0-15	15-30	30-45	45-60	60-90
1990	1.18	1.20	1.19	1.12	1.06

Table 2. Bulk density (2012).

Bulk density ($g\ cm^{-3}$)						
		depth (cm)				
Tillage	N source	0-5	5-15	15-30	30-45	45-60
NT	Ctrl	1.24	1.43	1.37	1.45	1.32
	OrgF	1.05	1.27	1.48	1.52	1.36
	MinF	1.00	1.45	1.43	1.42	1.34
CT	Ctrl	1.27	1.28	1.47	1.32	1.30
	OrgF	0.99	1.25	1.46	1.43	1.36
	MinF	1.09	1.36	1.45	1.43	1.31

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till

Table 3. Bulk density change (1992-2012) – Analysis of Variance.

Significant P-values (P < 0.10)						
		depth (cm)				
Effect	df	0-5	5-15	15-30	30-45	45-60
Tillage (T)	1	*	*	-	*	-
N source	2	*	*	-	*	-
T x N source	2	-	-	-	-	-
Year	1	-	*	*	*	*
Year × T	2	*	*	*	*	-
Year × N source	2	*	*	-	-	-
Year × T × N source	2	*	-	*	-	-

*An * denotes significance P < 0.10.*

Table 4. Soil C concentration (g C kg^{-1}) for 2012 through the soil profile for the main effects of N source and tillage.

		Soil C (g C kg^{-1})								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	15.8 a	14.2 a	13.6	14.6	14.2	12.2	10.8	8.74	6.71
	OrgF	33.8 b	19.1 b	13.9	13.7	13.8	13.7	12.7	11.1	9.43
	MinF	19.1 a	13.9 a	12.6	14.2	15.4	15.9	14.4	11.2	8.49
Tillage	NT	24.9 a	14.8 a	13.5	13.9	14.3	13.9	12.4	10.0	7.51
	CT	20.9 b	16.7 b	13.2	14.4	14.5	13.9	12.9	10.7	8.91
Effect	df	P-value								
Tillage (T)	1	0.062	0.028	0.715	0.352	0.899	0.965	0.850	0.665	0.235
N source	2	<0.001	<0.001	0.370	0.467	0.440	0.304	0.477	0.394	0.172
T × N source	2	0.646	0.052	0.839	0.135	0.499	0.706	0.531	0.169	0.165

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at $P < 0.10$.

Table 5. Soil N concentration (g N kg^{-1}) for 2012 through the soil profile for the main effects of N source and tillage.

		Soil N (g N kg^{-1})								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	1.20 a	0.98 a	0.86	0.85	0.84	0.77	0.67	0.53	0.31 a
	OrgF	4.89 b	2.50 b	0.96	0.84	0.86	0.80	0.80	0.74	0.74 b
	MinF	1.58 a	1.11 a	0.89	0.94	0.98	0.94	0.85	0.61	0.41 a
Tillage	NT	3.06 a	1.47	0.90	0.83	0.86	0.81	0.79	0.63	0.43
	CT	2.05 b	1.59	0.91	0.92	0.93	0.86	0.76	0.63	0.54
Effect	df	P-value								
Tillage (T)	1	0.087	0.737	0.882	0.262	0.501	0.840	0.805	0.994	0.270
N source	2	<0.001	0.006	0.628	0.572	0.442	0.701	0.587	0.332	0.005
T × N source	2	0.174	0.888	0.716	0.319	0.653	0.881	0.926	0.793	0.643

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 6. Soil C:N ratio for 2012 through the soil profile for the main effects of N source and tillage.

		Soil C:N								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	13.5 a	14.7 a	16.0	17.6	17.9	17.7	19.0	18.8	24.3
	OrgF	7.87 b	9.34 b	14.8	16.5	16.6	17.9	16.3	15.4	17.2
	MinF	12.2 a	13.0 a	14.4	15.5	16.1	18.3	18.3	19.1	25.4
Tillage	NT	10.9	13.1	15.2	17.1	17.6	19.1	18.2	17.6	25.6
	CT	11.4	11.6	14.9	16.0	16.1	16.8	17.6	17.9	18.9
Effect	df	P-value								
Tillage (T)	1	0.501	0.150	0.665	0.315	0.235	0.228	0.783	0.879	0.119
N source	2	<0.001	0.002	0.258	0.306	0.440	0.966	0.601	0.269	0.232
T × N source	2	0.607	0.485	0.353	0.662	0.350	0.379	0.279	0.363	0.873

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 7. Soil δ13C (‰) for 2012 through the soil profile for the main effects of N source and tillage.

		Soil $\delta^{13}C$ (‰)								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	-17.1 a	-17.1 a	-16.1	-14.8 a	-14.7	-14.6	-15.2	-15.1	-16.2 a
	OrgF	-20.7 b	-18.7 b	-16.7	-16.2 b	-14.8	-15.5	-15.1	-15.5	-20.0 b
	MinF	-17.6 a	-17.4 a	-16.7	-14.9 a	-14.8	-14.9	-15.4	-15.3	-15.9 a
Tillage	NT	-18.7	-17.3	-16.6	-15.8 a	-14.8	-15.1	-15.0	-15.1	-16.2
	CT	-18.2	-18.1	-16.3	-14.9 b	-14.7	-14.9	-15.4	-15.5	-18.6
Effect	**df**	**P-value**								
Tillage (T)	1	0.159	0.143	0.544	0.025	0.695	0.659	0.308	0.268	0.165
N source	2	<0.001	0.043	0.470	0.013	0.964	0.334	0.789	0.670	0.059
T × N source	2	0.852	0.414	0.834	0.158	0.143	0.685	0.581	0.218	0.902

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 8. Soil δ15N concentration (‰) for 2012 through the soil profile for the main effects of N source and tillage.

		Soil $\delta^{15}N$ (‰)								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	6.52 a	5.97 a	6.75	6.43	5.56	5.18 a	5.01	4.29	3.56 a
	OrgF	10.0 b	8.54 b	6.91	7.11	6.42	6.74 b	5.48	5.12	5.81 b
	MinF	6.80 a	6.57 a	6.59	6.38	6.41	5.62 a	4.84	5.61	4.51 a
Tillage	NT	7.98	6.91	7.01	7.11 a	6.17	5.67	4.90	4.76	4.46
	CT	7.57	7.14	6.48	6.17 b	6.09	6.02	5.32	5.25	4.79
Effect	**df**	P-value								
Tillage (T)	1	0.380	0.605	0.389	0.052	0.846	0.536	0.379	0.346	0.543
N source	2	<0.001	<0.001	0.910	0.361	0.166	0.070	0.522	0.135	0.009
T × N source	2	0.329	0.922	0.627	0.438	0.352	0.202	0.540	0.293	0.210

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 9. Soil dissolved organic carbon concentration (mg kg^{-1}) for 2012 through the soil profile for the main effects of N source and tillage.

		Soil dissolved organic carbon (mg kg^{-1})								
		depth (cm)								
Effect		0-5	5-15	15-30	30-45	45-60	60-75	75-90	90-105	105-120
N source	Ctrl	71.0 a	53.4 a	35.0 a	32.9 a	33.7	33.8	32.9	32.0	29.6 a
	OrgF	155 b	107 b	57.3 b	44.6 b	40.9	39.0	39.1	39.5	38.1 b
	MinF	60.8 a	50.2 a	37.7 a	32.7 a	42.6	36.0	35.4	33.3	31.5 a
Till	NT	94.9	65.4	43.0	35.2	34.6 a	34.9	35.1	36.3	31.8
	CT	96.3	75.0	43.6	38.3	43.6 b	37.5	36.5	33.5	34.3
		P-value								
Effect	df									
Tillage (T)	1	0.926	0.493	0.880	0.338	0.083	0.365	0.560	0.600	0.341
N source	2	<0.001	0.007	0.005	0.014	0.341	0.376	0.179	0.454	0.039
T × N source	2	0.759	0.647	0.938	0.545	0.369	0.464	0.417	0.538	0.328

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 10. Change in ESM-C (Mg C ha^{-1}) for the main effects of N source and tillage by soil layer (1992-2012).

		ΔESM-C$_{Layer}$ (Mg C ha^{-1})				
		depth (cm)				
Effect	Treatment	0-5	5-15	15-30	30-45	45-60
N source	Ctrl	0.12 a	-1.34 a	0.75	-2.54 a	-15.2 ab
	OrgF	9.77 b	8.41 b	-1.05	-8.33 b	-12.2 a
	MinF	1.71 a	0.53 a	-3.24	-9.06 b	-21.0 b
Tillage	NT	5.06 a	1.06 a	-1.59	-6.81	-17.3
	CT	2.67 b	4.01 b	-0.77	-6.48	-14.9
Effect	df	P-value				
Tillage (T)	1	0.052	0.061	0.669	0.992	0.419
N source	2	<0.001	<0.001	0.230	0.004	0.015
T × N source	2	0.498	0.244	0.076	<0.001	0.229

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 11. Change in ESM-C (Mg C ha^{-1}) for the interaction of N source and tillage by soil layer (1992-2012).

		ΔESM-C$_{Layer}$ (Mg C ha^{-1})				
		depth (cm)				
Tillage	N source	0-5	5-15	15-30	30-45	45-60
NT	Ctrl	0.52	-1.10	-0.89	-5.65 ab	-18.48
	OrgF	10.91	5.76	1.58	-3.80 ab	-13.79
	MinF	3.75	-1.47	-5.45	-11.0 bc	-19.58
CT	Ctrl	-0.28	-1.59	2.39	0.58 a	-11.84
	OrgF	8.63	11.07	-3.67	-12.9 c	-10.65
	MinF	-0.33	2.54	-1.03	-7.14 abc	-22.3

Effect	df	P-value				
T × N source	2	0.498	0.244	0.076*	<0.001	0.229

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at $P < 0.10$.
**No significance determined by Bonferroni's adjustment* *in 15-30 cm layer.*

Table 12. Change in ESM-C (Mg C ha^{-1}) for the main effects of N source and tillage by cumulative soil layers (1992-2012).

		ΔESM-C$_{Cum}$ (Mg C ha^{-1})				
		depth (cm)				
Effect	Treatment	0-5	0-15	0-30	0-45	0-60
N source	Ctrl	0.12 a	-1.22 a	-0.48 a	-3.01 a	-18.2 a
	OrgF	9.77 b	18.2 b	17.1 b	8.81 b	-3.41 b
	MinF	1.71 a	2.24 a	-1.00 a	-10.1 a	-31.0 c
Tillage	NT	5.06 a	6.12	4.53	-2.28	-19.6
	CT	2.67 b	6.68	5.91	-2.57	-15.5
Effect	df	P-value				
Tillage (T)	1	0.054	0.803	0.665	0.578	0.319
N source	2	<0.001	<0.001	<0.001	<0.001	<0.001
T × N source	2	0.527	0.715	0.665	0.026	0.084

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 13. Change in ESM-C (Mg C ha^{-1}) for the interaction of N source and tillage by cumulative soil layers (1992-2012).

		ΔESM-C_{Cum} (Mg C ha^{-1})				
		depth (cm)				
Tillage	N source	0-5	0-15	0-30	0-45	0-60
NT	Ctrl	0.52	-0.58	-1.47	-7.12 a	-25.6 a
	OrgF	10.9	16.7	18.3	14.4 bc	0.66 b
	MinF	3.75	2.28	-3.18	-14.2 a	-33.8 a
CT	Ctrl	-0.28	-1.87	0.52	1.10 abc	-10.8 ab
	OrgF	8.63	19.7	16.0	3.16 abc	-7.49 ab
	MinF	-0.33	2.21	1.18	-5.97 a	-28.3 a
Effect	**df**	P-value				
T × N source	2	0.527	0.715	0.665	0.026	0.084

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at P < 0.10.

Table 14. Change in ESM-N (Mg N ha^{-1}) for the main effects of N source and tillage by soil layers (1992-2012).

		ΔESM-N$_{Layer}$ (Mg N ha^{-1})				
		depth (cm)				
Effect		0-5	5-15	15-30	30-45	45-60
N source	Ctrl	-0.01 a	-0.94 a	-3.20	-1.94 a	-4.20 a
	OrgF	5.50 b	4.56 b	-0.94	-2.54 b	-6.19 b
	MinF	0.71 a	-0.68 a	-3.14	-3.47 b	-4.20 a
Tillage	NT	1.88 a	-0.34 a	-3.11	-4.44	-6.96
	CT	2.26 b	2.30 b	-1.75	-0.86	-2.76
Effect	df	P-value				
Tillage (T)	1	0.054	0.063	0.669	0.823	0.330
N source	2	<0.001	<0.001	0.252	0.004	0.024
T × N source	2	0.527	0.269	0.104	0.991	0.281

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at $P < 0.10$.

Table 15. Change in ESM-N (Mg N ha^{-1}) for the main effects of N source and tillage by cumulative soil layers (1992-2012).

		ΔESM-N_{Cum} (Mg N ha^{-1})				
			depth (cm)			
Effect		0-5	0-15	0-30	0-45	0-60
N source	Ctrl	-0.01 a	-0.95 a	-4.15 a	-6.09 a	-10.3 a
	OrgF	5.50 b	10.1 b	9.12 b	6.57 b	0.38 b
	MinF	0.71 a	0.21 a	-3.12 a	-6.59 a	-10.8 a
Tillage	NT	1.88	1.53 a	-1.57 a	-6.01 a	-13.0 a
	CT	2.26	4.55 b	2.81 b	1.94 b	-0.82 b
Effect	df			P-value		
Tillage (T)	1	0.697	0.089	0.084	0.026	0.013
N source	2	<0.001	<0.001	<0.001	0.006	0.088
T × N source	2	0.699	0.736	0.733	0.888	0.915

N management: Ctrl: Control, OrgF: Organic fertilizer, MinF: Mineral fertilizer
Tillage: CT: Conventional tillage, NT: No-till
Results were considered significant at $P < 0.10$.

Appendix A - Site characteristics

Appendix A.1 – Pedon description (1991)

Soil Series: Kennebec
Classification: fine-silty, mixed, mesic Cumulic Hapludoll
Location: NE1/4 NE1/4 NW1/4 SE1/4 of sec. 1, T.10S., R.7E., Sheet 26 of the Riley County Soil Survey
Physiography: Floodplain
Parent Materials: Recent alluvium over old alluvium
Vegetation: Plowed field
Hydraulic Conductivity: moderately low
Drainage Class: moderately well drained
Described By: Ransom, M. D., W. A. Wehmueller
Date: July 10, 1991 (last horizon described by M. Ransom and D. Porter on July 15, 1991)
Weather: Hot, partly cloudy, followed by thunderstorm

Ap--0 to 17 cm; very dark brown (10YR 2/2) silt loam; dark grayish brown (10YR 4/2) dry; hard, friable; many fine roots throughout; few very fine and fine tubular pores; the structure is large clods that parts to small granular, vertical cracks 0.5 to 1 mm wide are between the large clods; the layer from 15 to 17 cm has thin platy structure from compaction; abrupt smooth boundary.

A--17 to 32 cm; very dark brown (10YR 2/2) silt loam; 70% dark grayish brown (10YR 4/2), and 30% very dark grayish brown (10YR 3/2) dry; weak fine subangular blocky structure; hard, friable; many fine roots throughout; common very fine and fine tubular pores; few horizontal cracks 0.5 mm wide; clear wavy boundary.

C--32 to 41 cm; stratified very dark brown (10YR 2/2), and dark brown (10YR 3/3) silt loam; dark grayish brown (10YR 4/2), and brown to dark brown (10YR 4/3) dry; weak thin platy structure; hard, friable; many fine roots throughout; very fine and fine tubular pores; abrupt wavy boundary.

Ab--41 to 59 cm; black (10YR 2/1) silty clay loam; very dark gray (10YR 3/1) dry; weak medium subangular blocky structure parting to moderate medium granular; slightly hard, friable; many fine roots throughout; common very fine and fine tubular, and few medium tubular pores; clear wavy boundary.

A/Eb--59 to 71 cm; very dark gray (10YR 3/1) silt loam; dark grayish brown (10YR 4/2), and grayish brown 10YR 5/2) exterior dry; moderate fine subangular blocky structure parting to moderate medium granular; hard, friable; common fine roots throughout; common very fine and fine tubular and , and few medium tubular pores; common distinct light brownish gray (10YR 6/2) continuous skeletans (sand or silt) on vertical and horizontal faces of peds; abrupt wavy boundary.

A'b--71 to 85 cm; very dark gray (10YR 3/1) silty clay loam; dark grayish bown (10YR 4/2) dry; few very fine distinct brown to dark brown (10YR 4/3) mottles; moderate medium angular blocky structure; very hard, firm; common fine roots throughout; few very fine and fine tubular pores; few vertical cracks less than 0.5 mm wide; clear wavy boundary.

ABb--85 to 121 cm; dark grayish brown (10YR 4/2) silty clay loam; grayish brown (10YR 5/2) dry; common fine distinct dark yellowish brown (10YR 4/4) mottles; moderate medium prismatic structure; very hard, firm; common fine roots throughout; few very fine and fine tubular pores; many distinct very dark gray (10YR 3/1) continuous organic coats on vertical and horizontal faces of peds, and very few very dark gray (10YR 3/1) discontinuous clay films (cutans) on faces of peds and in pores; few very fine gypsum crystals on faces of peds; gradual wavy boundary.

Btb--121 to 155 cm; dark grayish brown (10YR 4/2) silty clay loam; few fine distinct dark yellowish brown (10YR 4/4) mottles; weak medium prismatic structure parting to moderate medium subangular bloky; hard, firm; few very fine roots throughout; few very fine and fine tubular pores; common distinct very dark gray (10YR 3/1) discontinuous organic coats on vertical and horizontal faces of peds, and few very dark gray (10YR 3/1) clay films (cutans) on faces of peds and in pores; few very fine gypsum crystals on faces of peds; clear wavy boundary.

Btb2--155 to 193 cm; dark grayish brown (10YR 4/2) silty clay loam; common medium distinct brown (10YR 5/3), and few medium distinct yellowish brown (10YR 5/4) mottles; weak medium prismatic structure parting to moderate medium subangular bloky; hard, firm; few very fine roots throughout; common very fine and fine tubular pores; few distinct very dark gray (10YR 3/1) discontinuous organic coats on faces of peds, and many very dark gray (10YR 3/1) continuous clay films (cutans) on faces of peds and in pores; common very fine gypsum crystals on faces of peds; gradual wavy boundary.

Btb3--193 to 233 cm; dark grayish brown (10YR 4/2) clay loam; common medium distinct brown (10YR 5/3), and few medium distinct yellowish brown (10YR 5/4) mottles; weak medium prismatic structure parting to moderate medium subangular blocky; very hard, firm; few very fine roots throughout; common ver fine and fine tubular pores; many very dark gray (10YR 3/1) continuous clay films (cutans) on faces of peds and in pores; common very fine gypsum crystals on faces of peds.

Appendix A.2 – Pedon description (1999)

Sampled as on Sep 21, 1999: Kennebec ; Fine-silty, mixed, superactive, mesic Cumulic Hapludolls
Revised to :

State of Kansas
Kansas State University
Department of Agronomy
Throckmorton Plant Sciences Center
Manhattan, KS 66506-5501

SSL - Project KSU201101 Kansas State Data
- Site ID 99KS161011 Lat: 39° 12' 43.34" north Long: 96° 35' 37.12" west MLRA: 76
- Pedon No. 99KS161011
- General Methods 1B1A, 2A1, 2B

Layer	Horizon	Orig Hzn	Depth (cm)	Field Label 1	Field Label 2	Field Label 3	Field Texture	Lab Texture
KSUSS3521	Ap	Ap	0-13				SIL	SIL
KSUSS3522	Ap2	Ap2	13-29				SIL	SIL
KSUSS3523	Ab	Ab	29-66				SICL	SIL
KSUSS3524	Bwb1	Bwb1	66-113				SICL	SIL
KSUSS3525	Bwb2	Bwb2	113-145				SICL	SIL

PSDA & Rock Fragments

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-
					(- - - - - Total - - - - - -)			(- - Clay - - -)		(- - - - Silt - - - - -)		(- - - - - - - - - - - - Sand - - - - - - - - - - - -)					(Rock Fragments (mm))				
				Lab Text-ure	Clay < .002	Silt .002 -.05	Sand .05 -2	Fine < .0002	CO_3 < .002	Fine .002 -.02	Coarse .02 -.05	VF .05 -.10	F .10 -.25	M .25 -.50	C .5 -1	VC 1 -2	(- - - - - - - - Weight - - - - - - - -) 2 -5	5 -20	20 -75	.1- 75	>2 mm wt % whole soil
Layer	Depth (cm)	Horz	Prep		(- % of <2mm Mineral Soil -)												(- - - - - - - % of <75mm - - - - - -)				soil
					3A1a1a							3A1a1a	3A1a1a	3A1a1a	3A1a1a	3A1a1a					
KSUSS3521	0-13	Ap	S	sil	18.6	74.6	6.8				46.0	5.1	0.6	0.3	0.3	0.5					
KSUSS3522	13-29	Ap2	S	sil	21.7	71.6	6.7				43.7	5.8	0.6	0.1	0.1	0.1					
KSUSS3523	29-66	Ab	S	sil	24.2	70.8	5.0				39.1	4.5	0.5	--	--	--					
KSUSS3524	66-113	Bwb1	S	sil	21.7	74.1	4.2				42.7	3.9	0.3	--	--	--					
KSUSS3525	113-145	Bwb2	S	sil	21.6	72.9	5.5				42.7	5.2	0.3	--	--	--					

*** Primary Characterization Data ***

Pedon ID: 99KS161011 (Riley, Kansas)

Sampled As : Kennebec — Fine-silty, mixed, superactive, mesic Cumulic Hapludolls

Kansas State University Soil Characterization Laboratory ; Pedon No. 99KS161011

Carbon & Extractions				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-	-17-	-18-	-19-
				(- - - - - Total - - - - -)			Est	OC	C/N	(- - - Dith-Cit Ext - - -)			(- - - - - - Ammonium Oxalate Extraction - - - - - -)						(- - - Na Pyro-Phosphate - - -)			
	Depth			C	N	S	OC	(WB)	Ratio	Fe	Al	Mn	Al+½Fe	ODOE	Fe	Al	Si	Mn	C	Fe	Al	Mn
Layer	(cm)	Horz	Prep	(- - - - - - - - - - % of <2 mm - - - - - - - - - -)						(- - - - - - - - - - - - - - - - - - - % of < 2mm - - - - - - - - - - - - - - - - - -)								mg kg^{-1}	(- - - - - - % of < 2mm - - - - -)			
				4H2a	4H2a																	
KSUSS3521	0-13	Ap	S	1.36	0.12																	
KSUSS3522	13-29	Ap2	S	1.23	0.10																	
KSUSS3523	29-66	Ab	S	1.17	0.10																	
KSUSS3524	66-113	Bwb1	S	0.63	0.06																	
KSUSS3525	113-145	Bwb2	S	0.45	0.04																	

CEC & Bases

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-
				(- - - - - - NH_4OAC Extractable Bases - - - - -)								CEC8	CEC7	ECEC		(- - - - Base - - - -)	
								Sum	Acid-	Extr	KCl	Sum	NH_4	Bases	Al	(- Saturation -)	
	Depth			Ca	Mg	Na	K	Bases	ity	Al	Mn	Cats	OAC	+Al	Sat	Sum	NH_4OAC
Layer	(cm)	Horz	Prep	(- - - - - - - - - - - - - - - - - - cmol(+) kg^{-1} - - - - - - - - - - - - - - - - - - -)							mg kg^{-1}	(- - - - cmol(+) kg^{-1} - - -)			(- - - - - - - - % - - - - - - - -)		
				4B1a1	4B1a1	4B1a1	4B1a1		6H2a								
KSUSS3521	0-13	Ap	S	15.7	1.7	0.1	1.0	18.5	4.5			23.0					81
KSUSS3522	13-29	Ap2	S	11.5	2.3	0.1	0.7	14.7	5.9			20.6					71
KSUSS3523	29-66	Ab	S	11.1	2.9	0.2	0.6	14.8	5.8			20.5					72
KSUSS3524	66-113	Bwb1	S	9.1	2.9	0.3	0.5	12.9	5.1			18.0					72
KSUSS3525	113-145	Bwb2	S	8.9	3.0	0.1	0.6	12.5	4.8			17.3					73

pH & Carbonates

				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-
				(- - - - - - - - - - - - - - - - - - pH - - - - - - - - - - - - - - - - - -)						(- - Carbonate - -)		(- - Gypsum - - -)		
					$CaCl_2$					As $CaCO_3$		As $CaSO_4*2H_2O$		Resist
	Depth				0.01M	H_2O	Sat			<2mm	<20mm	<2mm	<20mm	ohms
Layer	(cm)	Horz	Prep	KCl	1:2	1:1	Paste	Oxid	NaF	(- - - - - - - - - - - - % - - - - - - - - - - - -)				cm^{-1}
					8C1e	8C1a								
KSUSS3521	0-13	Ap	S		6.9	7.3								
KSUSS3522	13-29	Ap2	S		6.0	6.7								
KSUSS3523	29-66	Ab	S		5.7	6.3								
KSUSS3524	66-113	Bwb1	S		5.9	6.4								
KSUSS3525	113-145	Bwb2	S		5.9	6.6								

*** Supplementary Characterization Data ***

Pedon ID: 99KS161011

(Riley, Kansas)

Sampled as on Sep 21, 1999: Kennebec ; Fine-silty, mixed, superactive, mesic Cumulic Hapludolls
Revised to :

SSL - Project KSU201101 Kansas State Data
- Site ID 99KS161011 Lat: 39° 12' 43.34" north Long: 96° 35' 37.12" west MLRA: 76
- Pedon No. 99KS161011
- General Methods 1B1A, 2A1, 2B

State of Kansas
Kansas State University
Department of Agronomy
Throckmorton Plant Sciences Center
Manhattan, KS 66506-5501

Tier 4				-76-	-77-	-78-	-79-	-80-	-81-	-82-	-83-	-84-	-85-	-86-	-87-	-88-	-89-	-90-	-91-	-92-	-93-	-94-	-95-	-96-	-97-	-98-
				(- - - Weight Fractions - Clay Free - - -)															Text	PSDA (mm)			pH	Elect.		Part-
				(--- Whole Soil ---)						(--- <2 mm Fraction ---)									-ure							-icle
										(--- Sands ---)					(--- Silts ---)				by	Sand	Silt	Clay	Ca	Res-	Con-	Den-
	Depth			>2	75 -20	20 -2	2- .05	.05- .002	< .002	VC	C	M	F	VF	C	F	Cl ay		PSDA	2- .05	.05- .002	< .002	Cl_2 .01M	ist. ohms	duct $dS\ m^{-1}$	sity
Layer	(cm)	Horz	Prep	(- % of >2 mm Sand and Silt -)						(--- % of Sand and Silt ---)									<2 mm	(---- % of 2 mm ----)			(--- <2 mm ---)			$g\ cm^{-3}$
																						3A1a1a8C1e				
KSUSS3521	0-13	Ap	S																sil	6.8	74.6	18.6	6.9			
KSUSS3522	13-29	Ap2	S																sil	6.7	71.6	21.7	6.0			
KSUSS3523	29-66	Ab	S																sil	5.0	70.8	24.2	5.7			
KSUSS3524	66-113	Bwb1	S																sil	4.2	74.1	21.7	5.9			
KSUSS3525	113-145	Bwb2	S																sil	5.5	72.9	21.6	5.9			

*** Taxonomy Characterization Data ***

Pedon ID: 99KS161011

(Riley, Kansas)

Sampled as on Sep 21, 1999: Kennebec ; Fine-silty, mixed, superactive, mesic Cumulic Hapludolls
Revised to :

SSL - Project KSU201101 Kansas State Data
- Site ID 99KS161011 Lat: 39° 12' 43.34" north Long: 96° 35' 37.12" west MLRA: 76
- Pedon No. 99KS161011
- General Methods 1B1A, 2A1, 2B

State of Kansas
Kansas State University
Department of Agronomy
Throckmorton Plant Sciences Center
Manhattan, KS 66506-5501

Taxonomy Tier 1

Layer	Depth (cm)	Horz	Prep	-1- Clay <.002	-2- Fine Clay <.0002	-3- $CaCO_3$ Clay <.002	-4- 1500 kPa /Clay	-5- Clay Est	-6- .1-75 mm Frac	-7- Bulk Den 33 kPa g cm^{-3}	-8- Cole Whole Soil cm cm^{-1}	-9- Vol % of Whole	-10- Resist Min %
				(---------% of <2 mm-------)				(-------- % --------)					
				3A1a1a									
KSUSS3521	0-13	Ap	S	18.6									
KSUSS3522	13-29	Ap2	S	21.7									
KSUSS3523	29-66	Ab	S	24.2									
KSUSS3524	66-113	Bwb1	S	21.7									
KSUSS3525	113-145	Bwb2	S	21.6									

Taxonomy Tier 2				-1-	-2-	-3-	-4-	-5-	-6-	-7-	-8-	-9-	-10-	-11-	-12-	-13-	-14-	-15-	-16-
				pH	pH	Org	Tot	Al+½ Fe		CO_3 as	(--- Base Sat ---)		NZ	ECEC	CEC7	ECEC	Al		
	Depth			H_2O	NaF	C	C	Oxal	ODOE	$CaCO_3$	NH_4	Bases	P Ret	cmol(+)	/Clay	/Clay	Sat	E C	ESP
Layer	(cm)	Horz	Prep			(-- % --)								kg $^{-1}$			%	dS m^{-1}	%
				8C1a			4H2a												
KSUSS3521	0-13	Ap	S	7.3			1.36				81								
KSUSS3522	13-29	Ap2	S	6.7			1.23				71								
KSUSS3523	29-66	Ab	S	6.3			1.17				72								
KSUSS3524	66-113	Bwb1	S	6.4			0.63				72								
KSUSS3525	113-145	Bwb2	S	6.6			0.45				73								

PEDON DESCRIPTION

Print Date: Apr 23 2019

Description Date: Sep 23 1999

Describer: W. Wehmueller, M.D. Ransom, J.C. Remley

Site ID: 99KS161011

Site Note:

Pedon ID: 99KS161011

Pedon Note: Practice site 6 for 1999 KSU collegiate soil judging contest. Area is located on the north Agronomy Farm. The second horizon is considered an Ap2 because we noted that there was discontinuous stratifcation in some places at the bottom of the horizon. Had there been continuous strata that were not disturbed the horizon would probably have been considered a C horizon. Water started entering the pit at 160 cm and is part of the apparent water table. The water table has been observed in nearby pits also. See pedon description 91KS161001.; Data from Kansas State University Pedology Laboratory. KSU # Depth Horizon VCS CS MS FS VFS TS TSI TC Class 3521 0-13 Ap1 0.5 0.3 0.3 0.6 5.1 6.8 74.6 18.6 sil 3522 13-29 Ap2 0.1 0.1 0.1 0.6 5.8 6.7 71.6 21.7 sil 3523 29-66 Ab 0.0 0.0 0.0 0.5 4.5 5.0 70.8 24.2 sil 3524 66-113 Bwb1 0.0 0.0 0.0 0.3 3.9 4.2 74.1 21.7 sil 3525 113-145 Bwb2 0.0 0.0 0.0 0.3 5.2 5.5 72.9 21.6 sil

Lab Source ID: KSU

Lab Pedon #: 99KS161011

User Transect ID:

Soil Name as Described/Sampled: Kennebec

Classification:

Soil Name as Correlated:

Classification:

Pedon Type: within range of map unit

Pedon Purpose: full pedon description

Taxon Kind:

Associated Soils:

Physiographic Division: Interior Plains

Physiographic Province: Central Lowland Province

Physiographic Section: Osage plain

State Physiographic Area: Flint Hills Upland

Local Physiographic Area:

Geomorphic Setting: on tread of flood plain on plains

Upslope Shape: linear

Cross Slope Shape: linear

Country:

State: Kansas

County: Riley

MLRA: 76 -- Bluestem Hills

Soil Survey Area: KS161 -- Riley County, Kansas

Map Unit:

Quad Name: Manhattan, Kansas

Std Latitude: 39.2120399

Std Longitude: -96.5936432

Primary Earth Cover: Crop cover

Secondary Earth Cover:

Vegetation:

Parent Material: fine-silty alluvium derived from mixed

Bedrock Kind:

Bedrock Depth:

Bedrock Hardness:

Bedrock Fracture Interval:

Particle Size Control Section: 25 to 100 cm.

Description origin: Converted from PDP 3.x

Diagnostic Features: ? to ? cm.

Surface Fragments:

Description database: MLRA05_Salina

Cont. Site ID: 99KS161011

Pedon ID: 99KS161011

Slope (%)	Elevation (meters)	Aspect (deg)	MAAT (C)	MSAT (C)	MWAT (C)	MAP (mm)	Frost-Free Days	Drainage Class	Slope Length (meters)	Upslope Length (meters)
0.0	322.0							moderately well		

Ap--0 to 13 centimeters (0.0 to 5.1 inches); very dark brown (10YR 2/2) exterior and very dark grayish brown (10YR 3/2) crushed silt loam; 26 percent clay; moderate medium granular structure; friable; many fine roots throughout; abrupt smooth boundary. Lab sample # KSUSS3521

Ap2--13 to 29 centimeters (5.1 to 11.4 inches); very dark brown (10YR 2/2) exterior silt loam; 28 percent clay; moderate coarse angular blocky structure; firm; common fine roots between peds; clear smooth boundary. Lab sample # KSUSS3522. the structure of this horizon is related to compaction

Ab--29 to 66 centimeters (11.4 to 26.0 inches); very dark brown (10YR 2/2) exterior and very dark grayish brown (10YR 3/2) crushed silty clay loam; 30 percent clay; moderate medium granular structure; friable; common fine roots between peds; gradual smooth boundary. Lab sample # KSUSS3523

Bwb1--66 to 113 centimeters (26.0 to 44.5 inches); very dark grayish brown (10YR 3/2) exterior and dark brown (10YR 3/3) crushed silty clay loam; 33 percent clay; weak medium prismatic parts to moderate medium subangular blocky structure; friable; common fine roots between peds; many fine high-continuity tubular pores; 1 percent faint 10YR 3/2), moist, clay films on faces of peds; iron-manganese concretions; 1 percent fine irregular; gradual smooth boundary. Lab sample # KSUSS3524. there was much discussion about the few patchy clay films observed in this horizon, the conclusion was that the Ap1 and Ap2 are post settlement alluvium and that the original A starts at 29 cm. There is not a big enough clay increase from the Ab to the underlying horizons to qualify for an argillic horizon.

Bwb2--113 to 145 centimeters (44.5 to 57.1 inches); very dark grayish brown (10YR 3/2) exterior and dark brown (10YR 3/3) crushed silty clay loam; 34 percent clay; 15 percent fine and medium distinct (10YR 5/2) mottles; weak medium prismatic parts to moderate medium subangular blocky structure; friable; common fine roots between peds; many fine high-continuity tubular pores; 1 percent faint 10YR 3/2), moist, clay films on faces of peds; iron-manganese concretions; 5 percent fine spherical roots between peds. Lab sample # KSUSS3525. Clay films in this horizon are similar to the horizon above and have a similar interpretation.

Appendix A.3 – Particle size analysis (Harris, 1993)

Particle size analysis				
Depth	Sand	Silt	Clay	Texture
cm		%		
0-5	8.8	69.2	22.0	SiL
5-15	7.8	71.7	20.5	SiL
15-30	5.4	71.6	23.1	SiL
30-45	3.7	70.2	26.1	SiL
45-60	4.4	66.5	29.1	SiCL
60-90	9.0	64.8	29.7	SiCL
90-120	15.3	62.8	28.2	SiCL
120-150	17.1	58.3	26.4	SiL
150-180	17.1	57.3	25.6	SiL

Appendix A.4 – Compost analysis example

Compost analysis – February 2013	
N analysis	Percent
Total N	2.00
Organic N	1.75
Ammonium N	0.25
Nitrate N	<0.01
Major/secondary nutrients	
P	0.37
P_2O_5	0.84
K	0.66
K as K_2O	0.79
Other	
Organic matter	30.2
C:N	8.8
*assumes 50% of organic N available, 100% of inorganic N available	