# SOIL AGGREGATION AND CARBON SEQUESTRATION FOLLOWING A SINGLE TILLAGE EVENT IN NO-TILL SOILS IN A SEMI-ARID ENVIRONMENT

by

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# Abstract

The sequestration of atmospheric $CO_2$ into soil through no-till management is an economic and viable method for reducing greenhouse gases, but maintaining no-till practices are necessary to sequester C in the long-term. Our study focused on the effects of a single tillage operation on soil organic C and N and aggregation in no-till soils when no-till practices are immediately resumed after tillage. Three locations in western Kansas were selected that had been in continuous dryland no-till for at least 5 years – Wallace, Tribune, and Spearville. Tillage treatments were administered in 2004 and consisted of no-till (NT), disk plow (DP), sweep plow (SwP), and chisel plow (CP). Treatments were arranged in a randomized complete block design with four replications. Soil samples were taken at 0-5, 5-15, and 15-30 cm depths. Composite samples were taken from each block prior to tillage and tested for whole soil organic C and N. Further soil samples were collected in spring 2005 at approximately nine months after tillage (MAT) and again in fall 2005 at approximately 12 MAT and tested for whole soil organic C and N and aggregate size distribution. Bulk density was measured for each plot and depth prior to sampling at 12 MAT. Twelve MAT samples were also tested for aggregate-associated C and N. The DP tillage had a greater C concentration than NT and CP when averaged over depth and time, but C mass did not vary between tillage systems. Changes in whole soil C and N over time varied by location, but the differences were similar between tillage treatments. Tillage treatments DP and SwP also had a greater mass of macroaggregate (250-1000 μm) associated C relative to CP (but not to NT) for Wallace in the surface 0-5 cm at 12 MAT. No other differences between tillages in aggregate-associated C were observed. A single tillage event did not have a significant impact on aggregate size distribution. The greatest amount of aggregate-associated C and N existed in the large microaggregate (53-250 μm) fraction. Changes in aggregate distribution or aggregate-associated C or N did not directly correlate to changes in whole soil C and N. We therefore conclude that a single tillage operation using these implements will not result in a measurable loss in sequestered C over time for dryland soils in a semi-arid climate such as western Kansas.

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# Dedication

This work is dedicated to my loving and wonderful wife, Candy. Her support, encouragement, and unselfish love are what made this possible. Thank you very much for what you have sacrificed to make this happen. I love and cherish you with all my heart.

Most of all, this thesis and the MS degree itself is dedicated to my Lord and Savior Jesus Christ, “in whom are hidden all treasures of wisdom and knowledge” *Colossians 2:3*.

To the only God our Savior, through Jesus Christ our Lord, be glory, majesty, dominion, and authority, before all time and now and forever. Amen. *Jude 25*

# CHAPTER 1 - General Introduction

Carbon dioxide ($CO_2$) is one of the greenhouse gases (GHG) in the Earth's atmosphere that traps a portion of the Sun's radiant energy and thereby warms the earth (Mitchell, 1989). Other pools of C in the Earth also exist in the oceans and in terrestrial reservoirs such as geologic formations, vegetation, and soils. Soil organic matter (SOM) is the largest global terrestrial pool (Kern and Johnson, 1993), with soils accounting for 1500 Pg C while vegetation only accounts for 550 Pg C (Houghton and Skole, 1990). Carbon sequestration is the process whereby C as $CO_2$ is transferred into long-lived pools and securely stored so it is not remitted back into the atmosphere (Lal, 2004). Soil organic carbon (SOC) is a large storehouse of C and changes within this reservoir have direct implications on atmospheric $CO_2$ (Janzen et al., 1998). Through photosynthesis, vegetation withdraws $CO_2$ from the atmosphere and stores it in above- or below-ground plant parts, thus providing a natural sink for $CO_2$ (Johnson, 1995). Plant residues are the major source of C inputs in all terrestrial ecosystems (Paustian et al., 1997). Conversely, plants and soils also return $CO_2$ back to the atmosphere during respiration (Johnson, 1995). Human activities have decreased the amount of C held in soils through cultivation, deforestation, and drainage of wet soils (Johnson, 1995). Over the past two centuries, almost half of all soil carbon in managed ecosystems has been lost to the atmosphere as $CO_2$ (McCarl et al., 2007). Cumulative losses of C from vegetation and soils from 1850 – 1980 was approximately 90-120 Pg, while current annual losses of C from plants and soils is estimated at 0.2 Pg from temperate regions and 2 Pg from tropical regions (Houghton and Skole, 1990).

Properly managed cropland in the US can be a major sink for C sequestration through residue management (Smith et al., 2007; Rice 2006). The estimated amount of C that can be sequestered through improved residue management varies in the literature, but there is an overwhelming consensus that significant amounts of C can be stored in the soil. For example, Lal et al. (1999b) projected the potential for soil C sequestration from improved management of U.S. cropland to be between 75 and 208 Tg over the next several decades. Warm, semi-arid regions of the United States are capable of sequestering atmospheric C as long as crop residues are retained on the soil surface and SOC in minimally disturbed (Martens et al., 2005). Specifically, 300 – 600 kg C $ha^{-1}$ $yr^{-1}$ could be sequestered in the U.S. Great Plains (Follett and McConkey, 2000). By adopting conservation tillage in the central United States, up to 1.7 million Mg C $yr^{-1}$ could be sequestered in reduced-fallow wheat-pasture systems and 6.2 million Mg C $yr^{-1}$ in row crop systems (Antle et al., 2007). Governmental policies need to be developed to encourage the adoption of improved soil, crop, and water management practices in order to increase SOC storage, reduce C lost as $CO_2$ to the atmosphere, and ameliorate the effects of global warming (Reilly and Asadoorian, 2007; Capalbo et al., 2004). Since organic C is a primary constituent of SOM, changes in SOM provide a primary measure for determining the direction which current management practices are headed, either as a source or sink for atmospheric $CO_2$ (Karlen and Cambardella, 1996).

In addition to being an important pool of global C, SOM is also an important soil quality attribute that influences productivity and the well-being of soils (Campbell et al., 1997; Follet et al., 2005). Soil organic matter is a major source of inorganic nutrients and microbial energy (Lal, 2004). It has a positive influence on soil structure by influencing the size, shape, and arrangement of aggregates and pore spaces (Monreal et al., 1998). Soil structure, in turn, influences the movement and storage of water and air, crop root development, and nutrient cycling (Monreal et al., 1998). Soil organic matter is a source of nutrient elements for plant growth, yielding N, P, and S upon decomposition (Yang et al., 2007). Soil organic matter also enhances the availability of micronutrients to plants by chelating with polyvalent cations (Tisdale et al., 1993). Severe depletion of SOC degrades soil quality, reduces biomass productivity, and increases the risk of erosion (Lal, 2004). In semiarid regions such as the Great Plains, SOM is of great importance because of its large impact on water conservation, nutrient availability, and yield (McVay et al., 2006).

Organic C exists in various degrees of stability and decomposition within the soil, and researchers have differentiated organic C into broad pools based on these characteristics. Plant litter is a form of SOC that consists of roots and residues that have been minimally affected by decomposition (Janzen et al., 1998). Inert SOC (Janzen et al., 1998), also called “passive” (Parton et al., 1987) and “recalcitrant” (van Veen and Paul, 1981), is highly stable and extremely tolerant to further biological decay because of its chemical configuration and/or association with soil minerals (Janzen et al., 1998). It has the longest turnover time of 200-1500 yr (Parton et al., 1987). Organic C in various stages of transformation between plant-litter and inert SOM is termed the dynamic pool (Janzen et al., 1998), and is also referred to as the “slow” and “active” pool (Parton et al., 1987), “decomposable” pool (van Veen and Paul, 1981), and “labile” SOM (Biederbeck et al., 1994). These fractions have turnover times ranging from a few years to several decades (Janzen et al., 1998). Plant and root biomass has turnover times of 1-5 yr, while microorganisms and microbial products have 0.1 – 1 yr turnover times (Parton et al., 1987). This dynamic SOM is inherently decomposable and is commonly referred to in the literature as light-fraction organic matter (LF), particulate organic matter (POM), macro-organic matter, and mineralizable C and N ($C_{min}$ and $N_{min}$) (Janzen et al., 1998). Included within this dynamic pool are microorganisms (Gregorich and Janzen, 1996) and their by-products of amino acids and polysaccharides (van Veen and Paul, 1981). Soil fauna, saprophytic fungi, and bacteria reduce dead roots and hyphae to POM, depositing polysaccharides and other organic substrates in the process (Jastrow and Miller, 1997). This dynamic pool is a good habitat for microorganisms and is the site of intense decomposer activity because of the LF's enrichment of C and N (Gregorich and Janzen, 1996). Although the LF is a small part of the soil mass, it constitutes a substantial portion of SOC because of its high C concentration (Gregorich and Janzen, 1996). The LF has a density < 2.0 g $cm^{-3}$ and is isolated from soil by flotation on a dense liquid. The most probable repository for SOC gains in the short term is this dynamic SOC pool (Janzen et al., 1998).

## Aggregates

Soil aggregates are combinations of soil organic and mineral components that are assembled together in varying degrees of size and stability. Aggregation is important to the overall productivity of a soil, influencing such factors as water infiltration, storage, structure, and root growth (Dalal and Bridge, 1996), water and wind erosion (Franzluebbers and Arshad, 1996), bulk density and compaction (Dexter, 1988), soil organic matter (SOM) (van Veen and Paul, 1981), and fertility (Elliot, 1986). Specifically, aggregates are vital for the protection of soil organic matter (SOM) from decomposition by microorganisms (Buyanovsky et al., 1994; Elliot and Coleman, 1988). Labile OM may become physically protected from decomposition by incorporation into soil aggregates (Oades, 1984; Gregorich et al., 1989), thereby providing a temporary storehouse of SOC that is less susceptible to decomposition than "free" labile OM outside of an aggregate (Janzen et al., 1998). Nearly 90% of SOM is located within soil aggregates (Jastrow et al., 1996).

Aggregate size ranges constitute a hierarchy that can include up to nine orders of magnitude (Waters and Oades, 1991). Generally, aggregates are classified based on their diameter as either macroaggregates (> 250 µm) or microaggregates (< 250 µm). Within those two classifications, macroaggregates are usually partitioned into 250 – 1000 µm, 1000 – 2000 µm, and >2000 µm classes, while microaggregates are divided into <20 µm, 20 – 53 µm, and 53 – 250 µm. All sizes of aggregates are bound together by various forms of SOM. The different aggregate sizes represent a hierarchy that is only applicable to soils with a predominantly 2:1 clay mineralogy (e.g. Alfisols and Mollisols), where OM serves as the primary binding agent (Tisdall and Oades, 1980a; Oades and Waters, 1991).

Tisdall and Oades (1982) developed a conceptual model describing the formation of micro- and macroaggregates. In this model, microaggregates form first and then are coalesced together by plant roots and/or organic binding agents. Small microaggregates (2-20 µm) develop from the combination of clay particles, bacterial colonies, and fungal hyphae fragments. This size of microaggregate is very stable and unaffected by agricultural practices (Tisdall and Oades, 1982). Organic matter in this fraction is dominated by microbial products and contains little to no plant debris (Oades and Waters,

1991) and is highly protected against decomposition (Hassink, 1997). Large microaggregates (20-250 µm) are also stable against agricultural practices and are bonded together by "persistent" organic materials such as humic acids that are linked by polyvalent cations to form organo-mineral associations (Turchenek and Oades, 1978; Tisdall and Oades, 1982). The decomposition products in the core of these microaggregates are responsible for the aggregate's stability after the plant material is gone (Oades and Waters, 1991). Macroaggregates, on the other hand, are formed by binding microaggregates together in one of two primary ways. One mechanism consists of "temporary" binding agents such as roots, saprophytic fungi, and arbuscular mycorrhizal hyphae that bind microaggregates together to form macroaggregates (Tisdall and Oades, 1979; Tisdall and Oades, 1982). Fungal mycelia are very important in macroaggregate formation (Gupta and Germida, 1988). The second mechanism consists of "transient" agents produced by the microbial biomass, such as polysaccharides and microbial mucilages, which are also responsible for stabilizing macroaggregates (Tisdall and Oades, 1982; Gupta and Germida, 1988). These two mechanisms are greatly influenced by fine roots (0.2-1 mm diameter) which act to improve macroaggregate structure because of their strong influence on external hyphae and microbial biomass C (Jastrow et al., 1998).

Oades (1984) slightly altered this model by proposing that macroaggregates develop first and break down into microaggregates over time. Golchin et al. (1998) further developed this concept, and Gale et al. (2000a) demonstrated this newer model by identifying three major stages of aggregate formation: 1) New additions of particulate organic matter (POM) as roots or litter are colonized by microorganisms and the free

POM is encrusted to form a macroaggregate; 2) Macroaggregates destabilize quickly into microaggregates (20-250 µm) which slowly decompose and then become more stable because the mucilages produced during decomposition bind the mineral particles together; and 3) Further decomposition of the microaggregate core renders it unstable once the organic core is consumed, releasing microaggregates <20 µm and recalcitrant POM upon disruption. This process whereby OM is first accumulated in macroaggregates and then is redistributed in a more decomposed form into microaggregates is defined as aggregate turnover (Six et. al, 2000b). A great deal of research has been conducted to substantiate this new model. Angers et al. (1997) traced C and N in decomposing wheat straw and found that it accumulated rapidly in macroaggregates, which in turn increased macroaggregate stability. After 18 months of decomposition, however, the straw-associated C and N were found primarily in large microaggregates (50-250 µm), thus demonstrating the redistribution of C from macroaggregates to microaggregates. Jastrow (1996) also found that macroaggregates developed first under a restored prairie system, and that roots and mycorrhizal fungi were essential for macroaggregate formation. These decomposing roots and hyphae constituted the highly labile POM (Cambardella and Elliot, 1992) and become the center of a macroaggregate (Buyanovsky et al., 1994; Golchin et al., 1995). Mucilages produced by microorganisms during POM decomposition were combined with inorganic clay particles to encrust large microaggregates (106 – 250 µm) that were highly stable within the macroaggregate (Oades, 1984; Beare et al., 1994a). These fragments of plant materials encrusted within microaggregates were then physically protected from rapid decomposition (Oades and Waters, 1991). As the encrusted OM is slowly decomposed, smaller microaggregates (53 – 106 μm, and then <53 μm) were subsequently released (Beare et al., 1994a).

Macroaggregates have higher concentrations of C and N than that of the whole soil (Oades and Waters, 1991). Crushed macroaggregates consistently have greater amounts of mineralized C and N than do crushed microaggregates (Elliot, 1986; Beare et al., 1994b), and intact macroaggregates have higher concentrations of microbial biomass C and N than do microaggregates (Gupta and Germida, 1988). This indicates that the OM associated with macroaggregates is more labile, less decomposed, and more readily mineralized than microaggregate-associated OM (Elliot, 1986; Gupta and Germida, 1988; Beare et al., 1994b). Conversely, microaggregate-associated OM is more recalcitrant and more resistant to further decomposition, and is also physically protected from microorganisms (Gregorich et al., 1989). Long-term stabilization of SOM is therefore partially dependent on microaggregate formation (Six et al., 2002).

## Factors Controlling SOC

Carbon accumulation in the soil is the net result of residue inputs minus what is lost due to decomposition and soil erosion (Rasmussen and Collins, 1991; Paustian et al., 1997). Inputs of C into the soil come from decomposing vegetation, plant litter, crop roots, residues, and manure (Mann 1986). Loss of SOC is governed by crop grain and residue removal, respiration of $CO_2$ during OM decomposition, and/or soil erosion (Reicosky et al. 1995; Janzen et al, 1998; Paustian et al. 1997). Regional trends in SOC accumulation are dependent on four main variables: 1) Climate (including temperature and precipitation), 2) Soil texture, 3) Vegetation (the amount produced, its C:N ratio and lignin C:N ratio), and 3) Management (Jastrow and Miller, 1997; Johnson, 1995; Parton et al., 1987).

### *Climate*

The effects of different climatic conditions on SOC are primarily due to differences in temperature and moisture (van Veen and Paul, 1981). Generally speaking, OM content increases with increasing precipitation and decreases with increasing temperature (Jenny, 1941). Soil water and temperature regimes regulate the rates of chemical and biological reactions of OM (Karlen et al., 1992). Higher temperatures increase the rate of OM decomposition (Stewart, 1993) and speeds the rate of microbial biomass regrowth after desiccation (McGill et al., 1986). Temperature in a given climate is inextricably tied with moisture, however, because as temperature increases precipitation decreases (Stewart, 1993). The amount of precipitation, in turn, directly drives the amount of plant biomass (roots and crop residues) that is produced to replenish decomposed C (Stewart, 1993). In semiarid environments, SOM increases from south to north because of lower northern temperatures, which reduces SOM decomposition rates and reduces soil water deficits, thereby increasing plant biomass production (Paustian et al., 1997). Also, precipitation is the major control on SOM moving eastwards from the Rockies because of the increasing precipitation's positive influence on plant productivity (Paustian et al., 1997). Dalal and Mayer (1986) found that the OC of virgin grassland soils was closely correlated to mean annual rainfall, and that mean annual rainfall influenced SOC by influencing the amount of dry matter produced. Sufficient water for maximum plant growth is also important for aggregate formation (Tisdall and Oades, 1980b). Therefore, since SOC levels are so dependent on plant production (as influenced by temperature and moisture), soils with severe constraints to productivity (e.g. aridity) may have limited potential for SOC gain (Janzen et al., 1998). The semiarid Great Plains, for example, has marginal dryland crop production due to limited amounts of available water that is induced by a high evapotranspiration demand relative to precipitation (Havlin et al., 1995).

### *Soil Texture*

Soil texture also plays an important role in SOM stabilization and accumulation. Fine-textured soils have higher OM contents than coarse-textured soils (Jenny, 1941; Paustian et al., 1997) for two reasons. First of all, plant biomass production is lower in sandy soils. Sandy soils have less vegetation, lower total plant cover, and more soil exposed to erosion, which is a direct result of the sand's lower field capacity and plant available water (Hook and Burke, 2000). Campbell et al. (1996) demonstrated this when they observed a 1.6 MT C $ha^{-1}$ gain in OC over 11 years, most of which occurred during the last 4-5 years of the study when favorable precipitation resulted in high crop production and crop residues. This was significantly lower than the 4-5 MT C $ha^{-1}$ a medium-textured soil gained over a 12 year period in a similar study (Campbell et al., 1995). Coarse-textured soils have lower water holding capacities, which reduces plant production and thus reduces SOM quantity and quality (Sherrod et al., 2005). Fine-textured soils, on the other hand, have higher amounts of OC and N because of the positive effects of silt on soil water availability and plant production (Burke et al., 1989). The second reason for higher SOM in fine-textured soils is because of the positive effects of clay on SOM protection. The capacity of a soil to store C and N is highly influence by the soil's respective silt and clay contents (Hassink, 1997; Six et al., 2002b). Clay protects OM by adsorption on to clay surfaces, entrapment between clay particles, and by increasing the degree of soil aggregation (Mortland, 1970). In particular, flocculated clay particles serve as building blocks for microaggregates (Adu and Oades, 1978). Therefore, physical protection of SOC by aggregates increases with increasing clay content (Six et al., 2002b). The decay rate of “active” SOM decreases as silt + clay content increases, and thus more C is stabilized in the “slow” pool in fine-textured soils (Parton et al., 1987). Coarse-textured soils, on the other hand, are more vulnerable to aggregate disruption that would expose previously hidden SOM to microbial attack (Franzluebbers and Arshad, 1996). Accumulation of whole-soil C, even with NT, is less for coarse-textured soils; this is due to greater turnover rates of aggregates < 250 μm and lower protection of SOC by clay adsorption (Franzluebbers and Arshad, 1996). Ultimately, there is limited opportunity for sequestering additional OC in coarse-textured soils in semiarid climates because of the above mentioned factors (Campbell et al., 1996).

### *Vegetation*

The influence of soil texture, precipitation, and temperature on plant production illustrates the importance of plant growth in building SOC. Plant residues are the largest source of C entering the soil because of decaying above-ground biomass, senescent root tissue, sloughed roots cells, and root exudates (Gregorich and Janzen, 1996). Plant residues provide C sources for decomposition processes that sustain SOM content, as well as influencing other biological processes that affect soil quality by providing energy sources for microbial processes such as N mineralization, fixation, and immobilization (Karlen et al., 1992). The amount of plant residue produced in cropped soils is directly correlated to crop yield. Many of the SOC gains in cultivated soils are a result of higher yields arising from better crop nutrition, more efficient water utilization, and higher yielding crop varieties (Janzen et al., 1998). Campbell et al. (1996) observed greater SOC increases in dry years under wheat-fallow (where moisture was accumulated) than under continuous wheat because of the low yields of the continuous wheat. The highest residue levels for row crops are produced by $C_4$ plants like corn and sorghum; soybeans produce half as much residue, while cereals are intermediate in their residue production (Paustian et al., 1997). Bruce et al. (1990) demonstrated that two or more years of grain sorghum, as compared to soybeans, resulted in improved soil quality indicators such as greater aggregate stability, higher air-filled pore space, and lower bulk density. Lignin content of the residue is an important factor in determining SOC accrual. Cereals like wheat and barley have higher lignin contents compared to corn, which retards decomposition and increases C stabilization (Paustian et al., 1997). Lignin and other phenolic compounds are the most resistant to microbial degradation (Rasmussen and Collins, 1991). Lignin is directly incorporated into the "slow" pool, which is highly stable, whereas the more labile components of plant structural materials (e.g. hemicellulose and cellulose) are more completely metabolized by the soil microbial biomass in the "active" pool (Parton et al., 1987; Paustian et al., 1992).

### *Management*

Soil management has a direct effect on SOC gains or losses. Overall gains in SOC can be prompted by management that increases C inputs relative to C losses through one or more of the following mechanisms: 1) increasing primary production, 2) increasing the proportion of primary production being returned to the soil, and 3) suppressing the rate of decomposition (Janzen et al., 1988). These mechanisms can be implemented in any number of ways, including crop rotation and fallow frequency, improved crop nutrition, cover cropping, and conservation tillage (Follett, 2001; Karlen et al., 1992; Lal, 2004).

*Fallowing and Crop Rotation.* Since the addition of plant biomass is an important factor in building SOM, one of the ways fallowing affects SOC is by reducing the amount of plant residue produced. The addition of root exudates would be the least under fallow rotations (McGill et al., 1986), and LF OM declines in fallow because of the absence of primary residue production (Gregorich and Janzen, 1996). Bare cultivated fallow is the worst management practice in regards to soil structure (Oades, 1984), so minimizing fallow periods by intensive cropping will result in greater SOC storage (Peterson et al., 1998) and macroaggregate stability (Tisdall and Oades, 1980a). The replacement of fallow with continuous cropping results in a steady input of new roots and fungal hyphae by which macroaggregates can be formed (Oades, 1984). In particular, crops with fine root systems (e.g. grasses) are very effective in adding decomposable OM to increase macroaggregation (Oades, 1984). Another by-product of fallowing is an increase of soil moisture that results in greater OM decomposition (Paustian et al., 1997). Campbell et al. (1995) proposed that OM decomposition is maximized under a fallow-wheat system because the more favorable moisture regime mineralizes most of the OC and N that is added each year, thus leaving little opportunity for build-up of SOM. OM decomposition rates are also higher during fallowing because of increases in soil temperature, erosion, and soil disturbance associated with mechanical weed control (Paustian et al., 1997). Annual cropping results in higher C and N additions and are less intensively cultivated than wheat-fallow, thus maintaining higher SOC and N (Collins et al., 1992). Labile OM tends to increase with annual cropping, whereas tillage coupled with fallowing decreases labile OM (Campbell et al., 1997) and microbial biomass (Biederbeck et al., 1984).

Using multiple crops in rotations also improves soil quality by mimicking natural ecosystems (Karlen et al., 1992). Multiple cropping systems will have the highest SOC and soil organic nitrogen (SON) storage whereas monoculture cropping will have the lowest (Wright and Hons, 2004). For example, McGill et al. (1986) found that a 5 yr rotation resulted in more OM and microbial biomass in the top 5 cm as opposed to just a 2 yr rotation. Increasing the frequency of sorghum in rotations will increase SOC and N in the top 2.5 cm, a direct result of the quantity of residue produced and left on the soil surface at harvest (Havlin et al., 1990). The combination of more annual cropping and less reliance on summer fallow will increase C contents within all SOC pools (Sherrod et al., 2005). Ultimately, though, crop rotations are restricted by climatic and economic factors and land suitability (Paustian et al., 1997). Limited precipitation and long periods of drought are common in the Great Plains. Therefore, yields (and residue production) are almost always lower under continuous cropping than under alternate cropping and fallowing (Haas et al., 1957). Farming practices in the Great Plains must be able to capitalize on available soil moisture in wet years while also having the flexibility to fallow during dry years (Havlin et al., 1995).

*Crop Nutrition*. Adequate levels of macro- and micronutrients in the soil ensure healthy crop production. Of all the required crop nutrients, N is the largest in both the quantity used by the plant and the amount amended to the soil with commercial or organic fertilizers. The primary effect of fertilizer N is to increase vegetative production and the amount of OC that can be recycled back into the soil system (Rasmussen and

Collins, 1991). Blevins et al. (1977) found increasing N fertilizer rates also increased organic C content in the surface 0-5 cm soil layer. In fact, the highest N rate, when combined with NT practices, maintained an organic C level nearly equal to the untreated native pasture plots. Phosphorous (P) is also an essential nutrient used in large amounts for plant growth. Campbell et al. (2001) found that fertilized plots (both N and P, based on soil tests) gained OC and N in the 0-15 cm depth while unfertilized plots remained unchanged. They also observed positive responses to fertilization in other soil quality indicators such as microbial biomass C (MBC), LF C and N, $N_{min}$, and wet aggregate stability. Furthermore, Juma et al. (1997) concluded that application of N, P, K, and S fertilizers increased SOM by increasing crop yields. Nitrogen is also a major constituent of SOM. Since the C:N ratio is relatively constant across a range of agricultural soils, an adequate amount of N is needed to build SOM; if N inputs are out of balance with C inputs, then C sequestration efficiency will be reduced (Paustian et al., 1997). Manure is an excellent organic source of plant nutrients and has been shown to increase SOM in even greater amounts than conventional fertilizer (Juma et al., 1997). Manure applications have been shown to increase the number of macroaggregates (Mikha and Rice, 2000). Manure also contains large amounts of lignin, which is more recalcitrant to decomposition, and thus results in higher SOC accumulations per unit C input than with low-lignin residues like wheat straw (Paustian et al., 1992). Since manure is already digested, it is more stabilized than plant residue and can directly enter the “slow” OM pool as opposed to non-lignin residue that is more completely metabolized by the soil microbial biomass in the “active” pool (Paustian et al., 1992).

*Cover Cropping*. In addition to manure, cover cropping has historically been used to increase SOM content (Stewart, 1993). Cover crops protect the soil from raindrop impact, slow runoff, and decrease erosion (Karlen et al., 1992). Upon death, they add OM to the soil which increases permeability, infiltration (Karlen et al., 1992), and enhances soil aggregation (Karlen and Cambardella, 1996). A common method of cover cropping utilizes leguminous crops, or "green manure" as alfalfa and clovers. The contribution of alfalfa, for example, in maintaining OC can result from the extra residue added by the alfalfa, lower C oxidation because of the absence of tillage during the cover crop growth cycle, or by the additional residue produced by succeeding crops that benefit from the residual symbiotically fixed N (Bauer and Black, 1981). Green manure cover crops are not effective in semiarid environments where moisture limits crop production. Haas et al. (1957) reported that the low yields of green manure crops, and the negative effects of their water use on the following grain crop, did not increase (or may have decreased) C inputs when compared with cereal-only rotations.

*Tillage*. Tillage intensity is the one management factor that directly affects the third mechanism cited by Janzen et al. (1998) -- suppressing the rate of decomposition. Losses of SOC occur through the decomposition and mineralization of organic compounds by soil heterotrophs to produce $CO_2$ (Paustian et al., 1997). Soil disturbance by tillage introduces large amounts of oxygen into the soil, stimulating the consumption of OM by aerobic microorganisms (Doran and Smith, 1987). Organic residues are incorporated and mixed with the soil immediately after tillage, creating a moist, aerated environment favorable for microbial activity (Blevins et al., 1984). Conservation tillage practices can result in a buildup of SOM because they greatly reduce the rates of decomposition of both the native SOM and of the crop residues (Stewart, 1993). Tillage systems that meet the criteria for conservation tillage include no-till (NT), slot planting, ridge-till, strip-till, mulch-till, and reduced-till (Karlen et al., 1992). The combination of less soil disturbance and reduced litter decomposition usually results in greater amounts of SOC in NT vs. conventional tillage (CT) (Paustian et al., 1997). Adoption of conservation tillage results in an increase in the "labile" fraction of SOC, including microbial biomass and LF (Janzen et al., 1998). The specific influences of tillage on C sequestration, aggregation and the soil microbial community will be highlighted in the next section.

## Tillage Effects on SOC

An extensive amount of literature exists that illustrate the negative effects of tillage on SOM and SOC. Soil organic carbon decreases upon conversion from native prairie to cultivated agriculture. Compared to grass pasture, cultivation reduced total C and N by 40% and 51%, respectively (Collins et al., 1992). Haas et al. (1957) found that 50 years of cultivation decreased SOC 46% at 0-15 cm, and 18% at 15-30 cm. More specifically, at Hays, KS, SOC lost was 51% and at Garden City, KS, SOC lost was 39% over 37 years of cropping. The loss of OM with cultivation is usually exponential, declining rapidly during the first 10-20 years before approaching a new equilibrium in 50-60 years (Haas et al., 1957). Initial conversion of virgin land to agriculture results in a loss of LF because it is a highly decomposable, transitory substrate (Gregorich and Janzen, 1996). Bowman et al. (1990) found that labile fractions of SOC declined by 67-72% after 60 years of cultivation on a sandy loam soil, but over 80% of the labile C loss occurred during the first 3 years of cultivation. Furthermore, Woods and Schuman

(1988) consistently found SOC concentrations to be lower in cultivated, as opposed to native grassland sites, and total OC and mineralizable C declined by 14% and 62%, respectively, after only one year of cultivation.

Even comparing between cultivated soils, conventional-tillage (CvT) consistently has lower amounts of SOC than do soils under conservation tillage management regimes like mulch-till or no-till (NT). Conventional-tillage usually includes a primary tillage event to invert or bury much of the crop residue, followed by secondary and tertiary tillage events that pulverize the soil, prepare a firm seedbed, and control weeds (Gajri, 2002). Conservation-tillage (CT) refers to any tillage and planting system that leaves a minimum of 30% of the soil surface covered by residue after planting (to reduce soil erosion by water) and at least 1000 kg $ha^{-1}$ of flat small grain residue on the soil surface to reduce wind erosion during the critical wind erosion period (NRCS, 1989). In NT, the soil is left undisturbed from harvest to planting with all crop residues being retained on the soil surface (Gajri, 2002).

Conservation tillage, and especially NT, is generally effective in increasing SOC (Paustian et al., 1997). Bauer and Black (1981) noted that OC was 44% and 13% higher in coarse- and fine- textured soils, respectively, between CT (stubble mulch) and CvT treatments. Angers et al. (1993) found that after only 4 years, at the 0-7.5 cm depth, NT and CT (chisel plow) had 20% higher OC than CvT (moldboard plow). Arshad et al. (1990) also proved that NT increases the quality and quantity of OM, since total C and N contents of NT were 26% higher than under CvT management. Differences between NT and CvT in total C and N are largely confined to the 0-7.5 cm soil layer (Doran, 1987), and usually have little effect on SOC below 8 cm (Doran and Smith, 1987). Losses of

SOM with the use of CvT result from enhanced OM decomposition (Bowman et al., 1990) because of the oxidation of easily decomposable root and crown tissue, degradation of soil aggregates (Rasmussen and Collins, 1991), improved aeration and moisture regimes for decomposition (Paustian et al., 1997), and increased exposure to wind and water erosion (Bowman et al., 1990).

Aggressive tillage not only opens the soil to allow rapid $O_2$ and $CO_2$ exchange, but also incorporates crop residues into the soil where microorganisms flourish as the fresh food source is placed in contact with moisture and oxygen, which is plentifully supplied through the large pores of the recently tilled soil (Reicosky et al., 1995). Furthermore, tillage increases C availability to the microbial biomass by disrupting soil structure and exposing protected OM (Rasmussen and Collins, 1991). Tillage also breaks apart large pieces of plant residue, thus increasing the surface area available for microbial attack (Blevins et al., 1984). Fifty percent of the OM is considered to be protected under grassland conditions, but this value decreases to 20% for the 0-15 cm layer under cultivation (van Veen and Paul, 1981). The rapid decrease in OM at the onset of cultivation of a virgin soil is due in large part to the decomposition of grass and forb roots (van Veen and Paul, 1981). This pool of easily mineralizable OM is also called labile OM, and is very sensitive to agronomic variables (Biederbeck et al., 1994). Using LF and mineralizable-C to represent this labile OM fraction, Biederbeck et al. (1994) showed that the LF in continuous, NT wheat was 1.98 mg C $kg^{-1}$ soil higher than bare fallow CvT wheat; also, mineralizable-C was 213 mg C $kg^{-1}$ soil higher for NT than for bare fallow CvT as well.

Disruption of soil aggregates is one of the major factors that enhances the mineralization of SOC (van Veen and Paul, 1981), and is one of the mechanisms proposed for lower SOC under CvT systems than NT (Janzen et al., 1998). Tillage exposes aggregates to physical disruption by rapid wetting, raindrop impact, and implement shearing (Tisdall and Oades, 1982), in addition to freeze-thaw and wet-dry cycles (Paustian et al., 1997). Repeated cultivation disrupts recently formed macroaggregates that developed around POM, thus exposing previously inaccessible labile organic matter to mineralization (Tisdall and Oades, 1980b; Tisdall and Oades, 1982; Cambardella and Elliot, 1993). Increased tillage causes a loss of C binding agents that bind microaggregates into macroaggregates (Six et al., 2000a). This OM which exists between microaggregates inside macroaggregates is the primary source of nutrients released upon cultivation (Elliot, 1986). The constant exposure and decomposition of POM upon macroaggregate disruption by tillage inhibits the formation of new microaggregates, which would normally form through POM decomposition inside the macroaggregate (Six et al., 1998; Six et al., 2000b). Cultivation has the net effect of increasing aggregate turnover rates, thus never allowing macroaggregates to exist long enough to promote long-term C storage in stable microaggregates (Six et al., 1999). Cultivation also decreases the amount of microbial-biomass C in macroaggregates (Gupta and Germida, 1988). The combined effect cultivation has on the mechanical disruption of aggregates and on fractions of the microbial biomass (e.g. fungal hyphae, mucilages, and polysaccharides) is responsible for the decline of aggregation in cultivated soils (Angers, et al. 1992).

Soils subjected to long-term cultivation have a disproportionately higher amount of microaggregates to macroaggregates, which is paralleled by a reduction in total SOM (Elliot, 1986). Tisdall and Oades (1980a) found that after 50 years of conventional tillage (CT), microaggregates (20-250 μm) were the dominant size fraction. Six et al. (2000a) observed that increased cultivation led to a loss of C-rich macroaggregates and an increase in C-depleted microaggregates. Although stable microaggregates form slowly in soil, the persistent nature of microaggregate binding agents is responsible for the microaggregates' inability to be influenced by cultivation (Tisdall, 1996). Interestingly, however, the influence of tillage on aggregation is only limited to the surface soil depths. Emmond (1971) found no significant effect of cultivation on aggregation below 7.5 cm. Other studies have shown no significant effect of cultivation on aggregation below 5 cm (Beare et al., 1994a; Franzluebbers and Arshad, 1996; Six et al., 1999).

Bare soils under CvT are also more susceptible to wind and water erosion. Erosion results in a loss of C-rich topsoil and dilutes it with subsoil (Paustian et al., 1997). Kinetic energy from raindrops or blowing wind disrupts aggregates and exposes C within the aggregates (Lal, 2001). Consequently, light fraction soil particles like clay and SOM are preferentially removed and redistributed over the landscape (Lal, 2001). Wind-blown soil, for example, can contain 11 times more SOC than the topsoil (0-1 cm) left in the field (Leys and McTainsh, 1994). Sediments transported by water runoff can have 2 to 5 times more clay and OM than what exists in the remaining topsoil (Lal, 1976). Soil C transported in water runoff may include POM, and dissolved organic and inorganic C (Lal, 2001). Eroded soils are also less productive, thus reducing the amount of C inputs back into the soil (Paustian et al., 1997). In conclusion, the rate of SOC sequestration will be improved when soil management focuses on adding more biomass to the soil, minimizing soil disturbance, conserving soil and water, and improving soil structure (Lal, 2004).

## Benefits of No-Till

### *Carbon Sequestration*

As previously illustrated, NT management can consistently raise SOC levels over time by reducing SOC losses and thereby turning the entire soil system into a C sink (Karlen and Cambardella, 1996; Follett, 2001). Havlin et al. (1990) found that NT increased SOC on average by 0.7% per year, and that the rate of OC accumulation in NT was 2.5 times greater than under CT. West and Post (2002) concluded that moving from CvT to NT can sequester 48 ± 13 g C $m^{-2}$ $yr^{-1}$. A delayed response may occur in SOC accrual upon the onset of NT management, but peak C sequestration rates can be reached five to ten years after NT implementation and decline to near zero in 15 to 20 years (West et al., 2003; West and Post, 2002). Lal et al. (1998) and Franzluebbers and Arshad (1996) concur that there may by little to no increase in SOC in the first two to five years after beginning NT, but large increases should occur in the next five to ten years. Soil organic C increases in arid soils that have limited plant residue inputs, however, will approach maximum the amount after only six years (Campbell et al., 1995). Gains in SOC under NT are a result of keeping crop residues on the surface and reducing tillage, which reduces the biological oxidation of SOC, a major cause of OM depletion in cultivated soils (Reicosky et al., 1995). Gale and Cambardella (2000) illustrated this by showing SOC accrual is primarily due to increased retention of root-derived C. A large amount of surface residue-C was respired as $CO_2$ and did not directly influence SOC accumulation. Roots and root exudates, hyphae, and microbial binding agents are primarily responsible for the formation of stable macroaggregates, and it is this pool of labile C in macroaggregates that is protected from decomposition through NT (Gale et al., 2000b). Decomposition of surface residue is also hindered in NT because of its placement on the soil surface, where it remains desiccated and away from contact with microorganisms and soil moisture (Reicosky et al., 1995).

No-till management positively alters the soil microbial environment beneath the surface residue layer, however, resulting in higher microbial biomass (MB) populations. Angers et al. (1993) reported a significant enrichment in labile OM (as MB and carbohydrates) as tillage intensity was reduced, and Doran (1987) found 54% higher MB in NT soils vs. CT in the surface 0-7.5 cm layer. The microbial biomass in coarse-textured soils is particularly vulnerable to tillage influences. Woods and Schuman (1988) found that a single year's worth of cultivation on an Ascalon sandy loam reduced MB-C by nearly the same amount as did 25 years of cultivation on a Renohill silty clay loam, when compared to native grassland. For microorganisms, the most important soil factors resulting from NT are 1) the distribution and quantity of OM, and 2) soil moisture regime (Blevins et al., 1984). Higher MB levels exist under reduced tillage because of the accumulation of crop residues near the soil surface (Doran, 1987; Carter and Rennie, 1982). The substrate for the generation and maintenance of that biomass may be recently dead biomass, plant root and shoot litter, root exudates, sloughing, and exfoliation (McGill et al., 1986). Lynch and Panting (1980) found that MB was greater under NT due to an abundance of plant roots and that MB populations were directly correlated to root growth and density. Furthermore, cropped soils have higher microbial populations than fallowed soils, indicating a strong rhizosphere influence on MB by the roots (Collins et al., 1992). Conventional-till soils, on the other hand, have lower MB populations in the surface horizon but greater populations at lower depths, correlating to the depth at which surface residue is mixed into the soil (Carter, 1986; Doran, 1987). Soil moisture conditions are improved as a consequence of leaving more residues on the soil surface in NT. This results in greater microbial activity and therefore higher MB populations, especially in the 0-7.5 cm depth (Doran, 1987). During dry weather, NT soils would stay wetter than CT, thus favoring microbial activity in NT soils and prolong that activity throughout most of the year (Blevins et al., 1984).

No-till also results in a greater abundance of macroaggregates and aggregate-protected C. Jastrow (1996) found that C accrual since restoring a soil to prairie grass occurred in the heavy fraction (> 1.85 g $cm^{-3}$), suggesting that C was accumulating as organic cores of undispersed microaggregates within macroaggregates. Since aggregation turnover is a critical component of SOC storage, maximizing soil aggregation is necessary to successfully sequester atmospheric C (Six et al., 2000b). The most obvious method to maximize aggregation is by minimizing or eliminating tillage (Tisdall and Oades, 1980a; Beare et al., 1994b). Beare et al. (1994a) reported that NT soils had more macroaggregates that were also more stable (at 0-5 cm depth) than did CVT soils. From the 5-15 cm depth, however, differences were not significant between CVT and NT. No-till will maintain or increase aggregate stability in two ways: 1) by slowing the decomposition loss of newly incorporated POM-C and N which exists between microaggregates inside macroaggregates (Cambardella and Elliot, 1993); and 2) roots and fungal hyphae are undisturbed, thus allowing them to initially bind the macroaggregate together (Elliot and Coleman, 1988). Undisturbed roots are important because macroaggregates form around root derived POM during vegetative growth and after senescence, and microbes exude binding agents to increase macroaggregate stability during POM decomposition (Gale et al., 2000a). All of these functions work together to minimize aggregate turnover, thereby allowing inter-aggregate POM within macroaggregates to be stabilized into microaggregates (Six et al., 1999; Six et al., 2000b). Macroaggregate turnover occurs over time as an aggregate is formed, becomes unstable, and is eventually disrupted. Tillage shortens this macroaggregate turnover time, thereby diminishing the formation rate of new microaggregates and thus the C sequestration rate within microaggregates (Six et al., 2000b). The formation and stabilization of macroaggregates under NT soil management is an important mechanism for protecting and maintaining SOM that would normally be lost under CvT practices (Beare et al., 1994a).

### *Improved Soil Quality*

Adoption of NT, coupled with continuous cropping practices, will always increase the content of living and non-living SOM components and thus positively affecting soil quality (Monreal et al., 1998). Soil quality can be defined as “the ability of the soil to serve as a natural medium for the growth of plants that sustains human and animal life” (Karlen et al., 1992). Implementing conservation tillage practices that are tailored to local soil and climatic conditions is an excellent strategy for improving soil quality by increasing soil biologic activity and OM content (Karlen et al., 1992). Higher SOM levels consistently result in higher soil fertility, which in turn increases plant productivity

(Doran and Smith, 1987). Increases in soil organic nitrogen under NT increases the N mineralization rates during the growing season and lessens the need for N fertilization (Wright and Hons, 2005). In addition to increased fertility, decomposing SOM contributes to better aggregation and soil physical conditions (Blevins et al., 1984). The increased aggregation, as defined by soil aggregate stability, greater amounts of macroaggregates, and higher percentage of macropores, leads to higher water infiltration capacity, easier rooting of plants, and greater water holding capacity (Blevins et al., 1984).

### ***Environmental Benefits***

Management practices that leave residue on the soil surface greatly reduces wind and water erosion, improves infiltration, and leads to increased soil water storage in arid environments (Stewart, 1993). Surface residue protects the soil against the erosive forces of rainfall, runoff, and wind (Lal et al., 1999b). Raindrop energy detaches soil particles from their structural units; this detachment is followed by crusting upon soil drying, which reduces the infiltration capacity of the soil and increases water runoff and erosion losses (Blevins et al., 1984). Conversely, the amount of rainfall that infiltrates the soil greatly increases with standing stubble, so soil loss by water erosion can be greatly decreased by increasing infiltration (Havlin et al., 1995). Sandy- and fine-textured soils are more susceptible to wind erosion then medium-textured soils, and benefit greatly from residues retained on the soil surface (Bauer and Black, 1981). Mulching of residue also leads to increases surface moisture and decreases soil temperature, which is a positive benefit for many dry climates (Paustian et al., 1997). Lafond et al. (1992) found that the use of stubble cropping (both NT and reduced-till) increased soil water in the 0-

60 cm depth by 9% and by 6% in the 0-120 cm layer over CvT. In arid regions of the High Plains, snowfall is an extremely valuable source of plant available water, and collecting snow with standing crop stubble is important for increasing plant available water (Havlin et al., 1995). Producers that utilize conservation tillage practices in the arid High Plains will ultimately enhance their productivity and profitability (Havlin et al., 1995).

## Experimental Objectives

Some authors have proposed that cropland must be maintained in continuous NT to avoid negating any gains in soil C sequestration (Grandy and Robertson, 2006a, b; Six et al., 2004). Previous work that has quantified changes in SOC after tillage of NT soils have either used the intensive tillage of a moldboard plow, utilized multiple tillage passes, or both (Tiessen and Stewart, 1983; Pierce et al., 1994; Kettler et al., 2000; VandenBygaart and Kay, 2004). Unfortunately, such aggressive tillage practices are not used for dryland cropping in the High Plains of western Kansas (McVay et al., 2006). Therefore our research has three objectives:

1. To identify the influence of a single tillage event on total soil C and N, aggregate C and N, and aggregate distribution, in order to determine if any measurable C was lost from the soil.
2. To identify differences between lower-intensity tillage implements on the above mentioned soil attributes. Tillage treatments include disk, chisel plow, sweep plow, and no-till.
3. To monitor the change in the above soil attributes over time after the single tillage event.

## Literature Cited

Allison, F.E. 1973. *Soil Organic Matter and Its Role in Crop Production.* P.637. Elsevier Science Publishers Ltd., New York, NY.

Adu, J.K., and J.M. Oades. 1978. Physical factors influencing decomposition of organic materials in soil aggregates. Soil Bio. Biochem. 10: 109-115.

Angers, D.A., A. Pesant, and J. Vigneux. 1992. Early cropping-induced changes in soil aggregation, organic matter, and microbial biomass. Soil Sci. Soc. Am. J. 56: 115-119.

Angers, D.A., N. Bissonnette, A. Legere, and N. Samson. 1993. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Can. J. Soil. Sci. 73: 39-50.

Angers, D.A., S. Recous, and C. Aita. 1997. Fate of carbon and nitrogen in water-stable aggregates during decomposition of $^{13}C^{15}N$-labelled wheat straw *in situ*. Eur. J. Soil Sci. 48: 295-300.Arshad, M.A., M. Schnitzer, D.A. Angers, and J.A. Ripmeister. 1990. Effects of till vs no-till on the quality of soil organic matter. Soil Biol. Biochem. 22: 595-599.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen, and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45: 1166-1170.

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994a. Water-stable aggregates on organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58: 777-786.

Beare, M.H., M.L. Cabrera, P.F. Hendrix, and D.C. Coleman. 1994b. Aggregate-protected and unprotected organic matter pools in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58: 787-795.

Bauer, A., and A.L. Black. 1981. Soil carbon, nitrogen and bulk density comparisons in two cropland tillage systems after 25 years and in virgin grassland. Soil Sci. Soc. Am. J. 45: 1166-1170.

Biederbeck, V.O., C.A. Campbell, and R.P. Zentner. 1984. Effect of crop rotation and fertilization on some biological properties of a loam in southwestern Saskatchewan. Can. J. Soil. Sci. 64: 355-367.

Biederbeck, V.O., H.H. Janzen, C.A. Campbell, and R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. Soil Biol. Biochem. 26: 1647-1656.

Blevins, R.L., M.S. Smith, and G.W. Thomas. 1984. Changes in soil properties under no-tillage. Pp.191-231. *In*: R.E. Phillips and S.H. Phillips (eds.). *No-tillage Agriculture: Principles and Practices*. Van Nostrand Reinhold, New York, NY.

Bowman, R.A., J.D. Reeder, and R.W. Lober. 1990. Changes in soil properties in a central plains rangeland soil after 3, 20, and 60 years of cultivation. Soil Sci. 150: 851-857.

Bruce, R.R., G.W. Langdale, and A.C. Dillard. 1990. Tillage and crop rotation effect on characteristics of a sandy surface soil. Soil Sci. Soc. Am. J. 54: 1744-1747.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in US grassland soils. Soil Sci. Soc. Am. J. 53: 800-805.

Buyanovsky, G.A., M. Aslam, and G.H. Wagner. 1994. Carbon turnover in soil physical fractions. Soil Sci. Soc. Am. J. 58: 1167-1173.

Capalbo, S.M., J.M. Antle, S. Mooney, and K. Paustian. 2004. Sensitivity of carbon sequestration costs to economic and biological uncertainties. Environ. Managem. 33: S238-S251.

Cambardella, C.A., and E.T. Elliot. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56: 777-783.

Cambardella, C.A., and E.T. Elliot. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57: 1071-1076.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F.B. Dyck, F. Selles, and D. Curtin. 1995. Carbon sequestration in a Brown Chernozem as affected by tillage and rotation. Can. J. Soil. Sci. 75: 449-458.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F.Selles, and D. Curtin. 1996. Tillage and crop rotation effects on soil organic C and N in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. Soil Till. Res. 37: 3-14.

Campbell, C.A., B.G. McConkey, V.O. Biederbeck, R.P. Zentner, S.Tessier, and D.L. Hahn. 1997. Tillage and fallow frequency effects on selected soil quality attributes in a coarse-textured Brown Chernozem. Can. J. Soil Sci. 77: 497-505.

Campbell, C.A., F. Selles, G.P. Lafond, V.O. Biederbeck, and R.P. Zentner. 2001. Tillage – fertilizer changes: Effect on some soil quality attributes under long-term crop rotation in a thin Black Chenrozem. Can. J. Soil Sci. 81: 157-165.

Carter, M.R. 1986. Microbial biomass as an index for tillage-induced changes in soil biological properties. Soil Till. Res. 7: 29-40.

Carter, M.R., and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62: 587-597.

Collins, H.P., P.E. Rassmussen, and C.L. Douglas, Jr. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56: 783-788.

Dalal, R.C., and B.J. Bridge. 1996. Aggregation and organic matter storage in sub-humid and semi-arid soils. Pp. 263-308. *In*: M.R. Carter and B.A. Stewart (eds.), *Structure and Organic Matter Storage in Agricultural Soils.* CRC Press, Boca Raton, FL.

Dalal, R.C., and R.J. Mayer. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. Aust. J. Soil Res. 24: 281-292.

Dexter, A.R. 1988. Advances in characterization of soil structure. Soil Till. Res. 11: 199-238.

Doran, J.W., and M.S. Smith. 1987. Organic matter management and utilization of soil and fertilizer nutrients. Pp. 54-72. *In*: R.F. Follett, J.W.B. Stewart, and C.V. Cole (eds.), *Soil Fertility and Organic Matter as Critical Components of Production Systems*, Spec. Publ. 19. ASA-CSSA-SSSA, Madison, WI.

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils. 5: 68-75.

Elliot, E.T. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50: 627-633.

Elliot, E.T., and D.C. Coleman. 1988. Let the soil work for us. Ecol. Bullet. 39:23-32.

Emmond, G.S. 1971. Effect of rotation, tillage treatments and fertilizers on the aggregation of a clay soil. Can. J. Soil Sci. 51: 235-241.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Till. Res. 61: 77-92.

Follett, R.F., and B. McConkey. 2000. The role of cropland agriculture for C sequestration in the Great Plains. Proceeding of the Great Plains Soil Fertility Conference. 8:1-15. Denver, CO. (March 7-8, 2000). Keynote paper (Invited).

Follett, R.F., S.R. Shafer, M.D. Lawson, and A.J. Franzluebbers. 2005. Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA. Soil Till. Res. 83: 159-166.

Franzluebbers, A.J., and M.A. Arshad. 1996. Water-stable aggregation and organic matter in four soils under conventional and zero tillage. Can. J. Soil Sci. 76: 387-393.

Gajri, P.R., V.K. Arora, and S.S. Prihar. 2002. *Tillage for Sustainable Cropping.* Food Products Press, Binghamton, NY.

Gale, W.J., and C.A. Cambardella. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64: 190-195.

Gale, W.J., C.A. Cambardella, and T.B. Bailey. 2000a. Root-derived carbon and the formation and stabilization of aggregates. Soil Sci. Soc. Am. J. 64: 201-207.

Gale, W.J., C.A. Cambardella, and T.B. Bailey. 2000b. Surface residue- and root-derived carbon in stable and unstable aggregates. Soil. Sci. Soc. Am. J. 64: 196-201.

Golchin, A., P. Clarke, J.M. Oades, and J.O. Skjemstad. 1995. The effects of cultivation on the composition of organic matter and structural stability of soils. Aust. J. Soil Res. 33: 975-933.

Golchin, A., J.A. Baldock, and J.M. Oades. 1998. A model linking organic matter decomposition, chemistry, and aggregate dynamics. Pp. 245-266. *In*: R.Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Grandy, A.S., and G.P. Robertson. 2006a. Aggregation and organic matter protection following tillage of a previously uncultivated soil. Soil Sci. Soc. Am. J. 70: 1398-1406.

Grandy, A.S., and G.P. Robertson. 2006b. Initial cultivation of a temperate-region soil immediately accelerates aggregate turnover and $CO_2$ and $N_2O$ fluxes. Glob. Change Biol. 12: 1507-1520.

Gregorich, E.G., R.G. Kachanoski, and R.P. Voroney. 1989. Carbon mineralization in soil size fractions after various amounts of aggregate disruption. J. Soil Sci. 40: 649-659.

Gregorich, E.G., and H.H. Janzen. 1996. Storage of soil carbon in the light fraction and macroorganic matter. Pp. 167-192.. *In*: M.R. Carter and B.A. Stewart (eds.), *Structure and Organic Matter Storage in Agricultural Soils.* CRC Press, Boca Raton, FL.

Gupta, V.V., and J.J. Germida. 1988. Distribution of microbial biomass and its activity in different soil aggregate size classes as affected by cultivation. Soil Biol. Biochem. 20: 777-786.

Haas, H.J., C.E. Evans, and E.F. Miles. 1957. Nitrogen and Carbon changes in Great Plains soils as influenced by cropping and soil treatments. Technical Bulletin No. 1164, USDA, State Agricultural Experiment Stations. Manhattan, KS

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soi. 191: 77-87.

Havlin, J.L, D.E. Kissel, L.D. Maddux, M.M. Claasen, and J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54: 448-452.

Havlin, J.L, A. Schlegel, K.C. Dhuyvetter, J.P. Shroyer, H. Kok, and D. Peterson. 1995. *Great Plains Dryland Conservation Technologies.* Cooperative Extension Service, Kansas State University, Manhattan, KS. MS6-95-3M.

Hook, P.B., and I.C. Burke. 2000. Biogeochemistry in a shortgrass landscape: control by topography, soil texture, and microclimate. Ecology 81: 2686-2703.

Houghton, R.A., and D.L. Skole. 1990. *The long-term flux of carbon between terrestrial ecosystems and the atmosphere as a result of changes in land use.* Research Project of the Month – July. Carbon Dioxide Research Program, Office of Health and Environmental Research, U.S. Department of Energy, Washington, D.C.

Janzen, H.H., C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1998. Soil carbon dynamics in Canadian agroecosystems. Pp. 57-80. *In*: R. Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Jastrow, J.D. 1996. Soil aggregate formation and the accrual of particulate and mineral-associated organic matter. Soil Biol. Biochem. 28: 665-676.

Jastrow, J.D., T.W. Boutton, and R.M. Miller. 1996. Carbon dynamics of aggregate-associated organic matter estimated by $^{13}C$-natural abundance. Soil Sci. Soc. Am. J. 60: 801-807.

Jastrow, J.D., and R.M. Miller. 1997. Soil aggregate stabilization and carbon sequestration: feedbacks through organo-mineral associations. Pp. 207-224. *In*: R. Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Jastrow, J.D., R.M. Miller, and J. Lussenhop. 1998. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. Soil Biol. Biochem. 30: 905-916.

Jenny, H. 1941. *Factors of Soil Formation*. McGraw Hill, New York, NY.

Johnson, M.G. 1995. The role of soil management in sequestering soil carbon. Pp. 351-363. *In*: R. Lal, J. Kimble, E. Levine, and B.A. Stewart (eds.), *Soil Management and the Greenhouse Effect*. CRC Press, Boca Raton, FL.

Juma, N.G., Izaurralde, R.C., Robertson, J.A., McGill, W.B. 1997. Crop yield and soil organic matter trends over 60 years in a Typic Cryoboralf at Breton, Alberta. Pp. 273-281. *In*: E.A. Paul, K.H. Paustian, E. T. Elliott, C.V. Cole (eds.), *Soil*

*Organic Matter in Temperate Agroecosystems. Long term Experiments in North America.* CRC Press, Boca Raton, FL.

Karlen, D.L., N.S. Eash, and P.W. Unger. 1992. Soil and crop management effects on soil quality indicators. Am. J. Alt. Agric. 7: 48-55.

Karlen, D.L., and C.A. Cambardella. 1996. Conservation strategies for improving soil quality and organic matter storage. Pp. 395-420. *In*: M.R. Carter and B.A. Stewart (eds.), *Structure and Organic Matter in Agricultural Soils*. CRC Press, Boca Raton, FL.

Kay, B.D., D.A. Angers, P.H. Groenevelt, and J.A. Baldock. 1988. Quantifying the influence of cropping history on soil structure. Can. J. Soil Sci. 68: 359-368.

Kern, J.S., and M.G. Johnson. 1993. Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci. Soc. Am. J. 57: 200-210.

Kettler, T.A., D.J. Lyon, J.W. Doran, W.L. Powers, and W.W. Stroup. 2000. Soil quality assessment after weed-control tillage in a no-till wheat-fallow cropping system. Soil Sci. Soc. Am. J. 64: 339-346.

Lal, R. 1976. Soil erosion problems on Alfisols in western Nigeria and their control. Pp.208. IITA Mongraph 1, IITA, Ibadan, Nigeria.

Lal, R., R.F. Follett, J. Kimble, and C.V. Cole. 1999a. Managing U.S. cropland to sequester carbon in soil. J. Soil Water Conserv. 54: 375-381.

Lal, R., J. Kimble, R.F. Follet, and C.V. Cole (eds.). 1999b. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect.* CRC Press, Boca Raton, FL.

Lal, R. 2001. Keynote: soil conservation for C sequestration. Pp. 459-465. *In*: D.E. Stott, R.H. Mohtar, and G.C. Steinhardt (eds). Sustaining the Global Farm – Selected papers from the 10th International Soil Conservation Organization Meeting, May 24-29, 1999, West Lafayette, IN. International Soil Conservation Organization in cooperation with the USDA and Purdue University, West Lafayette, IN.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304: 1623-1628.

Lafond, G.P., H. Loeppky, and D.A. Derksen. 1992. The effects of tillage systems and crop rotations on soil water conservation, seedling establishment and crop yield. Can J. Plant Sci. 72: 103-115.

Lynch, J.M., and L.M. Panting. 1980. Cultivation and the soil biomass. Soil Biol. Biochem. 12: 29-33.

Leys, J., and G. McTainsh. 1994. Soil loss and nutrient decline by wind erosion – cause for concern. Aust J. Soil Water Cons. 7: 30-35.

Mann, J.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142: 279-287.

Martens, D.A., W. Emmerich, J.E.T. McLain, and T.N. Johnsen. 2005. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. Soil Till. Res. 83: 95-119.

Monreal, C.M., H. Dinel, M. Schnitzer, and D.S. Gamble. 1998. Impact of carbon sequestration on functional indicators of soil quality as influenced by management in sustainable agriculture. Pp. 435-458. *In*: R. Lal, J.M. Kimble, R.F. Follet, and

B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

McCarl, B.A., F.B. Metting, and C. Rice. Soil carbon sequestration. Clim. Change. 80: 1-3.

McGill, W.B., K.R. Cannon, J.A. Robertson, and F.D. Cook. 1986. Dynamics of soil microbial biomass and water-soluble organic C in Breton L. after 50 years of cropping to two rotations. Can. J. Soil. Sci. 66: 1-19.

McVay, K.A., J.A. Budde, K. Fabrizzi, M.M. Mikha, C.W. Rice, A.J. Schlegel, D.E. Peterson, D.W. Sweeney, and C. Thompson. 2006. Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Sci. Soc. Am. J. 70: 434-438.

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68: 809-816.

Mitchell, J.F.B. 1989. The greenhouse effect and climate change. Reviews of Geophysics. 27: 115-139.

Monreal, C.M., H. Dinel, M. Schnitzer, D.S. Gamble, and V.O. Biederbeck. 1998. Impact of carbon sequestration on functional indicators of soil quality as influenced by management in sustainable agriculture. Pp. 435-458. *In*: R. Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Mortland, M.M. 1970. Clay-organic complexes and interactions. Adv. Agron. 22: 75-117.

NRCS. 1989. *Tillage Options for Conservation Farmers.* Program Aid Number 1416. USDA, Washington, D.C.

Oades, J.M. 1984. Soil organic matter and structural stability: Mechanisms and implications for management. Plant Soil 76: 319-337.

Oades, J.M., and A.G. Waters. 1991. Aggregate hierarchy in soils. Aust. J. Soil Res. 29: 815-828.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Till. Res. 47: 207-218.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51: 1173-1179.

Paustian, K., W.J. Parton, and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci. Soc. Am. J. 56: 476-488.

Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls on soil carbon. Pp. 15-49. *In*: E.A. Paul, K.H. Paustian, E. T. Elliott, C.V. Cole (eds). *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America.* CRC Press, Boca Raton, FL.

Pierce, F.J., M.-C. Fortin, and M.J. Staton. 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58: 1782-1787.

Rasmussen, P.E., and H.P. Collins. 1991. Long-term impacts of tillage, fertilizer, and crop residue on soil organic matter in temperate semiarid regions. Adv. Agron. 45: 93-135.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas, Jr., and P.E. Rassmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50: 253-261.

Reilly, J.M., and M.O. Asadoorian. 2007. Mitigation of greenhouse gas emissions from land use: creating incentives within greenhouse gass emissions trading systems. Clim. Change. 80: 173-197.

Rice, C.W. 2006. Introduction to special section on greenhouse gases and carbon sequestration in agriculture and forestry. J. Environ. Qual. 35: 1338-1340.

Sherrod, L.A., G.A. Peterson, D.G. Westfall, and L.R. Ahuja. 2005. Soil organic carbon pools after 12 years in no-till dryland agroecosystems. Soil Sci. Soc. Am. J. 69: 1600-1608.

Six, J., E.T. Elliot, K. Paustian, and J.W. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62: 1367-1377.

Six, J., E.T. Elliot, and K. Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63: 1350-1358.

Six, J.,K. Paustian, E.T. Elliot, and C. Combrink. 2000a. Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64: 681-689.

Six, J., E.T. Elliot, and K. Paustian. 2000b. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32: 2099-2103.

Six, J., R.T. Conant, E.A. Paul, and K. Paustian. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241: 155-176.

Six, J. S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier, and K. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. Glob. Change Biol. 10: 155-160.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach, and J. Smith. 2007. Greenhouse gas mitigation in agriculture. Phil. Trans. R. Soc. B. doi:10.1098/rstb.2007.2184.

Stewart, B.A. 1993. Managing crop residues for the retention of carbon. Water Air Soil Poll. 70: 373-380.

Tiessen, H., and J.W.B. Stewart. 1983. Particle size fractions and their use in studies of soil organic matter: II. Cultivation effects on organic matter composition in size fractions. Soil Sci. Soc. Am. J. 47: 509-514.

Tisdall, J.M. 1996. Formation of soil aggregates and accumulation of soil organic matter. Pp. 57-96. *In*: M.R. Carter and B.A. Stewart (eds.), *Structure and Organic Matter Storage in Agricultural Soils*. CRC Press, Boca Raton, FL.

Tisdall, J.M., and J.M. Oades. 1979. Stabilization of soil aggregates by the root systems of ryegrass. Aust. J. Soil Res 17: 429-441.

Tisdall, J.M., and J.M. Oades. 1980a. The effect of crop rotation on aggregation in a red-brown earth. Aust. J. Soil Res. 18: 423-433.

Tisdall, J.M., and J.M. Oades. 1980b. The management of ryegrass to stabilize aggregates of a red-brown earth. Aust. J. Soil Res. 18: 415-422.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33: 141-163.

Turchenek, L.W., and J.M. Oades. 1978. Organo-mineral particles in soils. Pp. 137-144. *In*: W.W. Emerson, R.D. Bond, and A.R. Dexter (eds.). *Modification of Soil Structure*. Wiley, London, England.

Van Veen, J.A., and E.A. Paul. 1981. Organic carbon dynamics in grassland soils. I. Background information and computer simulation. Can. J. Soil Sci. 61: 185-201.

VandenBygaart, A.J. and B.D. Kay. 2004. Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. Soil Sci. Soc. Am. J. 68: 1394-1402.

Waters, A.G., and J.M. Oades. 1991. Organic matter in water stable aggregates. Pp. 163-174. *In*: W.S. Wilson (ed.). *Advances in Soil Organic Matter Research. The impact on Agriculture and the Environment*. Roy. Soc. Chem., Cambridge, England.

West, T.O., G. Marland, A.W. King, W.M. Post, A.K. Jain, and K. Andrasko. 2003. Carbon management response curves: estimates of temporal soil carbon dynamics. Environ. Manag. 33: 507-518.

Woods, L.E., and G.E. Schuman. 1988. Cultivation and slope position effects on soil organic matter. Soil Sci. Soc. Am. J. 52: 1371-1376.

Wright, A.L., and F.M. Hons. 2004. Soil aggregation and carbon and nitrogen storage under soybean cropping sequences. Soil Sci. Soc. Am. J. 68: 507-513.

Yang, Z., B.R. Singh, and S. Hansen. 2007. Aggregate associated carbon, nitrogen and sulfur and their ratios in long-term fertilized soils. Soil Till. Res. 95: 161-171.

# CHAPTER 2 - Materials and Methods

## Site Description

Three long term no-tillage sites were selected for this study.  All three sites were organized as a randomized complete block design with four treatments and four replications.  Treatments consisted of the following: 1) no-till (NT), where the crop was planted directly into the residue; 2) chisel-plow (CP) with straight shank chisel points; 3) sweep-plow (SwP), where a large V-blade sweep undercut the residue and rotary pickers smoothed the soil surface behind the blades; and 4) disking (DP) with an offset tandem disk.  Each tillage treatment was only applied once at the onset of the experiment with no subsequent tillage.  Each site was returned to NT management after the treatments were applied.

*Tribune.*  The Tribune, KS, experiment site was located at the Kansas State University Southwest Research and Extension Center (38° 28’ N, 99° 20’ W).  The 30-yr average annual precipitation is 443 mm, with an annual mean temperature of 10.7 °C.  Elevation is 1108 m above sea level.  The soil was a Richfield silt loam (fine-smectic, mesic, Aridic Argustolls).  Particle size analysis for selected samples of this soil is shown in Table 2.1.  The site had been in continuous NT since 1998, 6 years before the tillage treatments were administered on 30 August 2004.  A wheat-corn-grain sorghum-fallow rotation began in 2000.  The site was in fallowed wheat stubble at the time of tillage in August 2004 and was planted to corn in Spring 2005.  Plots measured 6.1 m wide X 5.5 m long.  The CP treatment was done using a Blu-Jet model 4410CC chisel (Thurston

Mfg. Co., Smithfield, RI) with a width of 6.1 m with 30.5 cm spacings, which tilled to an average depth of 18 cm. The SwP treatment consisted of a Flex-King model KM-15 sweep (Flex King, Quinter, KS), 6.1 m wide with 1.52 m blades, tilled to an average depth of 9 cm. The DP treatment consisted of an International Harvester model offset disk (Case IH, Racine, WI), 6.1 m wide with 30 cm disk blades, tilled to an average depth of 11 cm. Throughout the study, NT row crops were planted with a John Deere model JD7300 planter (John Deere, Moline. IL), and small grains were planted with a John Deere model JD752 grain drill.

*Wallace Co.* The Wallace County, KS, experiment site (hereafter referred to as Wallace) was located on the private property of a farmer-cooperator (38° 45’ N, 101° 41’ W). The 30-yr average annual rainfall amount was 511 mm, with an annual mean temperature of 10.9 °C. Elevation is 1052 m above sea level. The soil was a Kuma silt loam (fine-silty, mixed, superactive, mesic Pachic Argiustolls). Particle size analysis for selected samples of this soil is shown in Table 2.1. The site had been in continuous NT since 1980, 14 years before the tillage treatments were administered on 1 September 2004. A wheat-corn-fallow rotation was begun in 1986. The site was in fallowed wheat stubble at the time of tillage in September 2004 and was planted to corn in Spring 2005. Plots measured 6.1 m wide X 5.5 m long. The same tillage implements and grain drill were used as at the Tribune site.

*Spearville*. The Spearville, KS, experiment site was located on the private property of a farmer-cooperator (37° 44’ 31 N, 99° 34’ 40 W). The 30-yr average annual rainfall amount was 568 mm, with an annual mean temperature of 12.9 °C. Elevation was 684 m above sea level. The soil was a Canadian fine sandy loam (coarse-loamy, mixed, superactive, thermic Udic Haplustolls). Particle size analysis for selected samples of this soil is shown in Table 2.1. The site had been in wheat-sorghum-fallow rotation under conservation tillage from 1995 to 2000, with the only tillage being limited operations with a sweep plow prior to planting wheat. The last tillage operation was August 2000, four years before the tillage treatments were administered on 1 September 2004. The site had been in continuous wheat for the entire duration of the study. The wheat was topdressed each year with 56 kg $ha^{-1}$ N, and 38 kg $ha^{-1}$ $P_2O_5$ was dribbled in the row as 10-34-0 with the drill. The site was in wheat stubble prior to fall wheat drilling at the time of tillage on 18 August 2004. Each plot measured 12.2 m X 30.5 m. The CP treatment consisted of a VPS model subsoiler (Acra Co., Garden City, KS) 6.1 m wide with 76.2 cm spacings, tilled to an average depth of 30 cm. The SwP treatment consisted of a Sunflower model sweep (Sunflower, Beloit, KS) 12.2 m wide with 1.8 m blades, tilled to an average depth of 9 cm. The DP treatment was done with a Sunflower model disk (9.8 m wide with 58 cm disk blades), which tilled to an average depth of 20 cm. The SwP and DP treatments consisted of one tillage pass through each respective plot, while the CP treatment consisted of two passes side-by-side within a plot. Throughout the study, wheat was planted with a Great Plains model 3000SS grain drill (Great Plains Mfg., Inc., Salina, KS).

## Soil Sampling

Three soil sampling depths were collected for each sampling date: 0-5, 5-15, and 15-30 cm. For all three sites, composite soil samples of all three depths within each block were collected in August 2004 prior to tillage (hereafter referred to as Pre-Tillage) and tested for total C and N. Soil samples were collected by hand with a 2-cm diameter

Oakfield probe (Oakfield Apparatus, Inc., Oakfield, WI) at all three sites. The Tribune and Wallace sites averaged eight cores each of 0-5, 5-15, and 15-30 cm per block, while the Spearville site averaged 30 0-5 cm cores, 15 5-15 cm, and 15 15-30 cm cores per block.

After tillage, each individual plot was randomly sampled at all three depths at three different times (Fig. 2-1). The Tribune site was sampled on 15 April 2005 and 28 October 2005. The Wallace site was sampled on 18 April 2005 and 15 November 2005. The Spearville site was sampled on 5 May 2005 and 21 October 2005. For the October 2005 sampling dates at the Spearville site, approximately 15 of the 0-5 cm cores were pulled with a modified K-probe (Oakfield Apparatus, Inc., Oakfield, WI) that limited soil sampling depth to 0-5 cm. All samples were placed in a 3.78 L Zip-Lock bag and refrigerated at 4° C until analyzed as described in the following sections. Because of the slight difference in sampling dates between the three locations, for the purpose of our study the spring 2005 sampling dates will be referred to as nine months after tillage (MAT) and the fall 2005 sampling dates as twelve MAT. These two sampling times were chosen to evaluate any changes that may have occurred during and after the cropping season following tillage. Sampling immediately after tillage might have exaggerated the influence of tillage on aggregation, while also not allowing sufficient time for native SOC to be decomposed and/or incorporated surface residue to become affiliated with SOC pools. Prolonging sampling much beyond one year after tillage, however, may also mask subtle changes in SOC that may be undetectable once multiple cropping seasons pass.

Bulk density samples were collected with a Giddings probe mounted on the back of a Case tractor at all three sites. Samples were taken in each individual plot at all three sampling depths. Sample core widths were 4.76 cm for the Tribune and Wallace sites and 6.67 cm for the Spearville site. Tribune bulk density samples were taken on 16 May 2005, Wallace samples were taken on 14 November 2005, and Spearville samples were taken on 20 September 2005.

## Laboratory Analysis

*Bulk Density*. Soil samples were oven dried at 105° C for 48 hrs and weighed. Bulk density was calculated by dividing the dry soil weight by the core volume (Table 2.2).

*Aggregate-Size Distribution*. Water-stable aggregates (WSA) were separated using a wet sieve method described by Yoder (1936) with modifications my Mikha and Rice (2004). A 1000 µm sieve was stacked on top of a 250 µm sieve and held by a bracket connecting to the wet-sieving apparatus. This bracket was then placed within a 19 L bucket. Distilled water was added to the bucket so that at its highest point it wetted the 1000 µm sieve from below but did not overflow from the top. To slake the air-dried soil, 1 L of distilled water was then rapidly added until the soil was covered with water. Soils were submerged for 10 min and then oscillated for 10 min with a stroke length of 4 cm and frequency of 30 cycles $min^{-1}$. Soil remaining on the 1000 µm and 250 µm sieves was then backwashed into separate round aluminum pans (11 cm top diameter, volume of 200 mL) and air-dried at 50° C until all the water had evaporated. The dried aggregates were weighed and stored in crush-resistant containers at room temperature. The soil + water solution from the bucket was then passed through a 53 µm sieve. The sieve was shaken horizontally for one minute to allow water and particle fractions smaller than the sieve size to pass through. Aggregates greater than 53 µm were backwashed into an aluminum pan as described above, and the remaining soil + water solution passed through a 20 µm sieve. Soil remaining on the 20 µm sieve was then backwashed into another aluminum pan as described above.

Four aggregate size classes (>1000 µm, 250-1000 µm, 53-20 µm, and 20-53 µm) were collected from each sampling date, location, plot, and depth. Macroaggregates were defined as >1000 µm and 250-1000 µm diameter, large microaggregates as 53-250 µm diameter, and small microaggregates as 20-53 µm diameter. Sand free WSA was measured using a subsample of intact aggregates (2-5 g) and combined with fivefold volume (10-25 mL) of 5 g $L^{-1}$ sodium hexametaphosphate, left overnight and shaken on an orbital shaker at 350 RPM for 4 hours. The dispersed organic matter and sand was collected on a 53 µm mesh sieve, washed with deionized water, and dried at 105° C for 24 hours, and the aggregate weights were recorded for estimating the sand-free correction.

*Aggregate-associated C and N Analysis.* Percent C and N were determined by direct combustion of 5 g of soil using a Carlo Erba C:N Analyzer (Carlo Erba Instruments, Milan, Italy). Subsamples of whole aggregates were ground to a fine powder using mortar and pestle. Aggregate-associated total C and N for each aggregate-size fraction were calculated by multiplying the percent C and N for that fraction by 10 to achieve the weight of C and N per $kg^{-1}$ soil. Aggregate-associate C and N mass for each aggregate-size fraction were calculated by multiplying the percent C and N by the sand-free aggregate mass for that respective aggregate-size fraction. Aggregate-associated C and N mass, and aggregate-associated total C and N were only analyzed for twelve MAT.

*Whole Soil C and N Analysis.* Soil C and N were determined by direct combustion of 5 g of soil using a Carlo Erba C:N Analyzer (Carlo Erba Instruments, Milan, Italy). Whole soil C and N mass (Mg C $ha^{-1}$) were calculated by multiplying the percent C and N by the bulk density and soil depth. Pre-Tillage whole soil C and N concentration and mass were analyzed for each site, block, and depth. Composite Pre-Tillage soil samples at all depths for blocks 3 and 4 of the Spearville site contained inorganic C as $CaCO_3$ and was corrected for by adding 15 mL of $H_2SO_4$ to neutralize the free lime. Bulk density values for the NT treatment within each block were used to calculate Pre-Tillage values for that respective block. Whole soil C concentration and mass were analyzed for each tillage treatment and depth for Wallace and Tribune at nine and twelve MAT; Spearville was only analyzed at twelve MAT because of insufficient soil quantity for nine MAT. Whole soil N concentration and mass were analyzed for each tillage treatment and depth for Wallace at nine and twelve MAT; Spearville and Tribune were only analyzed at twelve MAT.

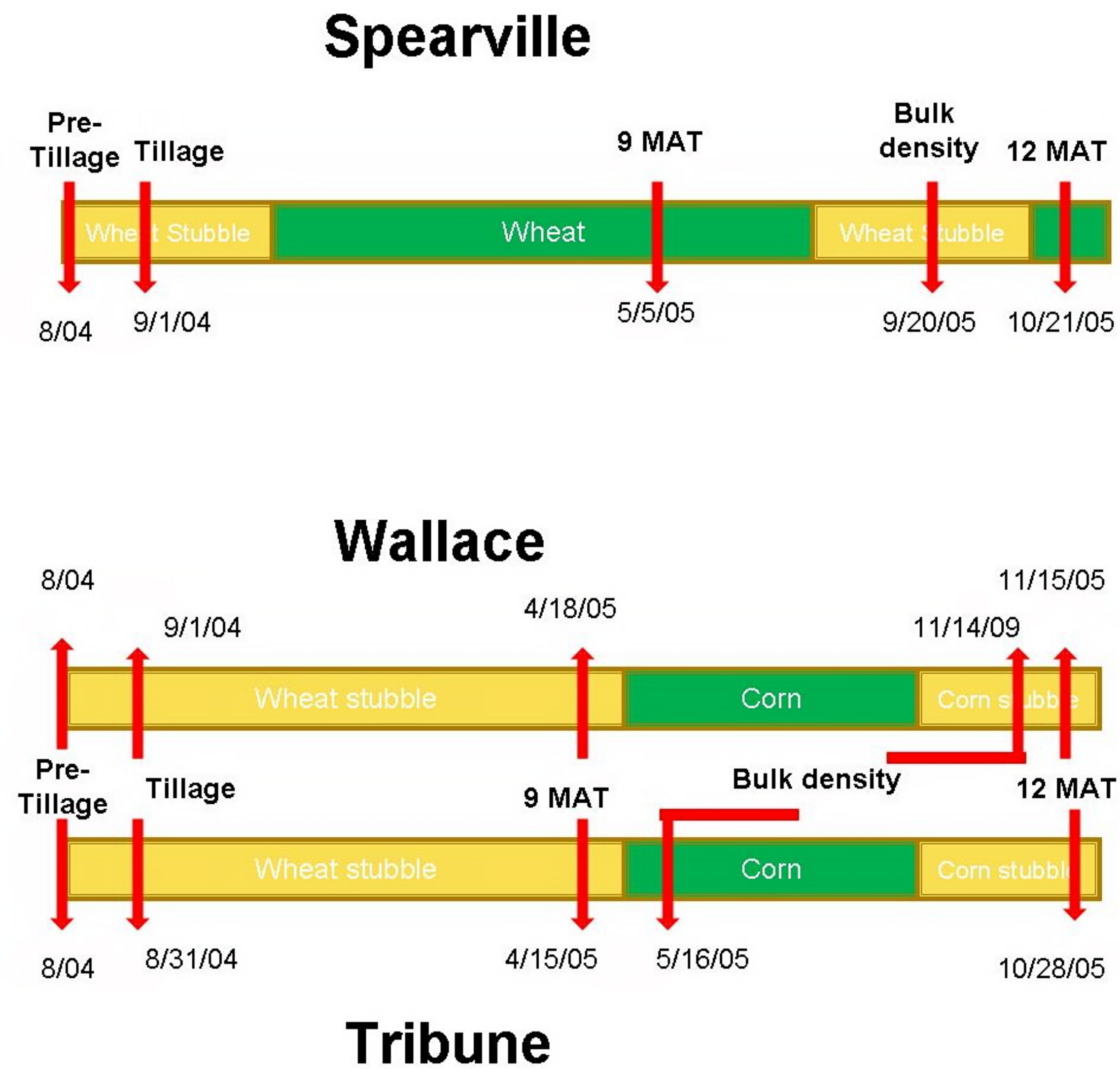
## Statistical Analyses

All three locations were laid out in a randomized complete block design. Each site contained four blocks, with each tillage treatment randomized within a block. The ANOVA F-test was used for treatment factor main effects and interactions. All results were considered significantly different at $P < 0.05$ unless noted otherwise. The F-protected *t* test was used on pairwise comparisons to follow up on significant findings. Proc Mixed in SAS 9.1.3 was used for analysis of variance and differences of least mean squares (SAS Institute Inc., 2003). Sites were not compared with each other because of climate, cropping, and soil textural differences. Whole soil C concentration and whole soil N concentration were analyzed using tillage, time, and depth as fixed effects, with tillage as a plot, depth as a sub plot, and time as a sub-sub plot. Whole soil C mass and N mass were analyzed by depth using tillage and time as fixed effects, with tillage as a plot and time as a sub plot. Depth was not considered to be an effect because the mass calculation includes multiplying by the depth of soil, which is different for all three depth layers. Aggregate size distributions were analyzed by each aggregate size fraction (250-1000 µm, 53-250 µm, and 20-53 µm) using tillage, depth, and time as fixed effects, with tillage representing plot, depth a sub plot, and time a sub-sub plot. Individual aggregate size fractions were not compared with each other in this analysis because the fractioning of aggregates are interdependent. Aggregate-associated C and N for 12 MAT were analyzed using tillage, depth, and aggregate size fraction as fixed effects, with tillage representing a plot, depth a sub plot, and aggregate size fraction a sub-sub plot. Aggregate size fractions were considered to be an effect in this analysis in order to identify differences among aggregate size fractions in their nutrient concentrations and their contributions to overall nutrient mass.

**Table 2-1. Average particle size distribution for each site by depth.**

| Site | Depth cm | Sand | Silt | Clay |
|---|---|---|---|---|
| | | --------- % --------- | | |
| Tribune | 0-5 | 18.8 | 66.0 | 15.2 |
| | 5-15 | 19.9 | 63.8 | 16.3 |
| | 15-30 | 17.9 | 56.5 | 25.6 |
| Spearville | 0-5 | 57.2 | 32.0 | 10.8 |
| | 5-15 | 58.8 | 29.1 | 12.1 |
| | 15-30 | 58.0 | 28.5 | 13.5 |
| Wallace | 0-5 | 12.4 | 60.2 | 27.4 |
| | 5-15 | 13.5 | 57.2 | 29.3 |
| | 15-30 | 14.4 | 56.6 | 29.0 |

**Figure 2-1. Soil sampling timelines for all three locations.**



# CHAPTER 3 - Results

## Bulk Density

Tillage did not significantly affect bulk density at any location (Table 3.1). Bulk density significantly varied across depth for Wallace ($P<0.0001$) and Spearville ($P<0.0001$), where bulk density was the lowest in the surface 0-5 cm and increased below 5 cm for both locations. Bulk density did not vary with depth at the Tribune site.

## Whole Soil C and N

### *Whole Soil C Concentration (gC kg $^{-1}$ soil)*

***Wallace.*** Tillage significantly affected soil C concentration ($P=0.038$) (Table 3-2). When averaged across depth and time, DP had a significantly greater C concentration as compared to NT or CP (Table 3-3). Both depth and time also influenced whole soil C concentration, but not all soil depths behaved similarly over time as indicated by the depth x time interaction ($P<0.0001$) (Table 3-2). Overall, the C concentration increased from nine to 12 MAT in the upper 0-15 cm depth, but it did not change over time below the 15 cm depth (Table 3-4, Figure 3-1). Furthermore, the C concentration was consistently greatest in the surface 0-5 cm depth at all three times, and C concentration decreased for each subsequent depth (Table 3-4, Figure 3-1).

***Spearville.*** Tillage did not affect soil C concentration at Spearville, nor C concentration change over time, either (Table 3-5). Soil C concentration did vary over depth, where the C concentration was greatest in the surface 0-5 cm depth and lowest in the middle 5-15 cm depth (Table 3-6).

***Tribune***. Tillage did not affect the soil C concentration at Tribune, but the C concentration did vary over both depth and time (Table 3-7). The soil C concentration was greatest in the surface 0-5 cm depth and decreased significantly at each lower depth increment (Table 3-8). Soil C concentration also decreased over time, with the greatest amount existing prior to tillage and then declining at each sampling time (Table 3-9).

### *Soil C Mass (Mg C $ha^{-1}$)*

***Wallace***. Tillage did not affect the mass of soil C at any depth for Wallace (Table 3-10). At all three depths, however, soil C mass varied over time (Table 3-10). Average soil C mass in the 0-5 and 5-15 cm depths were the greatest at 12 MAT; at the 15-30 cm depth, soil C mass gradually increased over time, with 12 MAT having more soil C mass than at Pre-Tillage (Table 3-10).

***Spearville***. Tillage did not affect the mass of soil C at Spearville, nor did soil C mass change over time at any depth (Table 3-11).

***Tribune***. Tillage did not affect the mass of soil C at Tribune (Table 3-12). Soil C mass did not change over time in the surface 0-5 cm depth, but it did at lower depths (Table 3-12). At the 5-15 cm depth, the average soil C mass was greatest prior to tillage and decreased at each sampling date, even in the continuous NT. At the 15-30 cm depth, the average soil C mass significantly declined from Pre-Tillage to nine MAT, with no further change in soil C mass at 12 MAT (Table 3-12).

### *Whole Soil N Concentration (g N $kg^{-1}$ soil)*

***Wallace***. Soil N concentration varied between depths when averaged across tillage treatments (Table 3-13). The change in soil N concentration over time varied according to tillage, as indicated by a tillage x time interaction ($P$=0.0071) (Table 3-13).

When averaged across depths, the soil N concentration increased from nine to 12 MAT for NT, DP, and CP, with the greatest soil N concentration present at 12 MAT (Table 3-14, Figure 3-2). However, SwP was the only tillage to not significantly increase its soil N concentration from nine to 12 MAT (Table 3-14, Figure 3-2). Disk Plow and SwP also ended up with greater soil N concentrations at 12 MAT than what existed at Pre-Tillage, whereas for NT and CP the soil N concentration at 12 MAT recovered to Pre-Tillage levels (Table 3-14). Furthermore, the average soil N concentration for all tillage treatments was greatest in the surface 0-5 cm depth and decreased incrementally at each lower depth (Table 3-15).

***Spearville***. Tillage did not affect soil N concentration at Spearville (Table 3-16). Soil N concentration varied over both depth and time, but not all depths changed over time to the same degree, as indicated by the significant depth x time interaction ($P$=0.0001) (Table. 3-16). The average soil N concentration for all tillage treatments increased over time at every depth, with a sharper increase occurring in the surface 0-5 cm depth (Table 3-17, Figure 3-3). Soil N concentration was also greatest in the surface 0-5 cm depth and decreased incrementally at each lower depth (Table 3-17).

***Tribune***. Tillage did not significantly influence soil N concentration at Tribune, and soil N concentration did not change over time, either (Table 3-18). Soil N concentration significantly varied by depth, since soil N concentration was the greatest in the surface 0-5 cm depth and decreased incrementally at each lower depth (Table 3-19).

### *Whole Soil N Mass (Mg N ha$^{-1}$)*

***Wallace***. Tillage did not affect the mass of soil N at any depth for Wallace (Table 3-20). Soil N mass changed over time at all depths, with the average soil N mass increasing significantly from nine to 12 MAT at each depth (Table 3-20). Soil N mass decreased from Pre-Tillage to nine MAT in the surface 0-5 cm depth, but remained constant during the same time frame at the 5-15 and 15-30 cm depths (Table 3-20).

***Spearville***. Tillage did not affect the mass of soil N at any depth for Spearville (Table 3-21). Soil N mass changed over time for all depths, with the average soil N mass increasing significantly from Pre-Tillage to 12 MAT at each depth (Table 3-21).

***Tribune***. Neither tillage nor time significantly influenced the soil N mass at any depth for Tribune (Table 3-22).

## Aggregate Size Distribution

Since very low amounts of large macroaggregates (>1000 µm) were present at all three sites, this aggregate size fraction was excluded from the final analysis of the aggregate size distributions. For our discussion, macroaggregates will refer to the 250-1000 µm size fraction. Large microaggregates will refer to the 53-250 µm size fraction, and small microaggregates will refer to the 20-53 µm size fraction.

***Wallace.*** Tillage did not significantly influence aggregate distribution in any of the aggregate size fractions (Table 3-23). The quantity of macroaggregates varied by depth between the two sampling times, as indicated by the significant depth x time interaction ($P$=0.0019) (Table 3-23). The quantity of macroaggregates was greatest in the surface depth of 0-5 cm at nine MAT, whereas at 12 MAT the 0-5 cm depth had the same amount of macroaggregates as did lower soil layers (Table 3-24, Figure 3-4). Furthermore, the amount of macroaggregates decreased over time from nine to 12 MAT in the surface 0-5 cm, but there was no change over time below 5 cm (Table 3-24, Figure

3-4). This difference in behavior of depths over time was unique to macroaggregates, as both large and small microaggregates did not have a depth x time interaction (Table 3-23). Large microaggregates were greatest at the 5-15 cm depth, and on average they decreased over time for all soil layers (Table 3-25). Small microaggregates were fewest in the upper 0-5 cm and gradually increased with subsequent depths, and on average they increased over time for all soil layers (Table 3-26).

***Spearville.*** Tillage did not significantly influence aggregate distribution in any of the aggregate size fractions (Table 3-27). Not all depth layers behaved similarly over time for macroaggregates and large microaggregates, as indicated by their significant depth x time interactions ($P$=0.0093 and $P$=0.0243, respectively). Macroaggregates were greater at a depth of 0-5 cm than at the 5-15 cm depth for both nine and 12 MAT. However, at nine MAT, the amount of macroaggregates at a depth of 15-30 cm was equal to the amount found in the surface depth of 0-5 cm (Table 3-28, Figure 3-5). In contrast, at 12 MAT, the lower 15-30 cm depth had significantly fewer macroaggregates than found in the surface depth of 0-5 cm (Table 3-28, Figure 3-5). The quantity of macroaggregates also decreased over time for all three depth layers (Table 3-28). Large microaggregates did not vary over depth at nine MAT, but at 12 MAT there were more large microaggregates below a depth of 5 cm than found in the 0-5 cm depth (Table 3-29, Figure 3-5). Furthermore, the amount of large microaggregates decreased over time in the upper depth of 0-15 cm, but they did not change at a depth of 15-30 cm (Table 3-29, Figure 3-5). Depth did not significantly influence small microaggregates (Table 3-30). On average, small microaggregates increased over time for all soil layers (Table 3-30).

***Tribune.*** Tillage did not significantly influence aggregate distribution in any of the aggregate size fractions (Table 3-31). Both depth and time significantly affected all of the aggregates size fractions (Table 3-31). More macroaggregates existed at a depth of 15-30 cm than at a depth of 0-15 cm, and on average macroaggregates increased over time in all soil layers (Table 3-32). Large microaggregates were greatest in the 5-15 cm layer and least in the 15-30 cm layer; on average all the soil layers also decreased over time in the amount of large microaggregates (Table 3-33). More small microaggregates existed at a depth of 0-15 cm than at the 15-30 cm, and on average all the soil layers increased over time (Table 3-34).

## Aggregate Carbon and Nitrogen

### *Aggregate-associated C Concentration (g C kg$^{-1}$ soil)*

***Wallace.*** Tillage did not significantly affect the C concentration of aggregates at Wallace (Table 3-35). Aggregate size fractions differed in their C concentrations. At all three depths, the greatest concentration of C existed in the macroaggregate fraction, followed by the large microaggregate fraction (Table 3.36). Carbon concentration was the greatest in the upper 0-5 cm of soil and decreased incrementally over depth for all three aggregate size fractions (Table 3.35). However, the differences in C concentration between depths within a particular aggregate size fraction were more pronounced for the larger aggregate size fractions, as indicated by the depth x aggregate interaction ($P<0.0001$) (Figure 3-6).

***Spearville.*** Tillage did not significantly affect the C concentration of aggregates at Spearville (Table 3-37). Aggregate size fractions differed in their C concentrations, but not all aggregate size fractions behaved similarly at all depths, as indicated by the depth x aggregate interaction ($P$<0.0001). At all three depths, the greatest concentration of C existed in the small microaggregate fraction (Table 3-38, Figure 3-7). In the surface 0-5 cm depth, macroaggregates and large microaggregates had similar C concentrations, but at the 5-15 and 15-30 cm depths macroaggregates had less C concentration than did large microaggregates (Table 3-38, Figure 3-7). Macroaggregate C concentration was greatest in the surface 0-5 cm depth; large microaggregate C concentration was greater at the 0-5 cm depth than at the 5-15 cm depth, but neither were different from the 15-30 cm depth; small microaggregate C concentration was greater at the 15-30 cm depth than at shallower depths (Table 3-38, Figure 3-7).

***Tribune.*** Tillage did not significantly affect the C concentration of aggregates at Tribune (Table 3-39). The C concentration varied among aggregate size fractions, but not all aggregate size fractions behaved similarly across depths, as indicated by the depth x aggregate interaction ($P$<0.0001). In the surface 0-5 cm depth, macroaggregates had the greatest concentration of C, followed by large microaggregates and then small microaggregates (Table 3-40, Figure 3-8). Macroaggregates also had the highest C concentration in the 5-15 cm depth, but large and small microaggregates did not differ in C concentration as they did at the 0-5 cm depth. There were no differences between aggregate size fractions in C concentration at the 15-30 cm depth. Carbon concentration in macroaggregates was the greatest in the surface 0-5 cm layer and decreased for each subsequent depth (Table 3-40, Figure 3-8). Large microaggregate C concentration gradually decreased with depth, while small microaggregate C concentration did not vary between depths (Table 3-40, Figure 3-8).

### *Aggregate-associated C mass (g C sand-free aggregate$^{-1}$)*

***Wallace.*** Carbon mass associated with aggregates varied among tillage treatments based on depth and aggregate size fraction, as indicated by the three-way interaction of those terms ($P$=0.0228) (Table 3-41). Disk Plow and SwP both had a greater mass of C in macroaggregates as compared to CP in the surface 0-5 cm layer, and SwP had more C mass in macroaggregates than did CP in the 5-15 cm layer (Table 3-41, Figure 3-9). The mass of C contained in macroaggregates in the NT treatment was statistically equal to all of the tillage types, however. Disk Plow also had a lower mass of C in large microaggregates in the surface 0-5 cm as compared to all other tillage treatments, including NT (Table 3-41, Figure 3-9). At the 5-15 cm depth, though, DP had more C mass in the large microaggregate fraction as compared to NT and CP (but not compared to SwP) (Table 3-41, Figure 3-9). Carbon mass affiliated with small microaggregates did not vary between tillage treatments at any depth (Table 3-41, Figure 3-9). The greatest mass of C existed in the large microaggregate fraction at all three depths (Table 3-42). When averaged across tillage treatments, the mass of C in the macroaggregate and large microaggregate fractions was the greatest in the upper 0-5 cm layer; C mass associated with small microaggregates did not vary across depth (Table 3-42).

***Spearville.*** Carbon mass associated with aggregates was not influenced by tillage at Spearville (Table 3-43). Aggregate size fractions differed in their contribution to C mass, but not all aggregate size fractions contributed to C mass similarly at all depths, as indicated by the depth x aggregate interaction ($P$=0.0009) (Table 3-43). In the surface 0-5 cm depth, the greatest mass of C existed in the large microaggregate fraction, followed by the macroaggregate fraction and then the small microaggregate fraction (Table 3-44,

Figure 3-10). Similar to the 0-5 cm depth, the 5-15 and 15-30 cm depths also had the greatest mass of C in the large microaggregate fraction, but in contrast to the 0-5 cm depth, small microaggregates had a greater mass of C as compared to macroaggregates (Table 3-44, Figure 3-10). The mass of C contributed by macroaggregates was the greatest in the surface 0-5 cm depth (Table 3-44, Figure 3-10). Carbon mass from large microaggregates was the least in the 5-15 cm soil layer, while C mass from small microaggregates did not vary across depths (Table 3-44, Figure 3-10).

***Tribune.*** Carbon mass associated with aggregates was not influenced by tillage at Tribune (Table 3-45). Aggregate size fractions differed in their contribution to C mass, but not all aggregate size fractions contributed to C mass similarly at all depths, as indicated by the depth x aggregate interaction (*P*=0.0001) (Table 3-46). At all three depths, the greatest mass of C existed in the large microaggregate fraction (Table 3-46, Figure 3-11). The amount of C mass in macroaggregates was greatest in the surface 0-5 cm depth as compared to lower depths, while the C mass of large microaggregates was equal across the 0-5 and 5-15 cm depths and decreased at the 15-30 cm depth (Table 3-46, Figure 3-11). The amount of C mass contributed by small microaggregates did not vary over depth (Table 3-46, Figure 3-11).

### *Aggregate-associated N Concentration (g N kg$^{-1}$ soil)*

***Wallace.*** Tillage did not significantly influence the N concentration of aggregates at Wallace, but the stratification of aggregate N concentration by depth was not consistent among all tillage treatments, as indicated by the tillage x depth interaction (*P*=0.0285) (Table 3-47). For NT, SwP, and CP, the greatest concentration of aggregate N was in the surface 0-5 cm depth and decreased significantly for each depth layer (Table 3-48, Figure

3-12). Disk Plow was different, however, in that the 0-5 cm and 5-15 cm depths were equal in their aggregate N concentration (Table 3-48, Figure 3-12). Nitrogen concentration in aggregates also varied by depth depending on the aggregate size fraction, as indicated by the aggregate x depth interaction ($P$=0.0001) (Table 3-47). Macroaggregates and large microaggregates had the greatest N concentration in the surface 0-5 cm depth and N concentration decreased significantly for each lower depth layer (Table 3-49, Figure 3-13). Small microaggregates, however, had equal N concentrations across the 0-5 and 5-15 cm depths. Furthermore, the greatest N concentration at all depth layers existed in the macroaggregate fraction (Table 3-49, Figure 3-13). Large microaggregates also had greater N concentrations than small microaggregates at 0-5 and 5-15 cm depths, but not at the 15-30 cm depth (Table 3-49, Figure 3-13).

***Tribune.*** Tillage did not significantly influence the N concentration of aggregates at Tribune (Table 3-50). Aggregate N concentration varied between aggregate size fractions only at specific depths, as indicated by the aggregate x depth interaction ($P$<0.0001) (Table 3-50). In the 0-5 and 5-15 cm soil layers, macroaggregates had the highest concentration of N, whereas both microaggregate fractions were equal in their N concentration (Table 3-51, Figure 3-14). At the 15-30 cm depth, however, all three aggregate size fractions were equal in their N concentration (Table 3-51, Figure 3-14). The N concentration of macroaggregates was greatest in the surface 0-5 cm depth and decreased significantly at each lower depth; large microaggregate N concentration was greater in the 0-5 cm depth as opposed to the lower 15-30 cm depth (Table 3-51, Figure

3-14). Small microaggregates did not vary in their N concentration between depths (Table 3-51, Figure 3-14).

### *Aggregate-associated N mass (g N sand-free aggregate$^{-1}$)*

***Wallace***. Nitrogen mass associated with aggregates was not influenced by tillage at Wallace (Table 3-52). Aggregate size fractions differed in their contribution to N mass, but not all aggregate size fractions contributed to N mass similarly at all depths, as indicated by the depth x aggregate interaction (*P*=<0.0001) (Table 3-52). The greatest mass of N was contained in the large microaggregate fraction at all depths (Table 3-53, Figure 3-15). The mass of N contained in the macroaggregate fraction was greater in the surface 0-5 cm depth as compared to lower depths, while the mass of N contained in the large microaggregate fraction was equal across the 0-5 and 5-15 cm depths, but both depths were greater than what was contained in the 15-30 cm depth (Table 3-53, Figure 3-15).

***Tribune***. Nitrogen mass associated with aggregates was not influenced by tillage at Tribune (Table 3-54). Aggregate size fractions differed in their contribution to N mass, but not all aggregate size fractions contributed to N mass similarly at all depths, as indicated by the depth x aggregate interaction (*P*=<0.0001) (Table 3-54). The greatest mass of N was contained in the large microaggregate fraction at all depths (Table 3-55, Figure 3-16). The mass of N contained in macroaggregates was greater in the surface 0-5 cm depth than in the 5-15 cm depth, but neither depth was different from the 15-30 cm depth (Table 3-55, Figure 3-16). The mass of N contained in large microaggregates was greatest in the 0-5 and 5-15 cm depths, but decreased at the 15-30 cm depth (Table 3-55,

Figure 3-16). Small microaggregates contributed the same mass of N at all three depths (Table 3-55, Figure 3-16).

**Table 3-1 Bulk density averages for all three locations by depth.**

| Tillage | 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|---|
| **Wallace** | | | |
| | | g $cm^{-3}$ | |
| **NT** | 1.14 | 1.33 | 1.32 |
| **DP** | 1.03 | 1.31 | 1.34 |
| **SwP** | 1.12 | 1.37 | 1.34 |
| **CP** | 1.13 | 1.24 | 1.33 |
| **Mean** | 1.10 a* | 1.31 b | 1.33 b |
| **Spearville** | | | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g $cm^{-3}$ | |
| **NT** | 1.40 | 1.64 | 1.55 |
| **DP** | 1.25 | 1.73 | 1.59 |
| **SwP** | 1.27 | 1.63 | 1.62 |
| **CP** | 1.41 | 1.75 | 1.62 |
| **Mean** | 1.33 a | 1.69 b | 1.60 b |
| **Tribune** | | | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g $cm^{-3}$ | |
| **NT** | 1.15 | 1.39 | 1.26 |
| **DP** | 1.31 | 1.31 | 1.24 |
| **SwP** | 1.20 | 1.25 | 1.27 |
| **CP** | 1.20 | 1.20 | 1.24 |
| | | ***P* values** | |
| | **Wallace** | **Spearville** | **Tribune** |
| **Tillage (T)** | 0.3608 | 0.5441 | 0.8348 |
| **Depth (D)** | <0.0001 | <0.0001 | 0.3125 |
| **T x D** | 0.2564 | 0.7008 | 0.5178 |

*Lower case letters across a row indicate significant difference ($P$<0.05) between tillage means for the particular location. NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-2. Whole soil C concentrations by tillage, depth, and time for Wallace**

| | | | |
|---|---|---|---|
| | | **Pre-Tillage** | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C $kg^{-1}$ soil | |
| | 13.4 | 10.6 | 8.5 |
| | | **Time 9 MAT** | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C $kg^{-1}$ soil | |
| **NT** | 11.8 | 10.2 | 8.6 |
| **DP** | 13.5 | 11.0 | 9.6 |
| **SwP** | 13.4 | 10.4 | 9.7 |
| **CP** | 12.4 | 10.4 | 8.5 |
| | | **Time 12 MAT** | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C $kg^{-1}$ soil | |
| **NT** | 15.3 | 13.8 | 9.6 |
| **DP** | 21.4 | 13.0 | 10.0 |
| **SwP** | 17.6 | 13.1 | 9.4 |
| **CP** | 16.5 | 12.7 | 9.2 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.0380 | |
| **Depth (D)** | | <0.0001 | |
| **Time (t)** | | <0.0001 | |
| **T x D** | | 0.2311 | |
| **T x t** | | 0.3830 | |
| **D x t** | | <0.0001 | |
| **T x D x t** | | 0.3777 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-3. Whole soil C concentration tillage means for Wallace.**

| NT | DP | SwP | CP |
|---|---|---|---|
| | g C $kg^{-1}$ soil | | |
| 11.3 a* | 12.3 b | 11.8 ab | 11.3 a |

*Letters indicate significant difference between tillage treatments at $P<0.05$.

**Table 3-4. Whole soil C concentration means for time and depth for Wallace.**

| | Depth (cm) | | |
|---|---|---|---|
| | **0-5** | **5-15** | **15-30** |
| | | g C $kg^{-1}$ soil | |
| **Pre-Tillage** | 13.4 aA* | 10.6 aB | 8.5 aC |
| **9 MAT** | 12.8 aA | 10.5 aB | 9.1 aC |
| **12 MAT** | 17.7 bA | 13.1 bB | 9.5 aC |

*Upper case letters across a row indicate significant difference ($P<0.05$) between depths. Lower case letters indicate significant difference ($P<0.05$) over time.

**Table 3-5. Whole soil C concentration by tillage, depth, and time for Spearville.**

| | Pre-Tillage | | |
|---|---|---|---|
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C $kg^{-1}$ soil | |
| | 9.4 | 7.0 | 7.8 |
| | **Time 12 MAT** | | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C $kg^{-1}$ soil | |
| **NT** | 10.4 | 7.1 | 7.7 |
| **DP** | 10.2 | 7.4 | 8.1 |
| **SwP** | 10.0 | 6.7 | 8.2 |
| **CP** | 9.9 | 7.1 | 7.9 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.9860 | |
| **Depth (D)** | | <0.0001 | |
| **Time (t)** | | 0.2193 | |
| **T x D** | | 0.9973 | |
| **T x t** | | 0.9808 | |
| **D x t** | | 0.5323 | |
| **T x D x t** | | 0.9973 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-6. Whole soil C concentration depth means for Spearville.**

| 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|
| | g C $kg^{-1}$ soil | |
| 9.7 a* | 7.0 b | 7.9 c |

*Letters indicate significant difference over depth at $P$<0.05.

**Table 3-7. Whole soil C concentration by tillage, depth, and time for Tribune.**

| | Pre-Tillage | | |
|---|---|---|---|
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C kg$^{-1}$ soil | |
| | 20.5 | 14.5 | 10.6 |
| | **Time 9 MAT** | | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C kg$^{-1}$ soil | |
| **NT** | 18.6 | 13.3 | 8.9 |
| **DP** | 15.8 | 13.3 | 8.9 |
| **SwP** | 19.1 | 13.8 | 9.4 |
| **CP** | 18.7 | 12.8 | 9.1 |
| | **Time 12 MAT** | | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C kg$^{-1}$ soil | |
| **NT** | 15.8 | 11.5 | 8.7 |
| **DP** | 17.2 | 12.1 | 8.7 |
| **SwP** | 16.4 | 12.1 | 9.7 |
| **CP** | 16.6 | 11.1 | 7.9 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.9440 | |
| **Depth (D)** | | <0.0001 | |
| **Time (t)** | | <0.0001 | |
| **T x D** | | 0.9313 | |
| **T x t** | | 0.7201 | |
| **D x t** | | 0.1962 | |
| **T x D x t** | | 0.9078 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-8. Whole soil C concentration depth means for Tribune.**

| 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|
| | g C $kg^{-1}$ soil | |
| 18.4 a* | 13.3 b | 9.6 c |

*Letters indicate significant difference over depth at $P$<0.05.

**Table 3-9. Whole soil C concentration time means for Tribune.**

| Pre-Tillage | 9 MAT | 12 MAT |
|---|---|---|
| | g C $kg^{-1}$ soil | |
| 15.2 a* | 13.8 b | 12.3 c |

*Letters indicate significant difference over time at $P$<0.05.

**Table 3-10. Wallace whole soil C mass by depth, tillage, and time.**

| Treatments | Pre-Tillage | 9 MAT | 12 MAT |
|---|---|---|---|
| **0-5 cm** | | | |
| | | Mg C ha$^{-1}$ | |
| **NT** | 6.6 | 6.8 | 8.7 |
| **DP** | 6.6 | 6.6 | 10.9 |
| **SwP** | 6.6 | 7.4 | 9.8 |
| **CP** | 6.6 | 7.0 | 9.3 |
| **Time (mean)** | 6.6 a* | 7.0 a | 9.7 b |
| | | ***P* values** | |
| **Tillage (T)** | | 0.5994 | |
| **Time (t)** | | <0.0001 | |
| **T x t** | | 0.4892 | |
| **5-15 cm** | | | |
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg C ha$^{-1}$ | |
| **NT** | 11.6 | 13.4 | 18.4 |
| **DP** | 11.6 | 14.4 | 16.9 |
| **SwP** | 11.6 | 14.1 | 18.0 |
| **CP** | 11.6 | 12.6 | 15.7 |
| **Time (mean)** | 11.6 a | 13.6 a | 17.3 b |
| | | ***P* values** | |
| **Tillage (T)** | | 0.5129 | |
| **Time (t)** | | <0.0001 | |
| **T x t** | | 0.8509 | |
| **15-30 cm** | | | |
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg C ha$^{-1}$ | |
| **NT** | 18.0 | 17.1 | 19.0 |
| **DP** | 18.0 | 19.3 | 20.1 |
| **SwP** | 18.0 | 19.4 | 18.9 |
| **CP** | 18.0 | 16.9 | 18.3 |
| **Time (mean)** | 18.0 a | 18.2 ab | 19.1 b |
| | | ***P* values** | |
| **Tillage (T)** | | 0.5426 | |
| **Time (t)** | | 0.0326 | |
| **T x t** | | 0.8194 | |

*Lower case letters indicate significant difference between tillage means over time ($P<0.05$). NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-11. Spearville whole soil C mass by depth, tillage, and time.**

| | 0-5 cm | |
|---|---|---|
| **Treatments** | **Pre-Tillage** | **12 MAT** |
| | | Mg C ha$^{-1}$ |
| **NT** | 6.6 | 7.2 |
| **DP** | 6.6 | 6.3 |
| **SwP** | 6.6 | 6.4 |
| **CP** | 6.6 | 6.9 |
| | | ***P* values** |
| **Tillage (T)** | | 0.7903 |
| **Time (t)** | | 0.6565 |
| **T x t** | | 0.7903 |
| | **5-15 cm** | |
| **Treatments** | **Pre-Tillage** | **12 MAT** |
| | | Mg C ha$^{-1}$ |
| **NT** | 11.5 | 11.7 |
| **DP** | 11.5 | 12.6 |
| **SwP** | 11.5 | 10.9 |
| **CP** | 11.5 | 12.4 |
| | | ***P* values** |
| **Tillage (T)** | | 0.2491 |
| **Time (t)** | | 0.2969 |
| **T x t** | | 0.2491 |
| | **15-30 cm** | |
| **Treatments** | **Pre-Tillage** | **12 MAT** |
| | | Mg C ha$^{-1}$ |
| **NT** | 18.0 | 17.6 |
| **DP** | 18.0 | 19.3 |
| **SwP** | 18.0 | 19.8 |
| **CP** | 18.0 | 19.2 |
| | | ***P* values** |
| **Tillage (T)** | | 0.9536 |
| **Time (t)** | | 0.4632 |
| **T x t** | | 0.9532 |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-12. Tribune whole soil C mass by depth, tillage, and time.**

| | 0-5 cm | | |
|---|---|---|---|
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg C ha$^{-1}$ | |
| **NT** | 11.7 | 10.5 | 9.0 |
| **DP** | 11.7 | 10.0 | 10.8 |
| **SwP** | 11.7 | 11.5 | 10.2 |
| **CP** | 11.7 | 11.7 | 9.9 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.9530 | |
| **Time (t)** | | 0.1033 | |
| **T x t** | | 0.8793 | |

| | 5-15 cm | | |
|---|---|---|---|
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg C ha$^{-1}$ | |
| **NT** | 20.2 | 17.8 | 15.8 |
| **DP** | 20.2 | 17.9 | 15.7 |
| **SwP** | 20.2 | 17.2 | 15.0 |
| **CP** | 20.2 | 15.2 | 13.4 |
| **Time (mean)** | 20.2 a | 17.4 b | 15.0 c |
| | | ***P* values** | |
| **Tillage (T)** | | 0.1626 | |
| **Time (t)** | | <0.0001 | |
| **T x t** | | 0.6122 | |

| | 15-30 cm | | |
|---|---|---|---|
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg C ha$^{-1}$ | |
| **NT** | 20.0 | 17.1 | 16.3 |
| **DP** | 20.0 | 16.4 | 16.2 |
| **SwP** | 20.0 | 17.9 | 18.8 |
| **CP** | 20.0 | 17.0 | 14.7 |
| **Time (mean)** | 20.0 a | 17.2 b | 16.5 b |
| | | ***P* values** | |
| **Tillage (T)** | | 0.5342 | |
| **Time (t)** | | 0.0009 | |
| **T x t** | | 0.7285 | |

*Lower case letters indicate significant difference between tillage means over time ($P$<0.05). NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-13. Whole soil N concentration by tillage, depth, and time for Wallace.**

| | | Pre-Tillage | |
|---|---|---|---|
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N kg$^{-1}$ soil | |
| | 1.38 | 1.12 | 0.89 |
| | | **Time 9 MAT** | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C kg$^{-1}$ soil | |
| **NT** | 1.17 | 0.98 | 0.86 |
| **DP** | 1.14 | 0.92 | 0.82 |
| **SwP** | 1.42 | 1.25 | 0.97 |
| **CP** | 1.12 | 0.90 | 0.80 |
| | | **Time 12 MAT** | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N kg$^{-1}$ soil | |
| **NT** | 1.45 | 1.25 | 1.04 |
| **DP** | 1.76 | 1.22 | 1.06 |
| **SwP** | 1.57 | 1.25 | 1.04 |
| **CP** | 1.42 | 1.22 | 1.02 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.1602 | |
| **Depth (D)** | | <0.0001 | |
| **Time (t)** | | <0.0001 | |
| **T x D** | | 0.7341 | |
| **T x t** | | 0.0071 | |
| **D x t** | | 0.2486 | |
| **T x D x t** | | 0.8660 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-14. Whole soil N concentration means for tillage and time for Wallace.**

| Tillage | Pre-Tillage | 9 MAT | 12 MAT |
|---|---|---|---|
| | g N $kg^{-1}$ soil | | |
| **NT** | 1.13 Aab* | 1.00 Aa | 1.25 Ab |
| **DP** | 1.13 Aa | 0.96 Ab | 1.35 Ac |
| **SwP** | 1.13 Aa | 1.21 Bab | 1.29 Ab |
| **CP** | 1.13 Aab | 0.94 Aa | 1.22 Ab |

*Upper case letters within a column indicate significant difference ($P$<0.05) between tillage for the particular time. Lower case letters across a row indicate significant difference ($P$<0.05) over time for the particular tillage.

**Table 3-15. Whole soil N concentration depth means for Wallace.**

| 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|
| | g N $kg^{-1}$ soil | |
| 1.38 a* | 1.12 b | 0.93 c |

*Letters indicate significant difference over depth at $P$<0.05.

**Table 3-16. Whole soil N concentration by tillage, depth, and time for Spearville.**

| | Pre-Tillage | | |
|---|---|---|---|
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N kg$^{-1}$ soil | |
| | 0.79 | 0.61 | 0.55 |
| | | **Time 12 MAT** | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N kg$^{-1}$ soil | |
| **NT** | 0.94 | 0.66 | 0.58 |
| **DP** | 0.99 | 0.70 | 0.66 |
| **SwP** | 0.96 | 0.65 | 0.64 |
| **CP** | 0.97 | 0.70 | 0.62 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.6999 | |
| **Depth (D)** | | <0.0001 | |
| **Time (t)** | | <0.0001 | |
| **T x D** | | 0.9565 | |
| **T x t** | | 0.2708 | |
| **D x t** | | 0.0001 | |
| **T x D x t** | | 0.9565 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-17. Whole soil N concentration means for time and depth for Spearville.**

| | Depth (cm) | | |
|---|---|---|---|
| | **0-5** | **5-15** | **15-30** |
| | | g N kg$^{-1}$ soil | |
| **Pre-Tillage** | 0.79 aA* | 0.61 aB | 0.55 aC |
| **12 MAT** | 0.96 bA | 0.68 bB | 0.62 bC |

*Upper case letters across a row indicate significant difference ($P$<0.05) between depths. Lower case letters indicate significant difference ($P$<0.05) over time.

**Table 3-18. Whole soil N concentration by tillage, depth, and time for Tribune.**

| | Pre-Tillage | | |
|---|---|---|---|
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N kg$^{-1}$ soil | |
| | 1.50 | 1.17 | 1.03 |
| | **Time 12 MAT** | | |
| **Tillage** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N kg$^{-1}$ soil | |
| **NT** | 1.54 | 1.25 | 0.99 |
| **DP** | 1.48 | 1.17 | 0.96 |
| **SwP** | 1.46 | 1.23 | 1.03 |
| **CP** | 1.51 | 1.11 | 0.89 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.7672 | |
| **Depth (D)** | | <0.0001 | |
| **Time (t)** | | 0.5787 | |
| **T x D** | | 0.9583 | |
| **T x t** | | 0.6029 | |
| **D x t** | | 0.3544 | |
| **T x D x t** | | 0.9583 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-19. Whole soil N concentration depth means for Tribune.**

| **0-5 cm** | **5-15 cm** | **15-30 cm** |
|---|---|---|
| | g N kg$^{-1}$ soil | |
| 1.50 a* | 1.18 b | 1.00 c |

*Letters indicate significant difference over depth at $P$<0.05.

**Table 3-20. Wallace whole soil N mass by depth, tillage, and time.**

| Treatments | Pre-Tillage | 9 MAT | 12 MAT |
|---|---|---|---|
| **0-5 cm** | | | |
| | | Mg N $ha^{-1}$ | |
| **NT** | 0.79 | 0.67 | 0.83 |
| **DP** | 0.79 | 0.56 | 0.89 |
| **SwP** | 0.79 | 0.79 | 0.86 |
| **CP** | 0.79 | 0.63 | 0.80 |
| **Time (mean)** | 0.79 a | 0.66 b | 0.85 a |
| | | ***P* values** | |
| **Tillage (T)** | | 0.3731 | |
| **Time (t)** | | 0.0003 | |
| **T x t** | | 0.3381 | |
| **5-15 cm** | | | |
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg N $ha^{-1}$ | |
| **NT** | 1.48 | 1.29 | 1.66 |
| **DP** | 1.48 | 1.21 | 1.60 |
| **SwP** | 1.48 | 1.73 | 1.71 |
| **CP** | 1.48 | 1.09 | 1.50 |
| **Time (mean)** | 1.48 ab | 1.33 a | 1.62 b |
| | | ***P* values** | |
| **Tillage (T)** | | 0.0602 | |
| **Time (t)** | | 0.0098 | |
| **T x t** | | 0.2561 | |
| **15-30 cm** | | | |
| **Treatments** | **Pre-Tillage** | **9 MAT** | **12 MAT** |
| | | Mg N $ha^{-1}$ | |
| **NT** | 1.77 | 1.70 | 2.06 |
| **DP** | 1.77 | 1.65 | 2.13 |
| **SwP** | 1.77 | 1.95 | 2.09 |
| **CP** | 1.77 | 1.59 | 2.04 |
| **Time (mean)** | 1.77 a | 1.72 a | 2.08 b |
| | | ***P* values** | |
| **Tillage (T)** | | 0.5273 | |
| **Time (t)** | | <0.0001 | |
| **T x t** | | 0.4203 | |

*Lower case letters indicate significant difference between tillage means over time ($P<0.05$). NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-21. Spearville whole soil N mass by depth, tillage, and time.**

| Treatments | Pre-Tillage | 12 MAT |
|---|---|---|
| **0-5 cm** | | |
| | Mg N ha$^{-1}$ | |
| **NT** | 0.57 | 0.65 |
| **DP** | 0.57 | 0.61 |
| **SwP** | 0.57 | 0.61 |
| **CP** | 0.57 | 0.67 |
| **Time (mean)** | 0.57 a* | 0.63 b |
| | ***P* values** | |
| **Tillage (T)** | | 0.8487 |
| **Time (t)** | | 0.0241 |
| **T x t** | | 0.8487 |
| **5-15 cm** | | |
| | Mg N ha$^{-1}$ | |
| **NT** | 0.99 | 1.09 |
| **DP** | 0.99 | 1.20 |
| **SwP** | 0.99 | 1.06 |
| **CP** | 0.99 | 1.23 |
| **Time (mean)** | 0.99 a | 1.14 b |
| | ***P* values** | |
| **Tillage (T)** | | 0.1919 |
| **Time (t)** | | <0.0001 |
| **T x t** | | 0.1919 |
| **15-30 cm** | | |
| | Mg N ha$^{-1}$ | |
| **NT** | 1.28 | 1.35 |
| **DP** | 1.28 | 1.57 |
| **SwP** | 1.28 | 1.54 |
| **CP** | 1.28 | 1.51 |
| **Time (mean)** | 1.28 a | 1.49 b |
| | ***P* values** | |
| **Tillage (T)** | | 0.2413 |
| **Time (t)** | | <0.0001 |
| **T x t** | | 0.1858 |

*Lower case letters indicate significant difference between tillage means over time ($P<0.05$). NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-22. Tribune whole soil N mass by depth, tillage, and time.**

| | 0-5 cm | |
|---|---|---|
| **Treatments** | **Pre-Tillage** | **12 MAT** |
| | | Mg N ha$^{-1}$ |
| **NT** | 0.86 | 0.89 |
| **DP** | 0.86 | 0.95 |
| **SwP** | 0.86 | 0.89 |
| **CP** | 0.86 | 0.90 |
| | | ***P* values** |
| **Tillage (T)** | | 0.9865 |
| **Time (t)** | | 0.4096 |
| **T x t** | | 0.9865 |

| | 5-15 cm | |
|---|---|---|
| **Treatments** | **Pre-Tillage** | **12 MAT** |
| | | Mg N ha$^{-1}$ |
| **NT** | 1.62 | 1.73 |
| **DP** | 1.62 | 1.53 |
| **SwP** | 1.62 | 1.53 |
| **CP** | 1.62 | 1.34 |
| | | ***P* values** |
| **Tillage (T)** | | 0.1543 |
| **Time (t)** | | 0.1433 |
| **T x t** | | 0.1543 |

| | 15-30 cm | |
|---|---|---|
| **Treatments** | **Pre-Tillage** | **12 MAT** |
| | | Mg N ha$^{-1}$ |
| **NT** | 1.94 | 1.86 |
| **DP** | 1.94 | 1.78 |
| **SwP** | 1.94 | 1.99 |
| **CP** | 1.94 | 1.66 |
| | | ***P* values** |
| **Tillage (T)** | | 0.5865 |
| **Time (t)** | | 0.1591 |
| **T x t** | | 0.5865 |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-23. Change in aggregate weight over time by tillage and depth for Wallace.**

**250 – 1000 μm aggregates**

| Depth (cm) | NT 9 MAT | NT 12 MAT | DP 9 MAT | DP 12 MAT | SwP 9 MAT | SwP 12 MAT | CP 9 MAT | CP 12 MAT |
|---|---|---|---|---|---|---|---|---|
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 20.9 | 13.0 | 22.7 | 19.5 | 26.6 | 17.1 | 20.7 | 12.8 |
| **5-15** | 10.6 | 12.9 | 11.3 | 12.0 | 15.0 | 15.3 | 14.4 | 9.4 |
| **15-30** | 13.4 | 12.6 | 18.3 | 17.4 | 14.5 | 18.2 | 15.6 | 21.7 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.0890 | **T x D** | 0.3259 |
| **Depth (D)** | <0.0001 | **T x t** | 0.9704 |
| **Time (t)** | 0.0682 | **D x t** | 0.0019 |
| **T x D x t** | 0.3175 | | |

**53 - 250 μm aggregates**

| Depth (cm) | NT 9 MAT | NT 12 MAT | DP 9 MAT | DP 12 MAT | SwP 9 MAT | SwP 12 MAT | CP 9 MAT | CP 12 MAT |
|---|---|---|---|---|---|---|---|---|
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 64.8 | 60.6 | 63.0 | 55.9 | 60.9 | 58.5 | 65.3 | 63.1 |
| **5-15** | 71.7 | 63.7 | 71.5 | 62.1 | 69.4 | 62.6 | 71.4 | 63.9 |
| **15-30** | 66.7 | 57.8 | 61.9 | 57.0 | 66.2 | 57.5 | 64.7 | 52.3 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.5264 | **T x D** | 0.5797 |
| **Depth (D)** | <0.0001 | **T x t** | 0.9765 |
| **Time (t)** | <0.0001 | **D x t** | 0.2540 |
| **T x D x t** | 0.2540 | | |

**Table 3-23. Continued.**

| | 20 - 53 μm aggregates | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | NT | | DP | | SwP | | CP | |
| Depth (cm) | 9 MAT | 12 MAT | 9 MAT | 12 MAT | 9 MAT | 12 MAT | 9 MAT | 12 MAT |
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 6.7 | 10.6 | 7.4 | 13.0 | 5.6 | 11.4 | 6.4 | 12.2 |
| **5-15** | 9.2 | 12.6 | 7.7 | 15.3 | 6.6 | 10.3 | 6.5 | 12.9 |
| **15-30** | 9.2 | 13.6 | 6.6 | 14.5 | 9.0 | 13.0 | 7.7 | 13.7 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.4305 | **T x D** | 0.4349 |
| **Depth (D)** | 0.0238 | **T x t** | 0.1606 |
| **Time (t)** | <0.0001 | **D x t** | 0.9712 |
| **T x D x t** | 0.9290 | | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-24. Means of 250-1000 μm sized aggregates for Wallace.**

| Depth | Time | |
|---|---|---|
| cm | 9 MAT | 12 MAT |
| | g aggregate 100 $g^{-1}$ soil | |
| **0-5** | 22.7 aA* | 15.6 abB |
| **5-15** | 12.9 bA | 12.4 aA |
| **15-30** | 15.5 bA | 17.5 bA |

*Lower case letters within a column indicate significant difference (*P*<0.05) between depths for each time. Upper case letters across a row indicate significant difference (*P*<0.05) over time for each depth. MAT = months after tillage.

**Table 3-25. Means of 53-250 μm sized aggregates for Wallace**

| Depth | |
|---|---|
| cm | g aggregate 100 $g^{-1}$ soil |
| **0-5** | 61.5 a* |
| **5-15** | 67.5 b |
| **15-30** | 60.4 a |
| **Time** | |
| **9 MAT** | 66.5 a |
| **12 MAT** | 59.5 b |

*Letters indicate significant difference (*P*<0.05) within each set of means. MAT = months after tillage.

**Table 3-26. Means of 20-53 μm sized aggregates for Wallace**

| Depth | |
|---|---|
| cm | g aggregate 100 $g^{-1}$ soil |
| **0-5** | 9.2 a* |
| **5-15** | 10.1 ab |
| **15-30** | 10.9 b |
| **Time** | |
| **9 MAT** | 7.4 a |
| **12 MAT** | 12.8 b |

*Letters indicate significant difference (*P*<0.05) within each set of means. MAT = months after tillage.

**Table 3-27. Change in aggregate weight over time by tillage and depth for Spearville.**

**250 – 1000 μm aggregates**

| Depth (cm) | NT 9 MAT | NT 12 MAT | DP 9 MAT | DP 12 MAT | SwP 9 MAT | SwP 12 MAT | CP 9 MAT | CP 12 MAT |
|---|---|---|---|---|---|---|---|---|
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 30.5 | 23.4 | 25.9 | 25.1 | 31.4 | 26.8 | 29.9 | 22.7 |
| **5-15** | 24.3 | 20.5 | 25.6 | 20.0 | 30.8 | 21.1 | 25.7 | 18.0 |
| **15-30** | 29.8 | 17.5 | 27.0 | 19.2 | 29.5 | 17.8 | 28.9 | 18.0 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.7545 | **T x D** | 0.8341 |
| **Depth (D)** | 0.0017 | **T x t** | 0.2114 |
| **Time (t)** | <0.0001 | **D x t** | 0.0093 |
| **T x D x t** | 0.6260 | | |

**53 - 250 μm aggregates**

| Depth (cm) | NT 9 MAT | NT 12 MAT | DP 9 MAT | DP 12 MAT | SwP 9 MAT | SwP 12 MAT | CP 9 MAT | CP 12 MAT |
|---|---|---|---|---|---|---|---|---|
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 50.8 | 42.0 | 54.2 | 42.9 | 49.9 | 41.1 | 52.0 | 46.1 |
| **5-15** | 52.8 | 50.1 | 54.5 | 47.0 | 52.7 | 45.5 | 53.3 | 49.9 |
| **15-30** | 53.5 | 53.2 | 52.3 | 46.6 | 52.5 | 50.8 | 52.8 | 53.0 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.8807 | **T x D** | 0.4914 |
| **Depth (D)** | 0.0006 | **T x t** | 0.2701 |
| **Time (t)** | <0.0001 | **D x t** | 0.0243 |
| **T x D x t** | 0.9935 | | |

**Table 3-27. Continued.**

| | 20 - 53 µm aggregates | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | NT | | DP | | SwP | | CP | |
| Depth (cm) | 9 MAT | 12 MAT | 9 MAT | 12 MAT | 9 MAT | 12 MAT | 9 MAT | 12 MAT |
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 6.1 | 12.1 | 6.2 | 10.6 | 6.1 | 9.5 | 6.3 | 10.6 |
| **5-15** | 7.8 | 10.6 | 7.4 | 12.4 | 5.4 | 11.7 | 7.8 | 11.1 |
| **15-30** | 6.0 | 9.8 | 8.1 | 14.1 | 5.5 | 10.4 | 6.6 | 9.3 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.1389 | **T x D** | 0.1348 |
| **Depth (D)** | 0.2245 | **T x t** | 0.3532 |
| **Time (t)** | <0.0001 | **D x t** | 0.9905 |
| **T x D x t** | 0.3212 | | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-28. Means of 250-1000 μm sized aggregates for Spearville.**

| Depth | Time | |
|---|---|---|
| cm | 9 MAT | 12 MAT |
| | g aggregate 100 $g^{-1}$ soil | |
| **0-5** | 29.4 aA* | 24.5 aB |
| **5-15** | 26.6 bA | 19.9 bB |
| **15-30** | 28.8 abA | 18.1 bB |

*Lower case letters within a column indicate significant difference (*P*<0.05) between depths for each time. Upper case letters across a row indicate significant difference (*P*<0.05) over time for each depth. MAT = months after tillage.

**Table 3-29. Means of 53-250 μm sized aggregates for Spearville.**

| Depth | Time | |
|---|---|---|
| cm | 9 MAT | 12 MAT |
| | g aggregate 100 $g^{-1}$ soil | |
| **0-5** | 51.7 aA* | 43.0 aB |
| **5-15** | 53.3 aA | 48.1 bB |
| **15-30** | 52.8 aA | 50.9 bA |

*Lower case letters within a column indicate significant difference (*P*<0.05) between depths for each time. Upper case letters across a row indicate significant difference (*P*<0.05) over time for each depth. MAT = months after tillage.

**Table 3-30. Means of 20-53 μm sized aggregates for Spearville.**

| Time | |
|---|---|
| **9 MAT** | 7.4 a* |
| **12 MAT** | 12.8 b |

*Letters indicate significant difference (*P*<0.05). MAT = months after tillage.

**Table 3-31. Change in aggregate weight over time by tillage and depth for Tribune.**

**250 – 1000 µm aggregates**

| | **NT** | | **DP** | | **SwP** | | **CP** | |
|---|---|---|---|---|---|---|---|---|
| **Depth (cm)** | **9 MAT** | **12 MAT** | **9 MAT** | **12 MAT** | **9 MAT** | **12 MAT** | **9 MAT** | **12 MAT** |
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 11.9 | 20.5 | 17.5 | 15.1 | 11.8 | 15.0 | 12.3 | 16.2 |
| **5-15** | 11.5 | 15.9 | 16.1 | 15.6 | 13.4 | 17.4 | 11.7 | 12.2 |
| **15-30** | 21.3 | 28.5 | 21.1 | 25.4 | 21.9 | 24.9 | 21.3 | 34.1 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.9478 | **T x D** | 0.5475 |
| **Depth (D)** | <0.0001 | **T x t** | 0.3249 |
| **Time (t)** | 0.0031 | **D x t** | 0.3110 |
| **T x D x t** | 0.7674 | | |

**53 - 250 µm aggregates**

| | **NT** | | **DP** | | **SwP** | | **CP** | |
|---|---|---|---|---|---|---|---|---|
| **Depth (cm)** | **9 MAT** | **12 MAT** | **9 MAT** | **12 MAT** | **9 MAT** | **12 MAT** | **9 MAT** | **12 MAT** |
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 63.7 | 46.4 | 66.1 | 49.5 | 64.8 | 46.6 | 63.9 | 43.8 |
| **5-15** | 65.2 | 57.8 | 65.6 | 46.8 | 64.4 | 52.7 | 69.2 | 53.6 |
| **15-30** | 59.9 | 37.8 | 62.0 | 40.5 | 57.9 | 42.9 | 57.6 | 30.0 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.6880 | **T x D** | 0.2282 |
| **Depth (D)** | <0.0001 | **T x t** | 0.4108 |
| **Time (t)** | <0.0001 | **D x t** | 0.0897 |
| **T x D x t** | 0.7730 | | |

**Table 3-31. Continued.**

| | 20 - 53 µm aggregates | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | NT | | DP | | SwP | | CP | |
| Depth (cm) | 9 MAT | 12 MAT | 9 MAT | 12 MAT | 9 MAT | 12 MAT | 9 MAT | 12 MAT |
| | g aggregate 100 $g^{-1}$ soil | | | | | | | |
| **0-5** | 11.3 | 15.0 | 9.2 | 13.4 | 11.1 | 14.6 | 10.7 | 11.1 |
| **5-15** | 9.3 | 11.9 | 8.3 | 11.3 | 10.3 | 14.8 | 7.4 | 12.3 |
| **15-30** | 7.1 | 13.2 | 5.4 | 12.7 | 7.2 | 9.3 | 7.1 | 8.2 |

***P* values**

| | | | |
|---|---|---|---|
| **Tillage (T)** | 0.1982 | **T x D** | 0.6453 |
| **Depth (D)** | 0.0011 | **T x t** | 0.3991 |
| **Time (t)** | <0.0001 | **D x t** | 0.6853 |
| **T x D x t** | 0.3442 | | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow, MAT = Months After Tillage.

**Table 3-32. Means of 53-250 μm sized aggregates for Tribune.**

| Depth | |
|---|---|
| **cm** | g aggregate 100 $g^{-1}$ soil |
| **0-5** | 15.0 a* |
| **5-15** | 14.2 a |
| **15-30** | 24.8 b |
| **Time** | |
| **9 MAT** | 16.0 a |
| **12 MAT** | 20.0 b |

*Letters indicate significant difference ($P$<0.05) within each set of means. MAT = months after tillage.

**Table 3-33. Means of 20-53 μm sized aggregates for Tribune.**

| Depth | |
|---|---|
| **cm** | g aggregate 100 $g^{-1}$ soil |
| **0-5** | 55.6 a* |
| **5-15** | 59.4 b |
| **15-30** | 48.6 c |
| **Time** | |
| **9 MAT** | 63.4 a |
| **12 MAT** | 45.7 b |

*Letters indicate significant difference ($P$<0.05) within each set of means. MAT = months after tillage.

**Table 3-34. Means of 20-53 μm sized aggregates for Tribune.**

| Depth | |
|---|---|
| **cm** | g aggregate 100 $g^{-1}$ soil |
| **0-5** | 12.0 a* |
| **5-15** | 10.7 a |
| **15-30** | 8.8 b |
| **Time** | |
| **9 MAT** | 8.7 a |
| **12 MAT** | 12.3 b |

*Letters indicate significant difference ($P$<0.05) within each set of means. MAT = months after tillage.

**Table 3-35. Aggregate-associated C concentration for Wallace, 12 months after tillage.**

| 250 – 1000 μm aggregates | | | |
|---|---|---|---|
| | Depth (cm) | | |
| **Treatments** | **0-5** | **5-15** | **15-30** |
| | | g C kg$^{-1}$ soil | |
| **NT** | 20.2 | 15.9 | 9.8 |
| **DP** | 19.1 | 17.0 | 10.0 |
| **SwP** | 21.1 | 16.0 | 10.7 |
| **CP** | 19.5 | 15.6 | 10.2 |
| **53-250 μm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | | g C kg$^{-1}$ soil | |
| **NT** | 13.5 | 9.5 | 7.5 |
| **DP** | 10.7 | 11.4 | 7.5 |
| **SwP** | 13.5 | 10.3 | 8.3 |
| **CP** | 11.6 | 9.3 | 7.3 |
| **20-53 μm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | | g C kg$^{-1}$ soil | |
| **NT** | 8.5 | 7.3 | 6.3 |
| **DP** | 9.5 | 8.4 | 6.4 |
| **SwP** | 9.3 | 8.1 | 6.5 |
| **CP** | 8.7 | 7.7 | 6.7 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.2594 | |
| **Depth (D)** | | <0.0001 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.7574 | |
| **T x D** | | 0.1101 | |
| **A x D** | | <0.0001 | |
| **T x A x D** | | 0.7749 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-36. Means of aggregate-associated C concentration for Wallace by aggregate and depth.**

| **Aggregate Size** | **Depth (cm)** | | |
|---|---|---|---|
| | **0-5** | **5-15** | **15-30** |
| μm | | $g\ C\ kg^{-1}$ soil | |
| **250-1000** | 20.0 aA* | 16.1 aB | 10.2 aC |
| **53-250** | 12.3 bA | 10.1 bB | 7.7 bC |
| **20-53** | 9.0 cA | 7.9 cB | 6.5 cC |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-37. Aggregate-associated C concentration for Spearville, 12 months after tillage.**

| Treatments | 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| | **250 – 1000 µm aggregates** | | |
| | **Depth (cm)** | | |
| | g C kg$^{-1}$ soil | | |
| **NT** | 5.49 | 3.31 | 2.03 |
| **DP** | 8.73 | 2.59 | 2.14 |
| **SwP** | 8.06 | 2.18 | 2.02 |
| **CP** | 6.73 | 2.07 | 2.06 |
| | **53-250 µm aggregates** | | |
| | **0-5** | **5-15** | **15-30** |
| | g C kg$^{-1}$ soil | | |
| **NT** | 6.70 | 5.61 | 6.53 |
| **DP** | 8.02 | 5.87 | 6.71 |
| **SwP** | 7.92 | 5.15 | 7.16 |
| **CP** | 7.91 | 7.05 | 6.76 |
| | **20-53 µm aggregates** | | |
| | **0-5** | **5-15** | **15-30** |
| | g C kg$^{-1}$ soil | | |
| **NT** | 9.64 | 10.84 | 11.68 |
| **DP** | 10.83 | 10.47 | 11.89 |
| **SwP** | 10.15 | 9.18 | 11.59 |
| **CP** | 9.31 | 8.89 | 11.61 |
| | ***P* values** | | |
| **Tillage (T)** | 0.7910 | | |
| **Depth (D)** | <0.0001 | | |
| **Aggregate (A)** | <0.0001 | | |
| **T x A** | 0.5836 | | |
| **T x D** | 0.4299 | | |
| **A x D** | <0.0001 | | |
| **T x A x D** | 0.9626 | | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-38. Means of aggregate-associated C concentration for Spearville by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| μm | g C kg$^{-1}$ soil | | |
| **250-1000** | 7.2 aA | 2.5 aB | 2.1 aB |
| **53-250** | 7.6 aA | 5.9 bB | 6.8 bAB |
| **20-53** | 10.0 bA | 9.9 cA | 11.7 cB |

*Lower case letters indicate significant difference (*P*<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference (*P*<0.05) between depths for a particular aggregate size fraction.

**Table 3-39. Aggregate-associated C concentration for Tribune, 12 months after tillage.**

| Treatments | 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| **250 – 1000 µm aggregates** | | | |
| | **Depth (cm)** | | |
| **Treatments** | **0-5** | **5-15** | **15-30** |
| | g C $kg^{-1}$ soil | | |
| **NT** | 35.3 | 24.7 | 9.9 |
| **DP** | 33.9 | 22.7 | 12.1 |
| **SwP** | 36.4 | 28.7 | 10.9 |
| **CP** | 25.7 | 25.8 | 9.0 |
| **53-250 µm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | g C $kg^{-1}$ soil | | |
| **NT** | 15.2 | 12.0 | 9.3 |
| **DP** | 14.0 | 11.8 | 9.3 |
| **SwP** | 15.8 | 12.8 | 8.7 |
| **CP** | 13.8 | 11.2 | 8.4 |
| **20-53 µm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | g C $kg^{-1}$ soil | | |
| **NT** | 8.8 | 9.1 | 8.4 |
| **DP** | 10.4 | 9.5 | 8.9 |
| **SwP** | 9.1 | 9.4 | 7.3 |
| **CP** | 9.5 | 8.7 | 7.6 |
| | ***P* values** | | |
| **Tillage (T)** | 0.5510 | | |
| **Depth (D)** | <0.0001 | | |
| **Aggregate (A)** | <0.0001 | | |
| **T x A** | 0.8658 | | |
| **T x D** | 0.9126 | | |
| **A x D** | <0.0001 | | |
| **T x A x D** | 0.9872 | | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-40. Means of aggregate-associated C concentration for Tribune by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| μm | | g C $kg^{-1}$ soil | |
| **250-1000** | 31.2 aA | 25.5 aB | 10.5 aC |
| **53-250** | 14.7 bA | 11.9 bAB | 8.9 aB |
| **20-53** | 9.4 cA | 9.2 bA | 8.0 aA |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-41. Sand-free aggregate-associated C mass for Wallace, 12 months after tillage.**

| Treatments | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| **250 – 1000 µm aggregates** | | | |
| | g C sand-free aggregate$^{-1}$ | | |
| **NT** | 0.26 aABx* | 0.21 aABxy | 0.12 aAy |
| **DP** | 0.36 aBx | 0.21 aABy | 0.16 aAy |
| **SwP** | 0.36 aBx | 0.25 aAy | 0.19 aAy |
| **CP** | 0.25 aAx | 0.14 aBy | 0.21 aAxy |
| **53-250 µm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | g C sand-free aggregate$^{-1}$ | | |
| **NT** | 0.80 bAx | 0.61 bAy | 0.43 bAz |
| **DP** | 0.60 bBx | 0.71 bBy | 0.44 bAz |
| **SwP** | 0.79 bAx | 0.63 bABy | 0.48 bAz |
| **CP** | 0.73 bAx | 0.60 bAy | 0.39 bAz |
| **20-53 µm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | g C sand-free aggregate$^{-1}$ | | |
| **NT** | 0.09 cAx | 0.09 cAx | 0.09 aAx |
| **DP** | 0.12 cAx | 0.13 aAx | 0.09 aAx |
| **SwP** | 0.10 cAx | 0.08 cAx | 0.08 aAx |
| **CP** | 0.11 cAx | 0.10 cAx | 0.09 aAx |
| | | ***P* values** | |
| **Tillage (T)** | | 0.1083 | |
| **Depth (D)** | | <0.0001 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.2565 | |
| **T x D** | | 0.4207 | |
| **A x D** | | <0.0001 | |
| **T x A x D** | | 0.0228 | |

*Lower case letters a, b, and c indicate significant difference (*P*<0.05) between aggregate size fraction for the particular depth and tillage. Lower case letters x, y, and z indicate significant difference (*P*<0.05) between depths for the particular tillage and aggregate size fraction. Upper case letters within a column indicate significant difference (*P*<0.05) between tillage for the particular aggregate size fraction and depth. NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-42. Means for Wallace sand-free aggregate-associated C mass by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| μm | | g C $kg^{-1}$ soil | |
| **250-1000** | 0.31 aA | 0.20 aB | 0.17 aB |
| **53-250** | 0.73 bA | 0.64 bB | 0.43 bC |
| **20-53** | 0.11 cA | 0.10 cA | 0.09 cA |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-43. Sand-free aggregate-associated C mass for Spearville, 12 months after tillage.**

| 250 – 1000 µm aggregates | | | |
|---|---|---|---|
| **Treatments** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C sand-free aggregate$^{-1}$ | |
| **NT** | 0.12 | 0.07 | 0.03 |
| **DP** | 0.23 | 0.05 | 0.04 |
| **SwP** | 0.21 | 0.05 | 0.03 |
| **CP** | 0.14 | 0.04 | 0.03 |
| **53-250 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C sand-free aggregate$^{-1}$ | |
| **NT** | 0.29 | 0.29 | 0.36 |
| **DP** | 0.35 | 0.28 | 0.32 |
| **SwP** | 0.35 | 0.24 | 0.37 |
| **CP** | 0.37 | 34.5 | 0.37 |
| **20-53 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g C sand-free aggregate$^{-1}$ | |
| **NT** | 0.12 | 0.11 | 0.12 |
| **DP** | 0.11 | 0.13 | 0.17 |
| **SwP** | 0.10 | 0.11 | 0.12 |
| **CP** | 0.10 | 0.10 | 0.11 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.8817 | |
| **Depth (D)** | | 0.0080 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.6889 | |
| **T x D** | | 0.8772 | |
| **A x D** | | 0.0009 | |
| **T x A x D** | | 0.9732 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-44. Means for Spearville sand-free aggregate-associated C mass by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| µm | | g C $kg^{-1}$ soil | |
| **250-1000** | 0.18 aA | 0.05 aB | 0.03 aB |
| **53-250** | 0.34 bA | 0.29 bB | 0.36 bA |
| **20-53** | 0.11 cA | 0.11 cA | 0.13 cA |

*Lower case letters indicate significant difference (*P*<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference (*P*<0.05) between depths for a particular aggregate size fraction.

**Table 3-45. Sand-free aggregate-associated C mass for Tribune, 12 months after tillage.**

| Treatments | 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|---|
| **250 – 1000 µm aggregates** | | | |
| | g C sand-free aggregate$^{-1}$ | | |
| **NT** | 0.56 | 0.37 | 0.28 |
| **DP** | 0.48 | 0.33 | 0.29 |
| **SwP** | 0.54 | 0.40 | 0.25 |
| **CP** | 0.34 | 0.27 | 0.31 |
| **53-250 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | g C sand-free aggregate$^{-1}$ | | |
| **NT** | 0.72 | 0.70 | 0.36 |
| **DP** | 0.68 | 0.55 | 0.36 |
| **SwP** | 0.73 | 0.68 | 0.38 |
| **CP** | 0.61 | 0.60 | 0.25 |
| **20-53 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | g C sand-free aggregate$^{-1}$ | | |
| **NT** | 0.13 | 0.11 | 0.11 |
| **DP** | 0.14 | 0.10 | 0.14 |
| **SwP** | 0.13 | 0.14 | 0.07 |
| **CP** | 0.11 | 0.11 | 0.06 |
| | ***P* values** | | |
| **Tillage (T)** | 0.0995 | | |
| **Depth (D)** | <0.0001 | | |
| **Aggregate (A)** | <0.0001 | | |
| **T x A** | 0.7598 | | |
| **T x D** | 0.5939 | | |
| **A x D** | <0.0001 | | |
| **T x A x D** | 0.8642 | | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-46.** **Means for Tribune sand-free aggregate-associated C mass by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| μm | | g C $kg^{-1}$ soil | |
| **250-1000** | 0.48 aA | 0.34 aB | 0.28 aB |
| **53-250** | 0.68 bA | 0.63 bA | 0.34 bB |
| **20-53** | 0.13 cA | 0.11 cA | 0.09 cA |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-47. Aggregate-associated N concentrations for Wallace, 12 months after tillage.**

| | | | |
|---|---|---|---|
| | **250 – 1000 µm aggregates** | | |
| | | **Depth (cm)** | |
| **Treatments** | **0-5** | **5-15** | **15-30** |
| | | g N $kg^{-1}$ soil | |
| **NT** | 1.96 | 1.70 | 1.16 |
| **DP** | 1.74 | 1.83 | 1.10 |
| **SwP** | 1.96 | 1.63 | 1.14 |
| **CP** | 1.93 | 1.66 | 1.12 |
| | **53-250 µm aggregates** | | |
| | **0-5** | **5-15** | **15-30** |
| | | g N $kg^{-1}$ soil | |
| **NT** | 1.41 | 1.09 | 0.88 |
| **DP** | 1.08 | 1.17 | 0.85 |
| **SwP** | 1.35 | 1.10 | 0.89 |
| **CP** | 1.21 | 1.01 | 0.88 |
| | **20-53 µm aggregates** | | |
| | **0-5** | **5-15** | **15-30** |
| | | g N $kg^{-1}$ soil | |
| **NT** | 1.05 | 0.91 | 0.81 |
| **DP** | 1.06 | 0.99 | 0.80 |
| **SwP** | 1.04 | 1.00 | 0.81 |
| **CP** | 1.03 | 0.93 | 0.83 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.7826 | |
| **Depth (D)** | | <0.0001 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.8013 | |
| **T x D** | | 0.0285 | |
| **A x D** | | 0.0001 | |
| **T x A x D** | | 0.7441 | |

NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.

**Table 3-48. Means of aggregate-associated N concentration for Wallace by tillage and depth.**

| Tillage | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| | | g N kg$^{-1}$ soil | |
| **NT** | 1.47 aA* | 1.23 aB | 0.95 aC |
| **DP** | 1.29 bA | 1.33 aA | 0.91 aB |
| **SwP** | 1.45 aA | 1.24 aB | 0.95 aC |
| **CP** | 1.39 abA | 1.20 aB | 0.94 aC |

*Lower case letters indicate significant difference ($P$<0.05) between tillage for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular tillage.

**Table 3-49. Means of aggregate-associated N concentration for Wallace by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| µm | | g N kg$^{-1}$ soil | |
| **250-1000** | 1.90 aA* | 1.70 aB | 1.13 aC |
| **53-250** | 1.26 bA | 1.10 bB | 0.87 bC |
| **20-53** | 1.04 cA | 0.96 cA | 0.81 bB |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-50. Aggregate-associated N concentrations for Tribune, 12 months after tillage.**

| Treatments | 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| **250 – 1000 µm aggregates** | | | |
| | | **Depth (cm)** | |
| **Treatments** | **0-5** | **5-15** | **15-30** |
| | | g N $kg^{-1}$ soil | |
| **NT** | 2.21 | 1.62 | 0.88 |
| **DP** | 2.00 | 1.52 | 1.06 |
| **SwP** | 2.18 | 1.53 | 1.04 |
| **CP** | 1.91 | 1.45 | 0.87 |
| **53-250 µm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | | g N $kg^{-1}$ soil | |
| **NT** | 1.09 | 0.97 | 0.86 |
| **DP** | 1.05 | 0.93 | 0.95 |
| **SwP** | 1.16 | 1.05 | 0.82 |
| **CP** | 1.02 | 0.91 | 0.84 |
| **20-53 µm aggregates** | | | |
| | **0-5** | **5-15** | **15-30** |
| | | g N $kg^{-1}$ soil | |
| **NT** | 0.91 | 1.02 | 0.90 |
| **DP** | 1.12 | 1.02 | 1.00 |
| **SwP** | 0.91 | 1.00 | 0.92 |
| **CP** | 1.00 | 1.05 | 1.03 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.7238 | |
| **Depth (D)** | | <0.0001 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.6657 | |
| **T x D** | | 0.9244 | |
| **A x D** | | <0.0001 | |
| **T x A x D** | | 0.9913 | |

**NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.**

**Table 3-51.** **Means of aggregate-associated N concentration for Tribune by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| µm | | $g\ N\ kg^{-1}$ soil | |
| **250-1000** | 2.07 aA | 1.53 aB | 0.96 aC |
| **53-250** | 1.08 bA | 0.97 bAB | 0.87 aB |
| **20-53** | 0.98 bA | 1.02 bB | 0.96 aA |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-52. Sand-free aggregate-associated N mass for Wallace, 12 months after tillage.**

| Treatments | 0-5 cm | 5-15 cm | 15-30 cm |
|---|---|---|---|
| **250 – 1000 µm aggregates** | | | |
| | | g N sand-free aggregate$^{-1}$ | |
| **NT** | 0.025 | 0.022 | 0.014 |
| **DP** | 0.033 | 0.021 | 0.018 |
| **SwP** | 0.033 | 0.026 | 0.020 |
| **CP** | 0.025 | 0.015 | 0.023 |
| **53-250 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N sand-free aggregate$^{-1}$ | |
| **NT** | 0.084 | 0.069 | 0.051 |
| **DP** | 0.060 | 0.073 | 0.050 |
| **SwP** | 0.079 | 0.068 | 0.051 |
| **CP** | 0.076 | 0.065 | 0.046 |
| **20-53 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N sand-free aggregate$^{-1}$ | |
| **NT** | 0.011 | 0.012 | 0.011 |
| **DP** | 0.014 | 0.015 | 0.011 |
| **SwP** | 0.011 | 0.010 | 0.011 |
| **CP** | 0.013 | 0.012 | 0.011 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.6197 | |
| **Depth (D)** | | <0.0001 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.1341 | |
| **T x D** | | 0.3977 | |
| **A x D** | | <0.0001 | |
| **T x A x D** | | 0.0798 | |

**NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.**

**Table 3-53. Means of sand-free aggregate-associated N concentration for Wallace by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| μm | | g N kg$^{-1}$ soil | |
| **250-1000** | 0.029 aA | 0.021 aB | 0.019 aB |
| **53-250** | 0.075 bA | 0.069 bA | 0.049 bB |
| **20-53** | 0.012 cA | 0.012 cA | 0.012 cA |

*Lower case letters indicate significant difference ($P$<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference ($P$<0.05) between depths for a particular aggregate size fraction.

**Table 3-54. Sand-free aggregate-associated N mass for Tribune, 12 months after tillage.**

| 250 – 1000 µm aggregates | | | |
|---|---|---|---|
| **Treatments** | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N sand-free aggregate$^{-1}$ | |
| **NT** | 0.036 | 0.025 | 0.025 |
| **DP** | 0.029 | 0.023 | 0.026 |
| **SwP** | 0.033 | 0.024 | 0.024 |
| **CP** | 0.031 | 0.016 | 0.030 |
| **53-250 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N sand-free aggregate$^{-1}$ | |
| **NT** | 0.052 | 0.056 | 0.033 |
| **DP** | 0.052 | 0.044 | 0.037 |
| **SwP** | 0.053 | 0.056 | 0.036 |
| **CP** | 0.045 | 0.049 | 0.025 |
| **20-53 µm aggregates** | | | |
| | **0-5 cm** | **5-15 cm** | **15-30 cm** |
| | | g N sand-free aggregate$^{-1}$ | |
| **NT** | 0.013 | 0.012 | 0.012 |
| **DP** | 0.015 | 0.011 | 0.012 |
| **SwP** | 0.013 | 0.015 | 0.008 |
| **CP** | 0.011 | 0.013 | 0.009 |
| | | ***P* values** | |
| **Tillage (T)** | | 0.2034 | |
| **Depth (D)** | | <0.0001 | |
| **Aggregate (A)** | | <0.0001 | |
| **T x A** | | 0.7129 | |
| **T x D** | | 0.8300 | |
| **A x D** | | <0.0001 | |
| **T x A x D** | | 0.8318 | |

**NT = no-tillage, DP = disk plow, SwP = sweep plow, CP = chisel plow.**

**Table 3-55. Means of sand-free aggregate-associated N mass for Tribune by aggregate and depth.**

| Aggregate Size | Depth (cm) 0-5 | 5-15 | 15-30 |
|---|---|---|---|
| μm | | $g\ N\ kg^{-1}$ soil | |
| **250-1000** | 0.032 aA | 0.022 aB | 0.026 aAB |
| **53-250** | 0.050 bA | 0.051 bA | 0.033 bB |
| **20-53** | 0.013 cA | 0.013 cA | 0.010 cA |

*Lower case letters indicate significant difference (*P*<0.05) between aggregate size fraction for a particular depth. Upper case letters across a row indicate significant difference (*P*<0.05) between depths for a particular aggregate size fraction.

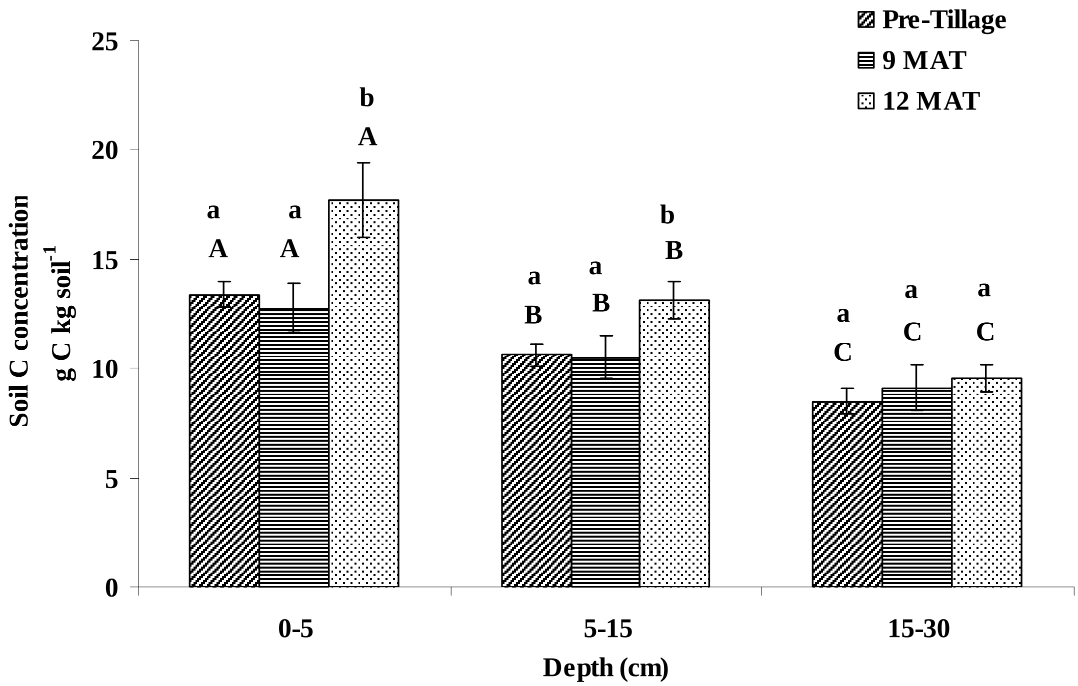



**Figure 3-1. Influence of time on soil C concentration by depth for Wallace.**
Upper case letters are significantly different between depth for each time ($P$<0.05). Lower case letters are significantly different between times for each depth ($P$<0.05).

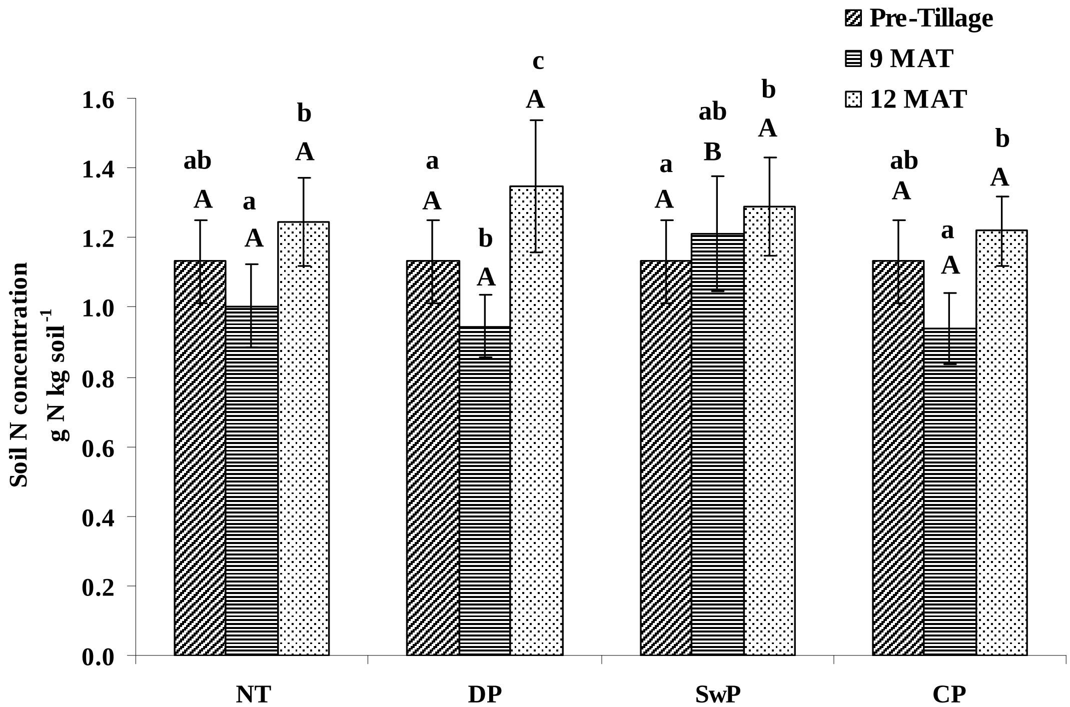



**Figure 3-2**. **Influence of time and tillage on soil N concentration for Wallace.**
Upper case letters are significantly different between tillage for each time ($P$<0.05). Lower case letters are significantly different between times for each depth ($P$<0.05).

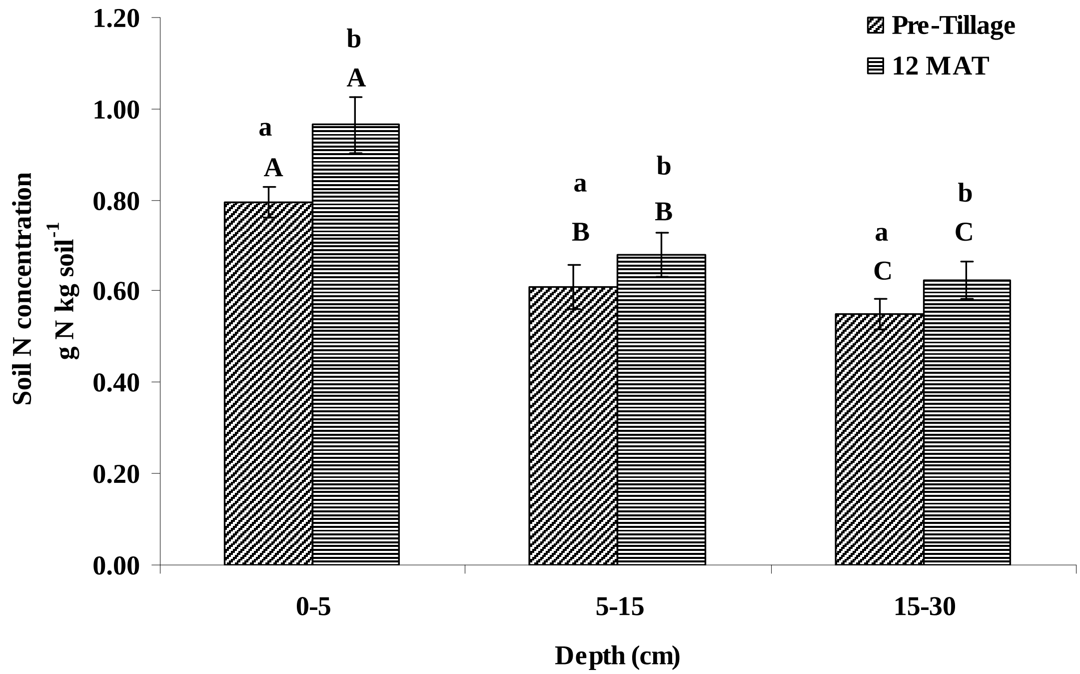



**Figure 3-3. Influence of time on soil N concentration by depth for Spearville.** Upper case letters are significantly different between depth for each time (*P*<0.05). Lower case letters are significantly different between times for each depth (*P*<0.05).

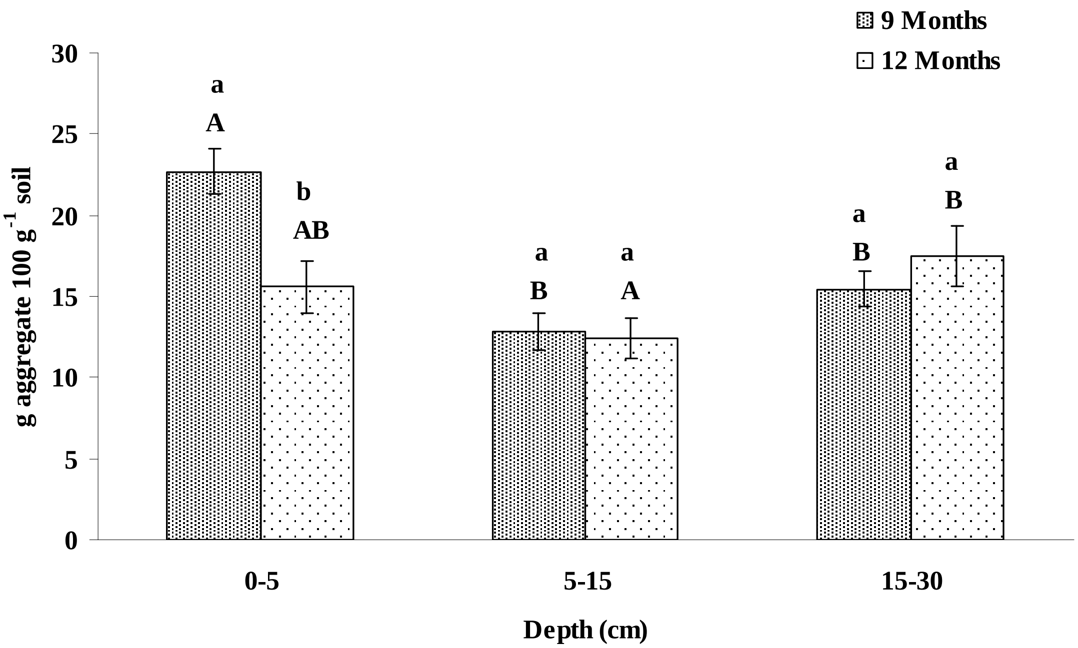



**Figure 3-4. Means of depth and time and their influence on 250-1000 µm sized aggregates for Wallace.**
Upper case letters within time after tillage are significantly different between depths ($P$<0.05). Lower case letters within a depth are significantly different between time after tillage ($P$<0.05).

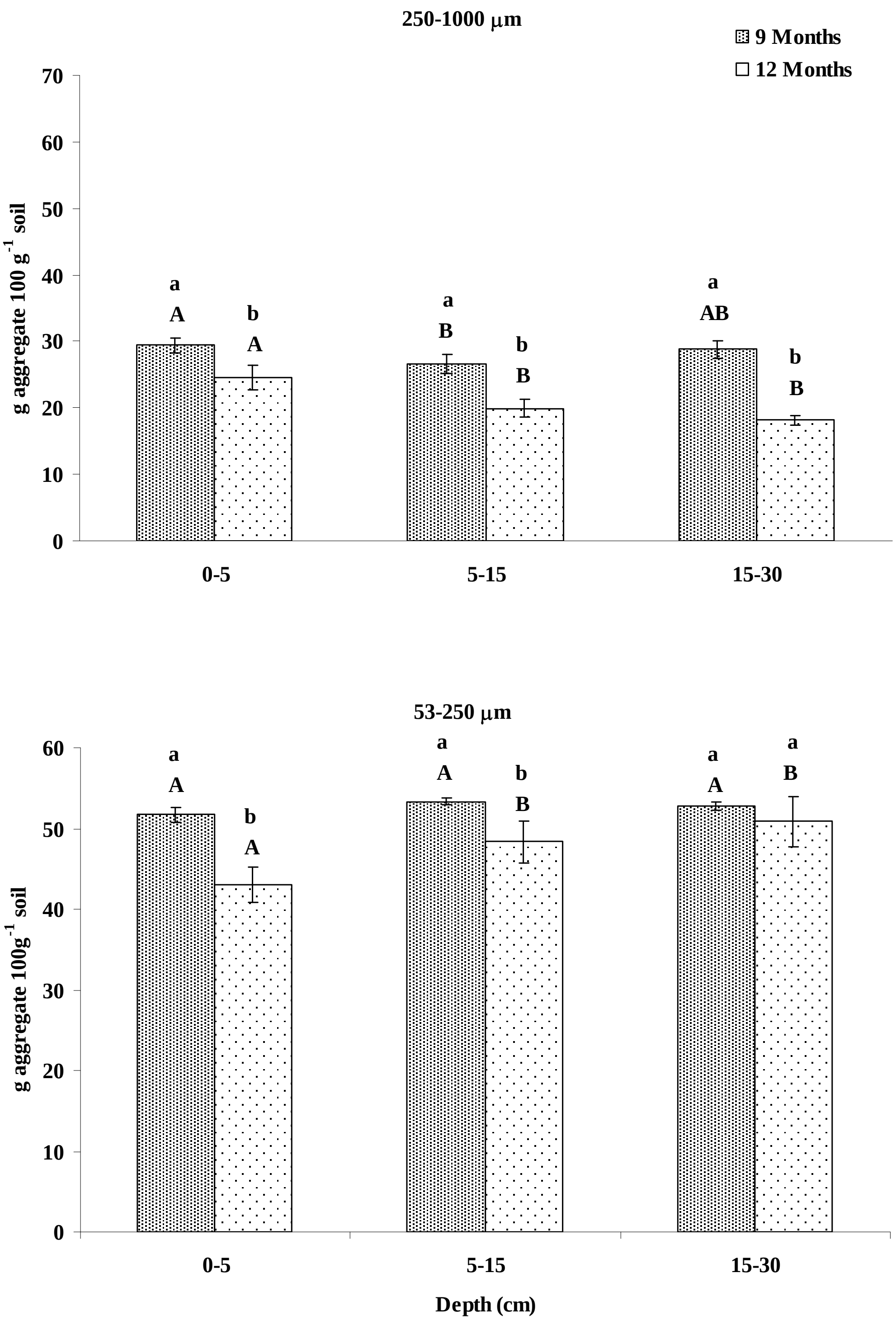



**Figure 3-5. Means of depth and time and their influence on 250-1000 μm and 53-20 μm sized aggregates for Spearville**.
Upper case letters within time after tillage are significantly different between depths (*P*<0.05). Lower case letters within a depth are significantly different between time after tillage (*P*<0.05).

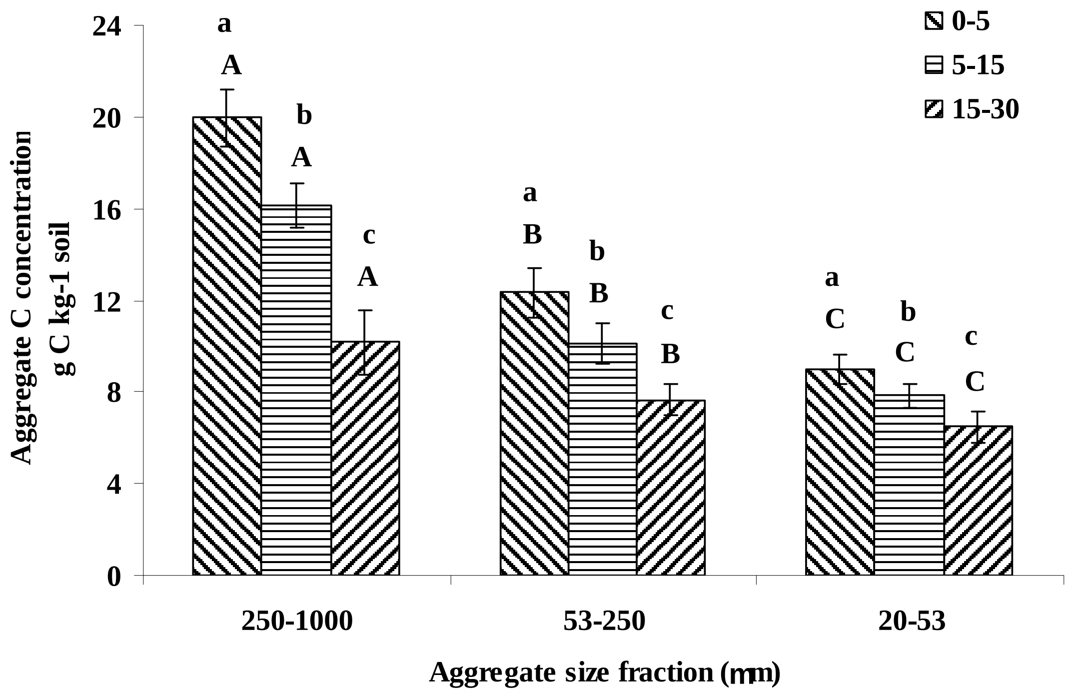



**Figure 3-6. Influence of aggregate size fraction and depth on aggregate-associated C for Wallace, 12 months after tillage.**
Upper case letters are significantly different between aggregate size fractions for each depth ($P$<0.05). Lower case letters are significantly different between depths for each aggregate size fraction ($P$<0.05).

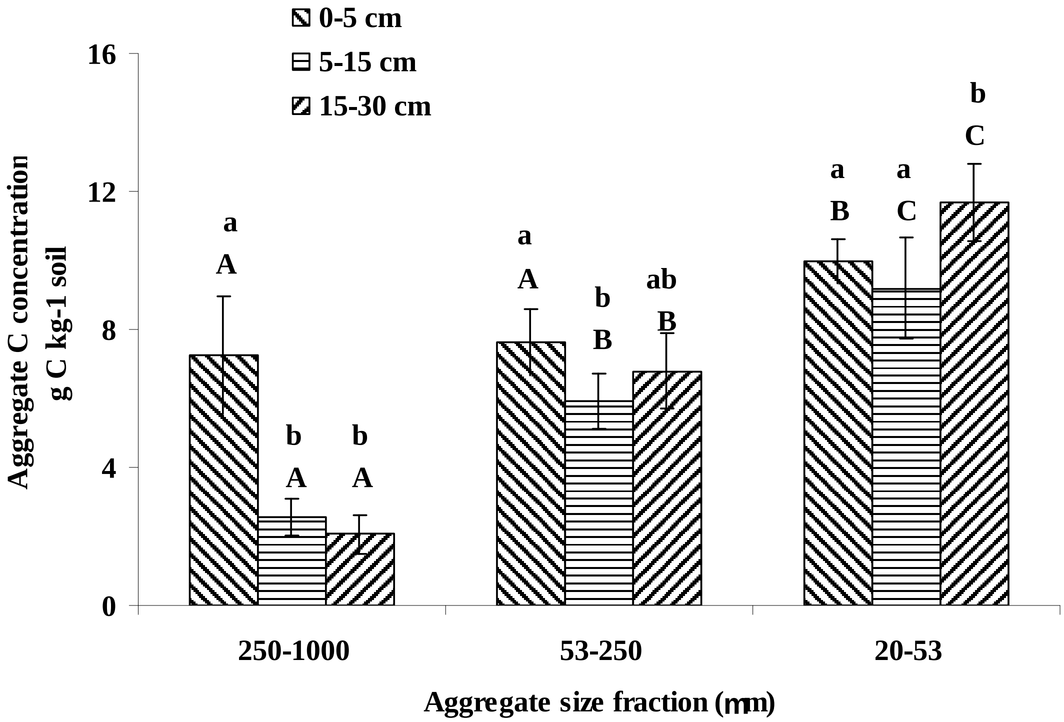



**Figure 3-7. Influence of aggregate size fraction and depth on aggregate-associated C concentration for Spearville, 12 months after tillage.**
Upper case letters are significantly different between aggregate size fractions for each depth (*P*<0.05). Lower case letters are significantly different between depths for each aggregate size fraction (*P*<0.05).

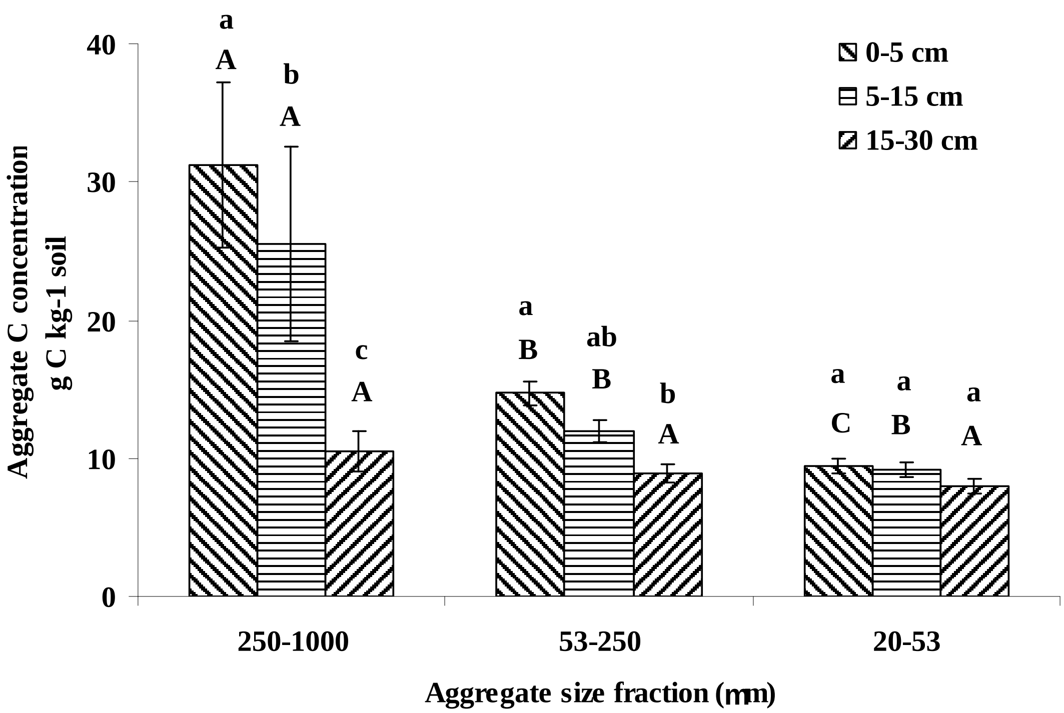



**Figure 3-8. Influence of aggregate size fraction and depth on aggregate-associated C concentration for Tribune, 12 months after tillage.**

Upper case letters are significantly different between aggregate size fractions for each depth ($P$<0.05). Lower case letters are significantly different between depths for each aggregate size fraction ($P$<0.05).

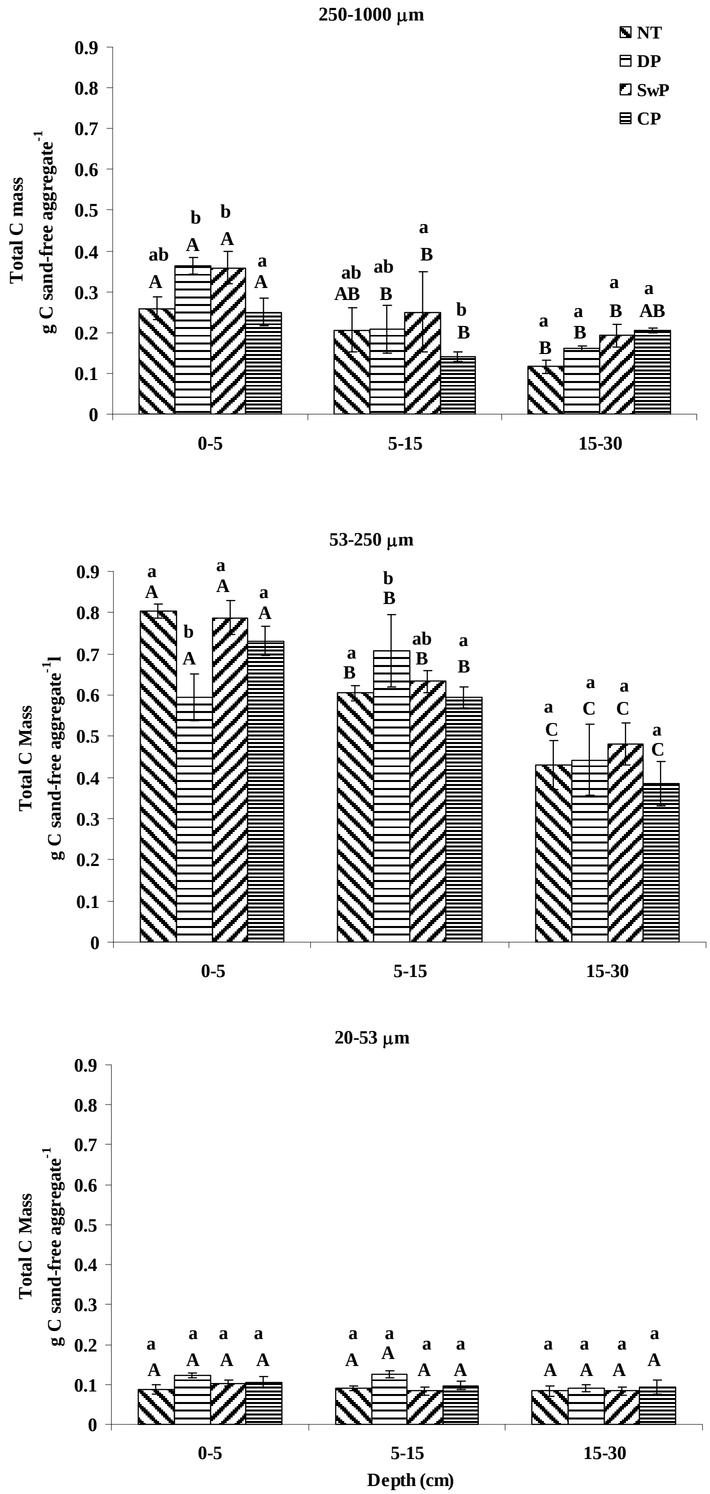



**Figure 3-9. Influences of tillage and depth on aggregate-associated C mass for Wallace, twelve months after tillage.**

NT = no tillage; DP = disk plow; SwP = sweep plow; CP = chisel plow. Values followed by a different lowercase letter within an aggregate size fraction and depth and among tillage treatments are significantly different (P<0.05). Values followed by a different uppercase letter within an aggregate size fraction and tillage treatment are significantly different between depths ($P$<0.05).

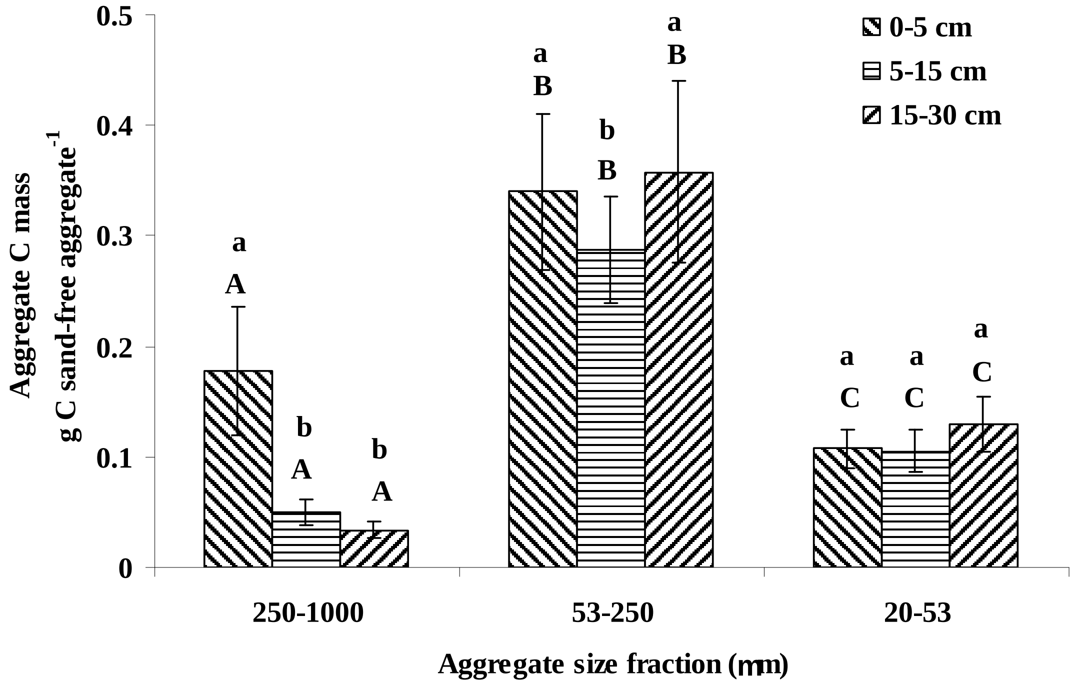



**Figure 3-10. Influence of aggregate size fraction and depth on aggregate-associated C mass for Spearville, 12 months after tillage.**

Upper case letters are significantly different between aggregate size fractions for each depth (*P*<0.05). Lower case letters are significantly different between depths for each aggregate size fraction (*P*<0.05).

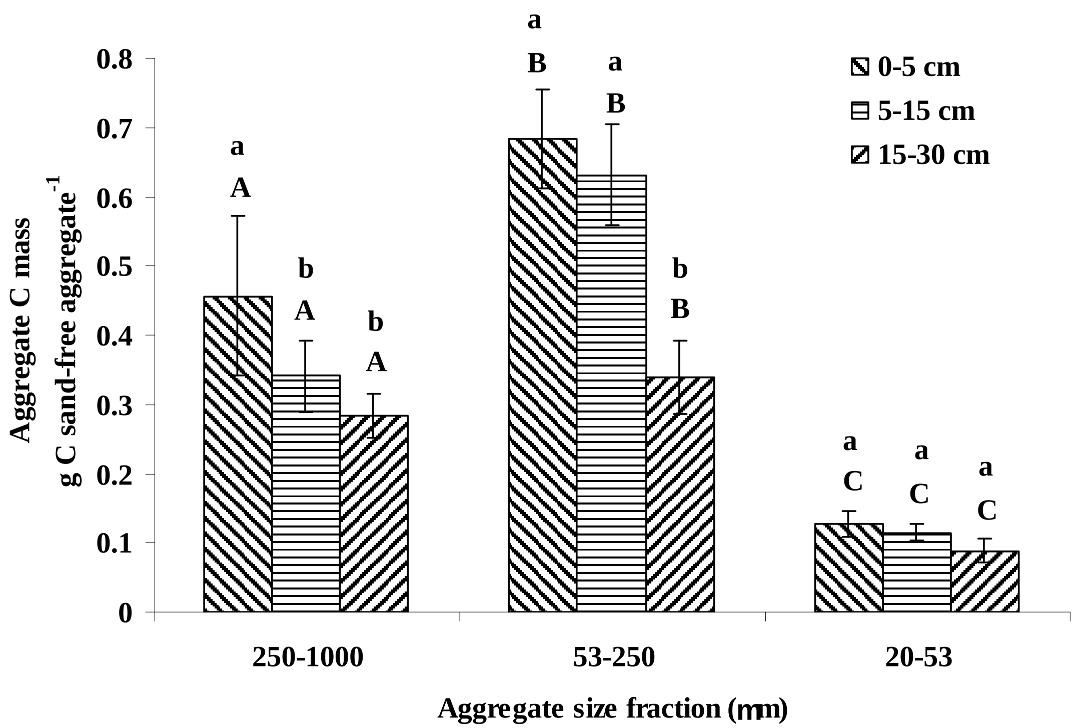



**Figure 3-11. Influence of aggregate size fraction and depth on aggregate-associated C mass for Tribune, 12 months after tillage.**

Upper case letters are significantly different between aggregate size fractions for each depth ($P$<0.05). Lower case letters are significantly different between depths for each aggregate size fraction ($P$<0.05).

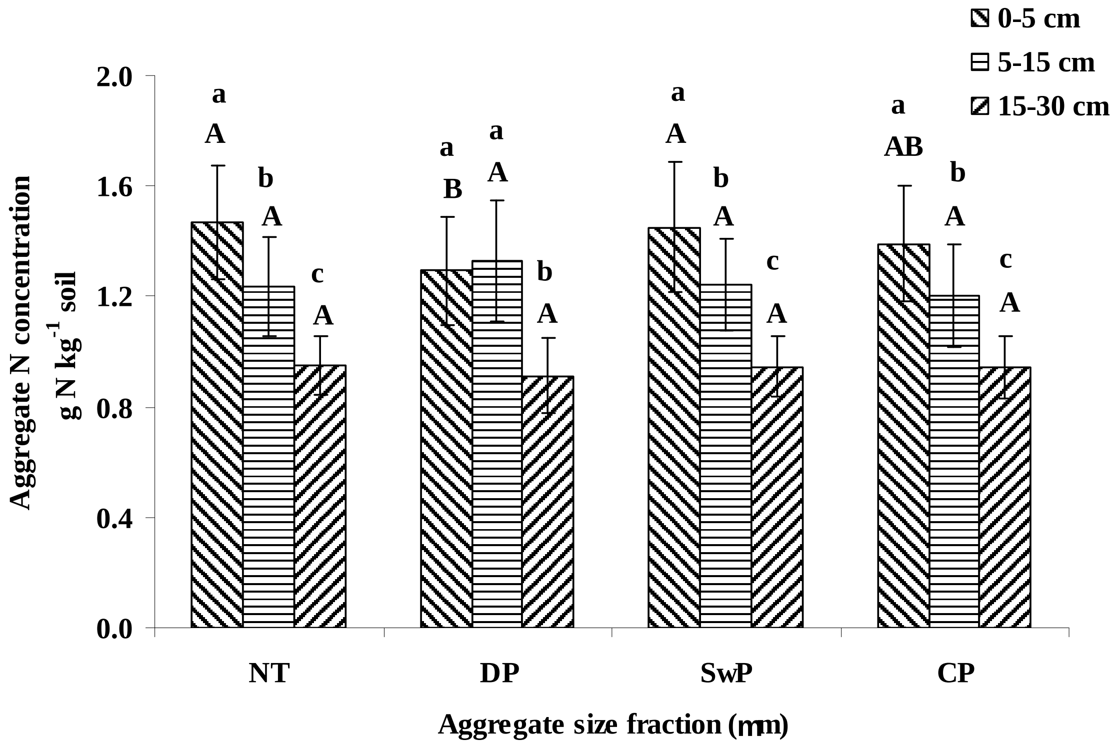



**Figure 3-12. Influence of tillage and depth on aggregate-associated N for Wallace, 12 months after tillage.**

Upper case letters are significantly different between tillages for each depth ($P$<0.05). Lower case letters are significantly different between depths for each tillage ($P$<0.05).

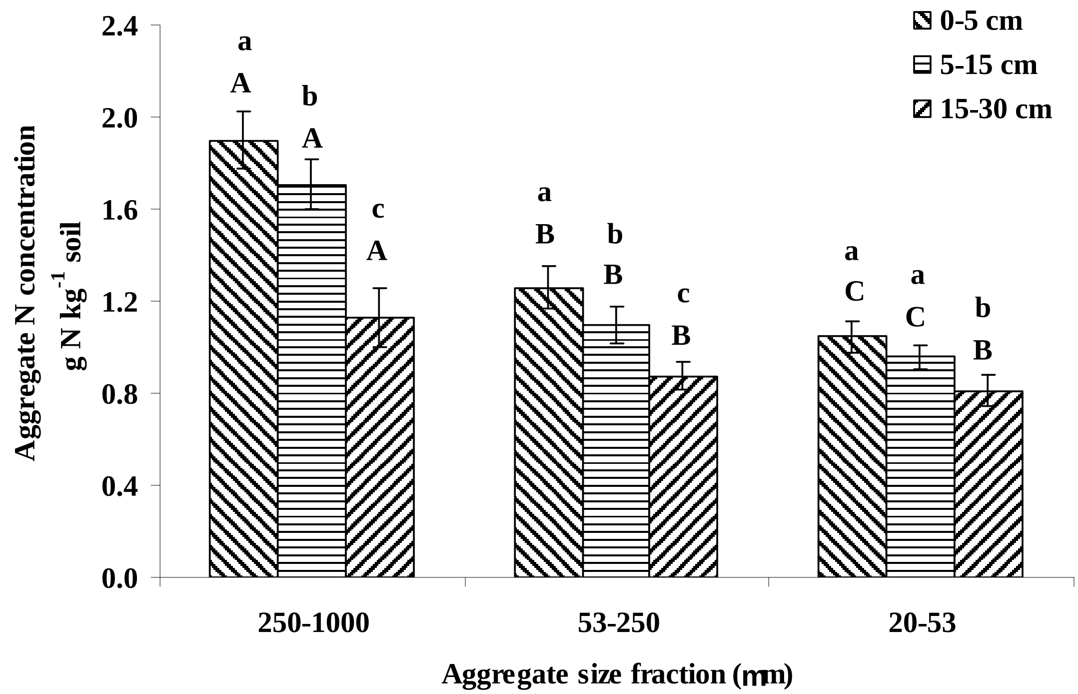



**Figure 3-13. Influence of aggregate size fraction and depth on aggregate-associated N for Wallace, 12 months after tillage.**

Upper case letters are significantly different between aggregate size fractions for each depth ($P$<0.05). Lower case letters are significantly different between depths for each aggregate size fraction ($P$<0.05).

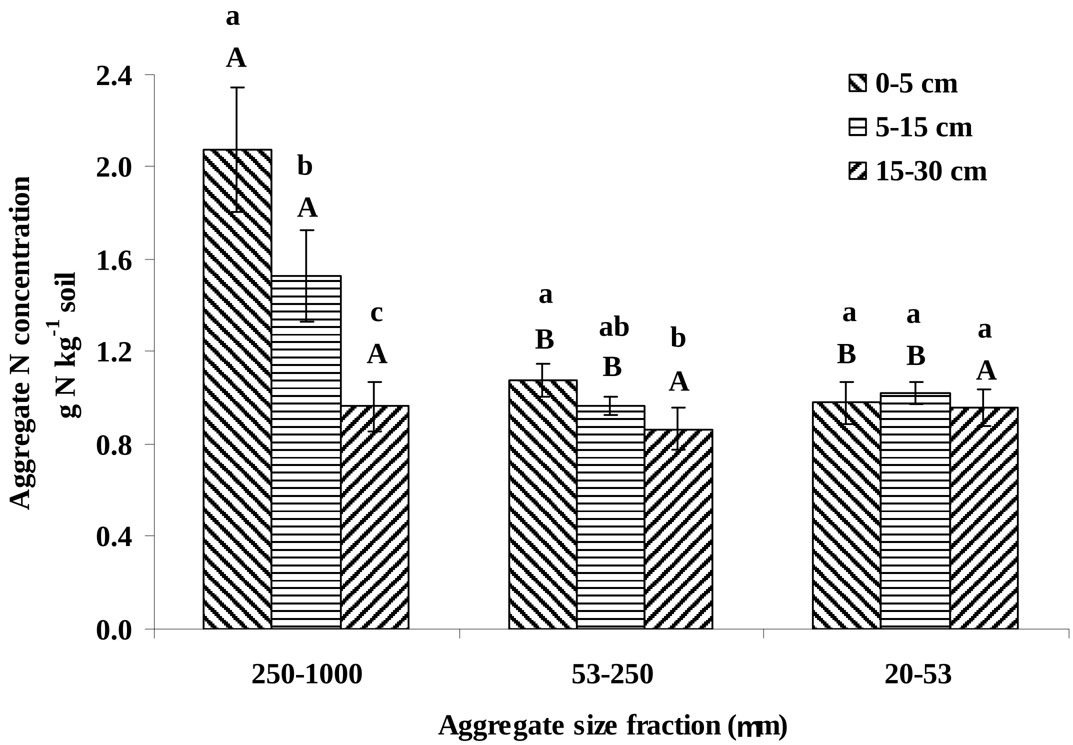



**Figure 3-14. Influence of aggregate size fraction and depth on aggregate-associated N for Tribune, 12 months after tillage.**
Upper case letters are significantly different between aggregate size fractions for each depth ($P$<0.05). Lower case letters are significantly different between depths for each aggregate size fraction ($P$<0.05).

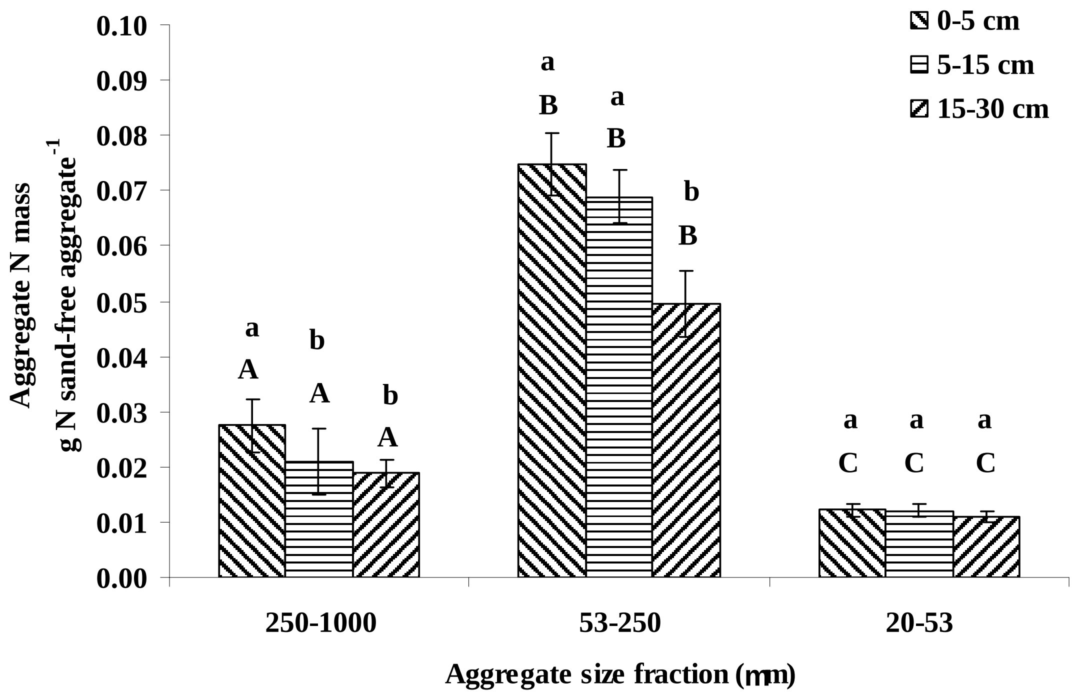



**Figure 3-15. Influence of aggregate size fraction and depth on aggregate-associated N mass for Wallace, 12 months after tillage.**

Upper case letters are significantly different between aggregate size fractions for each depth ($P$<0.05). Lower case letters are significantly different between depths for each aggregate size fraction ($P$<0.05).

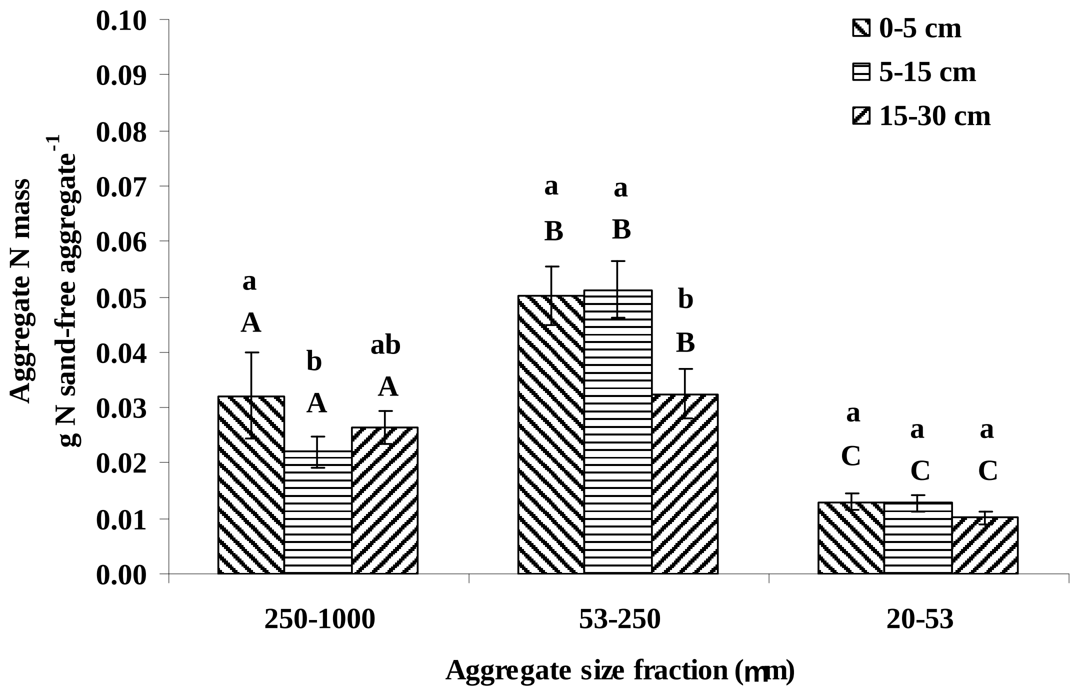



**Figure 3-16. Influence of aggregate size fraction and depth on aggregate-associated N mass for Tribune, 12 months after tillage.**

Upper case letters are significantly different between aggregate size fractions for each depth (*P*<0.05). Lower case letters are significantly different between depths for each aggregate size fraction (*P*<0.05).

# CHAPTER 4 - Discussion

## Bulk Density

A single tillage operation of a previously long-term NT field did not a significantly alter bulk density at any location 8 to 12 months after the tillage operation. There was a trend for bulk density to be lower for DP as compared to NT in the surface 0-5 cm at Wallace (Table 3-1). Tillage loosens the soil and decreases bulk density by increasing the number of macropores in the layer of disturbance (Pierce et al., 1994), and in particular the disk-harrow has been shown to reduce bulk density in the plow layer (Chen et al., 1998). The delay between the administration of tillage and when bulk density was measured in our study, however, may have allowed the soil to reconsolidate to the previous state. The rate of soil reconsolidation after tillage varies with the soil type and kind of tillage used (Chen et al., 1994). Cultivated soils tend to become denser over the growing season due to the effects of rain, wheel traffic, and natural subsidence (Weill et al., 1990). McCarty et al. (1998) found that as plow tillage was converted to NT, the bulk density increased during the first year of NT and did not increase any more the following year. Therefore, by allowing time to pass between tillage and bulk density sampling, the soil was able to reconstitute itself.

## Whole Soil C and N

A single tillage event only influenced soil C concentration at the Wallace site in our study. A single tillage event did not influence soil C concentration at either Spearville or Tribune. At Wallace, soil C concentration was greater for the DP tillage as compared to CP or continuous NT when averaged over the entire 0-30 cm sampling depth. This is in contrast to VandenBygaart and Kay (2004), who found tillage to reduce soil C concentration relative to NT. Their study, however, utilized a much more aggressive tillage implement with a moldboard plow. Furthermore, the moldboard plow was followed by a second tillage with a disk harrow. Our study used less intensive tillage implements, and the plots were returned to NT management immediately after the tillage operation. The increase in soil C concentration after tillage can be attributed to the incorporation and decomposition of surface residue (Coppens et al., 2006a). Although most of the residue-C and some of the SOC is respired as $CO_2$ following tillage, there can be a net increase in soil C if a sufficient amount of surface residue is introduced into the soil (Janzen et al., 1998).

The increase in soil C concentration for DP relative to NT at Wallace reflects an average of both time after tillage and depth, and was not significantly greater at either nine or 12 MAT, nor was it significantly greater at any particular depth, as indicated by the absence of tillage x depth and tillage x time interactions. There was a trend, however, for the greater soil C concentration of DP relative to NT to be more pronounced in the surface 0-5 cm, and for the soil C concentration of DP relative to NT to be greater at 12 MAT as compared to nine MAT. If the incorporation of surface residue from disking was the sole reason for the higher soil C concentration of DP, it stands to reason that a greater increase in C concentration would have occurred at nine MAT instead of at 12 MAT. The fact that this was not the case indicates that there may be another factor responsible for DP having a 40% higher C concentration than NT in the upper 0-5 cm depth at 12 MAT, as compared to a 14% greater C concentration at the same depth at nine MAT. This may be due to the trend at Wallace for DP to have a lower bulk density of DP relative to NT in the 0-5 cm layer. Soils with a lower bulk density have a more prolific root mass (Kukal et al., 2008). Since roots are the primary contributor to the accumulation of soil C (Gale and Cambardella, 2000), it is plausible that the trend for DP to have a greater C concentration in the surface 0-5 cm depth relative to NT at 12 MAT may have been due to a greater corn root mass over the previous growing season.

The presence of a growing crop between nine and 12 MAT would also account for the overall increase in soil C concentration from nine to 12 MAT in the 0-5 and 5-15 cm depths at Wallace. Crop rotations including fallow periods have lower soil C concentrations (Campbell et al., 1995; Collins et al., 1992); therefore, it is reasonable that the soil C concentration would be higher after a cropping season as opposed to after a fallow period, as was the case at Wallace. This increase in soil C concentration is assumed to be from the transformation of root-derived C into a transitory form of SOM, since visible root structures were removed prior to analysis of whole soil C. The increase in soil C concentration over time at Wallace was also mirrored by an increase in soil C mass. Soil C mass increased from nine to twelve MAT at the 0-5 cm and 5-15 cm depths, similar to soil C concentration. While soil C concentration did not increase over time at 15-30 cm, soil C mass did increase at that depth from Pre-Tillage to 12 MAT. A single tillage event, therefore, did not accelerate the loss of C when measured approximately nine months after tillage, nor did it hinder the accumulation of C during a growing season.

Although tillage significantly influenced the soil C concentration at Wallace, the mass of soil C did not vary between tillage treatments. Typically, when bulk density is used to calculate soil C mass, the lower bulk density of cultivated soils will result in a lower reported mass of soil C (Ellert and Bettany, 1995). Apparently, the higher C concentration of the DP soil (relative to NT) offset the trend for a lower bulk density for DP, thereby resulting in no net gain of C mass in the DP soil. A single tillage event did not significantly influence the mass of C present at Spearville and Tribune, either. Other studies using more aggressive forms of tillage have had mixed results concerning C mass when a NT soil is disturbed. Pierce et al. (1994) observed a decrease in soil C and N mass in the top 0-5 cm and a concurrent increase below 5 cm four to five years after moldboard plowing. Grandy and Robertson (2006a) found a decrease in soil C and N mass in the surface 0-7 cm after moldboard plowing and disking of a previously uncultivated soil, but C and N mass also increased in the 7-20 cm layer resulting in no net change over the entire 0-20 cm depth. Five years after moldboard plowing of a NT soil resulted in a decrease of soil C mass in the surface 0-7.5 cm by 12 – 20%, and a 9 – 15% increase in C mass at 7.5-15 cm (Kettler et al., 2000). They also reported that a reduced tillage treatment which included three yearly operations with a sweep plow but no moldboard plowing was not significantly different in soil C mass from the NT control. VandenBygaart and Kay (2004) only found one NT soil out of four that showed a significant loss of soil C mass as a result of moldboard plowing, and that instance did not occur until 18 months after tillage. The affected soil was a sandy loam similar in texture and organic C content to our Spearville site. Since an aggressive tillage operation like moldboard plowing does not consistently affect soil C mass in a NT soil over the long term, it is reasonable then that some less aggressive forms of tillage, such as in our study, would not affect soil C mass either. This is similar to Jarecki et al. (2005) who did not find a difference in whole soil C mass at any depth between NT and minimum-till which consisted of a disk and chisel plow. In fact, Purakayastha et al. (2008) even found that disrupting a ten year NT field with three years of CvT, followed by a one year resumption of NT actually raised soil C mass relative to the continuous NT plots.

In addition to differences in tillage, another important distinction between our study and the others listed above has to do with precipitation and climate. Our study was conducted under dryland conditions in the semi-arid portion of the Great Plains, whereas all of the previously mentioned studies (except Kettler et al., 2000) occurred in more temperate climates that received greater seasonal rainfall. Miller et al. (2004) noted that SOC losses from soil disturbance in the Great Plains increases with increasing precipitation. This is because adequate soil moisture is necessary for the microbial breakdown of SOM (McGill et al., 1986). Consequently, a single tillage event in western Kansas would have less potential to result in SOC losses as compared to the higher rainfall areas examined in other studies.

While a single tillage event influenced soil C concentration at Wallace, it did not influence soil N concentration when averaged across nine and 12 MAT. Nitrogen concentration did vary between tillage treatments for a particular time after tillage, however. At nine MAT, SwP had a greater soil N concentration as compared to the other tillage treatments including NT. SwP, however, did not increase in N concentration from nine to 12 MAT like the other tillage treatments. This can possibly be explained by a greater decomposition of incorporated surface residue (relative to the other treatments) during the time between tillage in late summer 2004 and the nine MAT sampling in spring 2005. This could have resulted from a unique soil environment created by the sweep-plow as compared to the other tillage treatments. The sweep-plow would have mixed a portion of the surface residue into the upper 0-9 cm, while also maintaining a relatively higher percentage of residue cover on the soil surface. The enhanced residue cover, especially as compared to the disk-plow, would have maintained higher soil moisture contents, thereby fostering a more favorable microenvironment for the decomposition of the incorporated residue. Since the soil C did not mirror the behavior of the N for SwP at Wallace, it can be assumed that the residue-derived C was lost as $CO_2$ during decomposition, while the residue-derived N was incorporated into the SOM pool. Given the short duration (approximately nine months) between tillage and the nine MAT sampling, the residue-derived N was most likely incorporated into the microbial biomass pool, since that pool has the fastest OM turnover time of 0.1 to 1 year (Parton et al., 1987). During the approximate three months between the nine and 12 MAT sampling times, the other tillage treatments may have incorporated the residue-derived N into their OM pools, so that by 12 MAT there was no difference between the tillage treatments in their amount of soil N. The residue-derived C would have been respired as $CO_2$ for these treatments, similar to SwP.

In contrast to the Wallace site, the Tribune site actually decreased in soil C concentration over time despite having a growing crop in between the nine and 12 MAT sampling dates. Soil C mass significantly decreased from nine to 12 MAT only at the 5-15 cm soil depth; nevertheless, the 0-5 and 15-30 cm depths both showed a trend to decrease as well over the same time frame. Meteorological records from the KSU Southwest Experiment Station at Tribune indicate that the 2004 – 2005 crop year was abnormally dry and the dryland corn yields were well below average (data not shown). In fact, many of the corn plants at Tribune did not even produce harvestable grain, whereas average dryland corn yields were still reported at the Wallace site (data not shown). High temperatures increase the decomposition of soil organic matter (Jenny, 1941). Since drought conditions severely limited both above- and below-ground vegetative growth during the summer of 2005 at Tribune, there was an insufficient amount of residue-derived C returned to the soil to offset the respiration of SOC by soil heterotrophs during the hot summer months. As a result, the soil C concentration declined over time at Tribune. Soil N concentration and N mass did not change over time, however. This is to be expected since N is recycled within the soil system, unlike C which is respired as $CO_2$ (Coppens et al., 2006a). Therefore, in circumstances of limited OM addition from crop residue, it is reasonable that soil C would decline over time while soil N would remain constant.

Soil C concentration and soil C mass did not change over time at Spearville, with the Pre-Tillage levels being identical to the 12 MAT levels. Spearville was under a continuous dryland wheat rotation, as opposed to a wheat – corn – fallow rotation of the other two sites. The absence of data for Spearville at nine MAT prevents us from drawing conclusions about the seasonal fluctuation of soil C under a continuous dryland wheat cropping system. Essentially, the Pre-Tillage and 12 MAT sampling times occurred at roughly the same time of the crop year (prior to or just after wheat planting). Therefore it is reasonable to expect the soil C be similar at both times, since both sampling times had the same previous crop and the same length of time between the senescence of that previous crop and soil sampling.

In contrast to soil C concentration, soil N concentration increased over time at all depths for Spearville. However, the increase was more pronounced in the surface 0-5 cm depth. Soil N mass also increased from Pre-Tillage to 12 MAT for all soil depths. The decomposition of residue-derived OM from the wheat crop grown between the times of Pre-Tillage and 12 MAT might have been partially responsible for the release of inorganic N and subsequent rise in soil N over that same time frame. Again, since the decomposition of residue-derived OM would have respired off organic C as $CO_2$, it is understandable that soil C would not change over time while soil N would increase. The sharper rise of N concentration in the upper 0-5 cm of soil as compared to lower soil depths may be the result of leaching of soluble N out of the wheat residue, thereby enriching N concentration near the soil surface (Angers et al., 1997; Coppens et al., 2006b). It also may be possible that some the increase in soil N concentration at 12 MAT was due to the addition of inorganic fertilizer at planting. As mentioned in the Methods section, 10-34-0 was applied in-furrow with the drill. This would have provided 11.2 kg $ha^{-1}$ of N, which might have contributed to the rise in soil N concentration since the 12 MAT sampling date occurred shortly after wheat planting. This could also explain why the increase in soil N concentration was greater in the surface 0-5 cm, since this is where the dribbled fertilizer would be the most concentrated.

Soil C and N concentrations were both highly stratified over depth at all three sites, with the greatest C and N concentrations existing in the surface 0-5 cm depth and decreasing for each lower soil depth range. It is important to note that there was no difference between the tilled plots and the continuous NT in the stratification of C and N concentrations throughout the soil sampling horizon. This finding differs from other studies that utilized greater tillage intensities and resulted in the elimination of stratified C concentrations. VandenBygaart and Kay (2004) found that C concentration was homogenized over depth after a single moldboard plowing 20 cm deep, resulting from a decrease of C concentration in the top 0-5 cm and an increase at lower depths. Bruce et al. (1995) applied primary (disk) and secondary (field cultivator) tillage to a NT soil and homogenized C concentration across 0-8 cm, which was still noticeable three years after tillage. In our study, we did not use such an aggressive tillage implement as a moldboard plow, nor did we apply tillage more than one time to the field. Consequently, a single tillage operation consisting of a disk, sweep-plow, or chisel-plow did not homogenize soil C and N concentrations over depth when the soil was immediately returned to NT management.

## Aggregate Size Distribution

The absence of macroaggregates >1000 µm and low number of 250-1000 µm macroaggregates for all three sites is to be expected given the low clay content of all three sites Denef et al. (2001) did not report measuring any macroaggregates 250-1000 µm in their sandy Akron soil (41% sand, 36% silt, 23% clay). For the sake of our discussion, macroaggregates will refer to the 250-1000 µm size class.

Our findings are interpreted using the aggregate turnover model proposed by Oades (1984), Golchin et al. (1994), and Six et al. (1998). In this model, new particulate organic matter (POM) is colonized by microorganisms to form macroaggregates, which protect the POM from rapid decomposition from soil heterotrophs. Over time, silt and clay sized particles encrust POM to form new microaggregates within the macroaggregate. As the quality of POM declines and microbial activity decreases, the macroaggregate disintegrates to release stable microaggregates, which contain a more recalcitrant form of SOM. These new microaggregates are then available to be bound together with new POM into macroaggregates to repeat the process again. The rate at which this process occurs is called aggregate turnover. Tillage has been shown to interrupt this process by breaking up macroaggregates before they are able to produce new stable microaggregates, thereby reducing the amount of new microaggregates (53-250 µm) in cultivated soils (Six et al., 1998, 1999). Consequently, a longer turnover time is required to sequester C in microaggregates (Six et al., 2000a; Paustian et al., 2000). More recent authors have proposed, however, that an intermediate turnover time is required so that new POM can be captured within macroaggregates and protected from decomposition that would otherwise result in the loss of organic C as $CO_2$ (Plante and McGill, 2002a,b).

A single tillage operation did not alter the distribution of the aggregate size fractions as compared to continuous NT for any location, depth, or time after tillage. Even more intensive forms of tillage than what we utilized in our study have not influenced aggregate size distributions below the 0-5 cm depth (Beare et al., 1994; Six et al., 1999; Bossuyt et al., 2002; Wright and Hons, 2005b). Other studies have also compared aggregate size distributions in the surface soil layers of cultivated soils with NT and/or native sod, and found that increasing cultivation intensity leads to a loss of macroaggregates and an increase in microaggregates (Six et al., 2000b; Mikha and Rice, 2004. Grandy and Robertson (2006) found that after moldboard plowing and disking of a previously uncultivated field, the reduction in aggregate mean weight diameter (MWD) was still present three years after tillage. This was a result of a reduction in 2000-8000 µm macroaggregates, however, of which none were found in our study. Their reduction in macroaggregates was also countered by an increase in <250 µm microaggregates. Wright and Hons (2005) observed that while NT had more macroaggregates than conventional-till (CvT) in the entire 0-15 cm sampling depth, microaggregate distributions did not vary between CvT and NT. Our study used a single tillage event, which may not be sufficient enough to break apart macro- and microaggregates (VandenBygaart and Kay, 2004). Therefore, we conclude that a single tillage event using low-intensity implements would not significantly change the aggregate distribution when measured nine months after tillage or later. This is similar to the findings of Lal et al. (1994) who found no difference between NT and CP in aggregate MWD.

While it is possible that the more aggressive tillage treatments of DP and SwP may have had a short-term impact on aggregation in the plow layer immediately after tillage, any alterations rectified themselves before the sampling times of nine and twelve MAT. Plante and McGill (2002) found that simulated tillage significantly reduced overall aggregation, but aggregates were also rapidly reformed between tillage events. Macroaggregates are less stable than microaggregates (Elliot, 1986; Cambardella and Elliot, 1993) and are good predictors of potential C responses to tillage because of their importance in protecting labile OM (Jastrow et al., 1998; Grandy and Robertson, 2006). Any macroaggregates that might have been destroyed by mechanical tillage were apparently replaced through the incorporation and degradation of surface and/or root residue, so that there was no net change in aggregation within the plow layer (Bossuyt et al., 2002; Wright and Hons, 2005b). Macroaggregate formation occurs at the same rate in both CvT and NT soils (Six et al., 1998). Since NT practices were immediately reinstituted after the single tillage operation, macroaggregates were allowed to reform without interruption from subsequent tillage operations. This confirms the work of Olchin et al. (2008), who did not find any differences in aggregate size distribution between continuous NT and a plowed NT soil after one year after simulated tillage during in-field incubation.

The vast majority of the soil weight existed in the large microaggregate fraction, regardless of time or depth. This is similar to the findings of Olchin et al. (2008), which also found the majority of the aggregate soil weight existing in the large microaggregate fraction. Within a particular aggregate size fraction, almost every site had certain depth(s) that contained a greater amount of aggregates than other depths. At Tribune, the greatest amount of macroaggregates existed in the lower 15-30 cm depth, which is also the same depth where both large and small microaggregates existed in the lowest amounts. Such an inverse relationship is to be expected, since microaggregates are occluded within macroaggregates (Elliot, 1986). Therefore it is reasonable that a particular depth which is markedly greater in macroaggregates would also contain fewer microaggregates.

Sometimes the differentiation among depths in aggregate weight occurred at one time after tillage and not at the other, thereby indicating an influence of time on a particular aggregate size fraction for only a specified depth. For example, at Wallace (nine MAT) macroaggregates were the greatest in the surface 0-5 cm depth, but at 12 MAT the surface 0-5 cm depth was not any different from lower depth layers. This reflects a loss of macroaggregate stability in the surface 0-5 cm depth, which is to be expected since the soil surface is the most prone to alternating wet/dry cycles that disrupt macroaggregates and hasten their turnover time (Denef et al., 2001). Large microaggregates were the greatest in the 5-15 cm depth when averaged across both times. As expected, macroaggregates trended to be lowest in the same 5-15 cm depth for both nine and 12 MAT as well.

At Spearville for the 9 MAT, macroaggregates were the greatest in the surface 0-5 cm depth but decreased 12 MAT. A growing wheat crop existed during the nine MAT sampling date of 5 May 2005, while the Wallace and Tribune locations were in fallow wheat stubble at nine MAT. Active root growth and increased biological activity in the rhizosphere leads to the stabilization of macroaggregates (Gale et al., 2000b; Jastrow et al., 1998). As a result, the actively growing wheat roots and fungal hyphae present at nine MAT helped to stabilize both macroaggregates and large microaggregates, but their absence at 12 MAT (after the wheat senesced) reduced the aggregates' ability to withstand slaking (Oades, 1984). This is illustrated by the significant reduction at 12 MAT in macroaggregates at all depths and large microaggregates at the 0-5 and 5-15 cm depths. Furthermore, in regards to soil texture's effect on aggregation, the sandier soil texture at Spearville was likely responsible for the rapid loss of macroaggregate strength in the absence of growing roots (Tisdall and Oades, 1982).

Unique to Tribune was a net increase from nine to 12 MAT in amount of water-stable macroaggregates. This was opposite of the Spearville and Wallace sites, which experienced a net decrease over time in water-stable macroaggregates. The positive change in macroaggregate stability over time at Tribune can be attributed to the abnormally dry climate conditions of the growing season between nine and 12 MAT. Corn plants in those plots produced above- and below-ground vegetation, but a drought which peaked in late summer severely limited final yield. Even though there was a net loss of soil C because of this drought (as previously discussed), the dry soil conditions actually enhanced macroaggregate stability. Lower soil water contents have been shown to increase the stability of water-stable aggregates (Perfect et al., 1990). As soil dries around roots, particles of clay, organic matter, and salts are deposited at points of contact, acting to strengthen bonds between larger particles (Tisdall, 1996). Cosentino et al. (2006) postulated in their study that the increase in macroaggregate cohesion upon drying of the soil was a result of intermolecular associations between polysaccharides and mineral surfaces. Macroaggregates can be stabilized in dry soil conditions despite the reduction in microbial activity that would occur under such conditions. This was demonstrated by Utomo and Dexter (1982) when they found an increase in macroaggregate stability after drying both sterilized and non-sterilized soils. Consequently, it is reasonable for macroaggregate stability to be greater at 12 MAT at Tribune even though there was a net loss of soil C.

It is generally accepted that an increase in the proportion of macroaggregates will also result in an increase of soil C (Wright and Hons, 2005). Our study, however, did not show a direct correlation between gains or losses in soil C to changes in macroaggregates. For instance, at Wallace, an increase in soil C concentration and C mass over time occurred at the 0-5 cm depth despite a decrease in macroaggregates. At the 5-15 cm depth, soil C concentration and C mass increased over time even though macroaggregates did not change. Finally, at the 15-30 cm depth, neither soil C nor macroaggregates changed over time. Given this observation, plus the observation at Tribune regarding the loss of soil C despite a gain in macroaggregates, it would appear that the microaggregate fractions have a much greater influence on soil C than macroaggregates in semi-arid soils with lower clay contents under dryland cropping practices. It is important to note that the change over time in the amount of aggregates in each size fraction was a result of natural processes affecting aggregates and was not influenced by a single tillage event, regardless of its intensity. At Wallace and Spearville, greater amounts of small microaggregates were being released as larger aggregates aged, weakened, and then dispersed. Furthermore, the quantity of aggregates in each size fraction did not vary among tillage treatments in their distribution across soil depths, even when considering the more aggressive forms of tillage such as DP and SwP. Consequently, a single tillage event neither improved nor destroyed water-stable aggregates when NT management was immediately resumed.

Continuous NT management results in better soil structure through improved aggregation (Blevins et al., 1984). Assuming that all three sites improved in their aggregation and soil structure during their years of NT management, it did not appear that a single tillage event (using the implements in our study) resulted in a measurable loss of soil aggregates relative to the continuous NT plots. Therefore, the benefits of improved aggregation and soil structure, such as higher water infiltration capacity, easier rooting of plants, and greater water holding capacity (Blevins et al., 1984), were not compromised with a single tillage operation in our semi-arid environment.

## Aggregate-associated C and N

A single tillage operation, regardless of its intensity, did not change the C concentration of any aggregate size fraction relative to NT at any location when measured approximately one year after tillage. The mass of C associated with aggregates was not affected by tillage, either, for the Spearville or Tribune sites. At Wallace, however, there were differences between tillage treatments in the mass of C associated with macroaggregates and large microaggregates. In the surface 0-5 cm depth, DP and SwP had a greater mass of C affiliated with macroaggregates as compared to CP. Although both were not significantly greater than NT ($P<0.05$), DP and SwP did also trend to have more macroaggregate-associated C mass than NT. The CP tillage also had less macroaggregate C mass than SwP at the 5-15 cm depth, and trended to be lower than the other two treatments as well. While the mass of macroaggregate C for DP tended to be higher than NT and CP in the surface 0-5 cm, the mass of large microaggregate C for DP was lower than all of the other tillage treatments at that same depth. Furthermore, at the 5-15 cm depth, DP had a greater mass of large microaggregate C as compared to NT and CP, and trended to be higher than SwP as well. The mass of N associated with aggregates at Wallace also followed the same trends as C mass, but without a significant tillage x depth interaction none of the variances were significant at $P<0.05$.

Essentially, the greater mass of macroaggregate-associated C for DP at the 0-5 cm was countered by a decrease in the mass of C in large microaggregates at the same depth. The trend for a greater mass of macroaggregate-associated C for the two tillage treatments DP and SwP relative to NT in the surface 0-5 cm contrasts with the findings of Mikha and Rice (2004), which showed that NT soils had a greater mass of macroaggregate C and a lower mass of large microaggregate C as compared to CvT. The CvT plots in their study, however, included yearly chisel plowing with secondary tillage operations, whereas our study focused on one tillage pass with less intensive soil disturbance. One explanation for the higher macroaggregate-associated C mass for DP in the surface 0-5 cm may be related to the trend for DP to have a lower bulk density at that same depth. As hypothesized earlier, the greater rooting mass afforded by the lower bulk density of the DP soil may be responsible for the greater amount of C occluded within macroaggregates, since macroaggregates form around recent root-derived POM (Gale et al., 2000). Angers and Carter (1996) also found that larger aggregate size fractions contained a greater proportion of corn-derived C. The bulk density hypothesis does not explain why SwP had a similarly high mass of C in the macroaggregate fraction, though, which (like DP) was also was higher than CP and trended to be higher than NT.

It is unlikely that the greater mass of macroaggregate-associated C for DP and SwP is related to the surface residue incorporated into the soil by those two tillage operations one year prior. Grandy and Robertson (2000a) found an increase in intra-macroaggregate light fraction OM 60 days after tillage, but that difference was already absent 120 days after tillage. Angers et al. (1997) found that incorporated wheat straw rapidly became associated with stable macroaggregates, but after one year the large microaggregate fraction contained most of the straw-derived C. Consequently, it is unlikely that the incorporated wheat straw from the previous year accounts for the higher mass of macroaggregate-associated C observed for DP and SwP in the surface 0-5 cm, since the macroaggregates which formed around that wheat straw would have long destabilized by 12 MAT. Rather, the extra mass of C in macroaggregates for those two tillage treatments was most likely due to the recent deposition of root-derived POM from the previous corn crop.

Although not significant at $P<0.05$, DP had quantitatively more macroaggregates and fewer large microaggregates in the 0-5 cm depth as compared to NT and CP at 12 MAT. This same trend can also be seen in the aggregate distribution for SwP, too, but it did not correlate into a lower mass of large microaggregate C as it did for DP. Therefore, a single tillage operation with either a disk-plow or sweep-plow may have an effect on the mass of C associated with macroaggregate and/or large microaggregate fractions in the upper 15 cm of soil when sampled one year after tillage. However, the fact that this response only occurred at one of the three locations suggests that secondary factors, such as crop rotation, soil texture, and climate differences, play a more dominant role in this influence than does the tillage itself.

Differences in the mass of C associated with macroaggregates can give some indication as to differences in soil C content, but a direct correlation did not always exist in our study. For example, the elevated amount of macroaggregate-associated C mass for DP at Wallace in the surface 0-5 cm depth may be correlated to the trend for higher soil C concentration and soil C mass for DP at the same depth (although there was no statistical difference between tillage treatments in that instance). This was not the case for SwP, however. Macroaggregate-associated C mass for SwP was almost identical to DP in the surface 0-5 cm depth at Wallace, but the soil C concentration and soil C mass for SwP at that depth were numerically less than DP, even though SwP also had a greater mass of large microaggregate-associated C at the same depth. Therefore, direct inferences about whole soil C cannot be made based on measurements of aggregate-associated C mass. The same is also true for the relationship between aggregate-associated N and whole soil N. The average N concentration of all the aggregate size classes was lower for DP at Wallace in the surface 0-5 cm depth. The uniquely lower aggregate-associated N concentration for DP did not correlate to a change in soil N concentration or whole soil N mass.

Tribune did not have any differences between tillage treatments in the N concentration of aggregates. Furthermore, neither Tribune nor Wallace exhibited an influence of tillage on the mass of N associated with aggregates. As was the case with aggregate-associated C mass, a single tillage event utilizing a disk-plow may reduce the N concentration of all aggregates when analyzed one year after tillage. This cannot be extrapolated to be the case in every circumstance, however, since only one of the three sites exhibited this response. As a result, the concentration of N in aggregates is not a reliable predictor of whole soil N concentration or N mass.

Both Wallace and Tribune had the greatest amount of aggregate-associated C and N concentration in the macroaggregate fraction, which is similar to the findings of Mikha and Rice (2004) and Kong et al. (2005). This is because macroaggregates not only contain microaggregates, which themselves contain OM, but also contain inter-microaggregate POM as well (Denef et al., 2004). This inter-microaggregate POM is highly labile and is rapidly mineralized upon macroaggregate disruption (Elliot, 1986), and it is this fraction of POM that is lost upon macroaggregate disturbance by tillage or other environmental factors (Olchin et al., 2008). The incorporation of new residue by tillage results in new macroaggregate formation around the added POM. Consequently, the new POM is protected from rapid decomposition and offsets C losses when previous POM is released from macroaggregates (Bossuyt et al., 2002). Our study suggests that a single tillage pass with either a disk or sweep plow will have a neutral to positive impact on macroaggregate-associated C and N. Furthermore, macroaggregates will not be disassociated enough to release labile POM existing between microaggregates so as to be detectable approximately one year after a single tillage with a disk or sweep plow.

Although the greatest concentration of aggregate-associated C and N existed in macroaggregates for Wallace and Tribune, the greatest mass of aggregate-associated C and N existed in the large microaggregate fraction. This validates the findings of Angers et al. (1997) who also found the greatest C storage exists in large microaggregates. This is contrary to Wright and Hons (2005), who found the greatest amount of C and N storage in macroaggregates. This discrepancy may be the result of the lower dry matter production of the semi-arid dryland cropping system represented by our three locations. Under lower C input systems such as ours, C storage occurs predominantly in the large microaggregate fraction, whereas under higher C input systems C is preferentially accumulated in macroaggregates (Kong et al., 2005). Our results are a reflection of the greater proportion of aggregates that existed in the large microaggregate fraction after slaking for soils such as these in a semi-arid climate (Cambardella and Elliot, 1994; Olchin et al., 2008). Large microaggregate-associated C was found to account for over

90% of the difference in whole SOC between NT and CvT soils (Denef et al., 2004). Carbon associated with large microaggregates is more recalcitrant and is not affected by changes in tillage management (Tisdall and Oades, 1982), and thus is highly important for the long-term sequestration of SOC (Jastrow and Miller, 1997; Six et al., 1998; Denef et al., 2004).

The concentration of C and N in macroaggregates was greatest in the surface 0-5 cm at Wallace. Although not significant at $P<0.05$, there was a trend for DP to be homogenized in macroaggregate N concentration across the 0-5 and 5-15 cm depth, resulting from a lower macroaggregate N concentration in the 0-5 cm depth and an increased N concentration at the 5-15 cm depth. The wider C/N ratio of macroaggregates for DP (data not shown) suggests enrichment in recent inter-microaggregate POM, possibly from roots (Turchenek and Oades, 1979). The greatest mass of macroaggregate C and N at Wallace existed in the surface 0-5 cm depth.

At Wallace, the greatest mass of large microaggregate C existed in the surface 0-5 cm, while the greatest mass of large microaggregate N existed across both the 0-5 and 5-15 cm depths. Large microaggregate C and N concentrations were the greatest in the surface 0-5 cm. Small microaggregate C concentration was greatest in the upper 0-5 cm, while small microaggregate N concentration was greatest in both the 0-5 and 5-15 cm depths. The mass of C and N associated with small microaggregates did not vary over depth.

At Tribune, the masses and concentrations of macroaggregate-associated C and N were greatest in the surface 0-5 cm. Large microaggregate C and N concentrations trended to be the highest in the surface 0-5 cm and then declined over depth. The mass of

C and N associated with large microaggregates was the greatest across both the 0-5 and 5-15 cm depths. Small microaggregates did not vary across depth layers in either their concentrations or masses of C or N. With the exception of small microaggregates, these results are similar to that of Bossuyt et al. (2002), who found that NT soils have the greatest aggregate-associated C concentration in the surface 0-5 cm for all aggregate size fractions.

Spearville was similar to Wallace and Tribune in that the greatest mass of aggregate-associated C existed in the large microaggregate fraction because of the large amount of aggregate weight in that size class. Spearville differed from the other two sites, however, in regards to the C concentration of aggregates. For Spearville, the greatest C concentration existed in the small microaggregate fraction. This is opposite of Wallace and Tribune, which had the greatest concentration of C in the macroaggregate fraction and the lowest C concentration in the small microaggregate fraction.

The C concentration of small microaggregates varies depending on soil texture and tillage regimes. Wright and Hons (2005) found that in the upper 0-5 cm, the highest C concentration was found in small microaggregates for CvT while NT had the highest C concentration in macroaggregates. Differences in tillage do not explain our results, however, since there were no tillage x aggregate interactions. Yang et al. (2007) found that <106 μm microaggregates had greater C concentration than did 106-1000 μm aggregates in a soil containing 52% sand, 34% silt, and 14% clay, which would somewhat parallel our Spearville results.

Perhaps the best explanation for the vast differences in aggregate-associated C concentration at Spearville is offered by Plante et al. (2006). They found that soils with greater amounts of silt + clay had lower C concentrations associated with small microaggregates; conversely, soils with lower silt + clay contents had higher small microaggregate C concentrations.  This is because small microaggregates are primarily built upon silt and clay particles (Tisdall, 1996).  Therefore, a sandy soil like Spearville would have a greater concentration of C in its small microaggregate fraction because of the lower silt + clay content of the soil.

There are also some stark differences between Spearville and the other two sites when comparing the ratio of aggregate-associated C concentration to whole soil C concentration.  For Spearville, the ratio is less than 1.0 for macroaggregates and greater than 1.0 for small microaggregates.  For Wallace and Tribune opposite is true: the ratio is greater than 1.0 for macroaggregates and less than 1.0 for small microaggregates (data not shown).  In other words, macroaggregates for Wallace and Tribune are more enriched in C compared to the surrounding soil, whereas for Spearville it is the small microaggregates which are more enriched in C relative to the surrounding soil.  This is true for Spearville because over half of the soil mass is made up of sand, which has minimal capacity to adsorb OM onto its surface.  At all three locations the C concentration of the large microaggregate fraction was similar to that of the whole soil. Therefore, of the three aggregate size fractions analyzed in this study, it is C which is associated with the large microaggregate fraction that has the greatest influence on whole soil C in a semi-arid, dryland cropping system.

Since large microaggregate-associated C is such a major contributor to whole soil C, it would stand to reason that a decline in large microaggregates over time would also translate into a loss of whole soil C over time as well.  Unfortunately this is not consistently shown in our data. At Tribune, large microaggregates decreased strongly from nine to 12 MAT, and whole soil C concentration and mass declined as well over the same time period. However, the same relationship was not true for Wallace. Wallace also experienced a decrease in large microaggregates from nine to 12 MAT, but both whole soil C concentration and mass increased in the upper 0-15 cm. Since declines over time in the amount of large microaggregates does not directly cause a loss of whole soil C, there must be other fractions of SOC that are important to whole soil C dynamics than just the fraction associated with large microaggregates. For example, POM that is released upon the slaking of aggregates would be accounted for in a whole soil analysis, but it would not be measured just by analyzing the intact aggregates that withstood slaking. Further quantification of OM fractions are necessary to determine what other forms of SOM have an impact on determining whole soil C, in addition to the pool of aggregate-protected analyzed in our study.

## Duration of No-Till Management

The three locations differed in their length of NT management prior to the single tillage event in August 2004. The Wallace site had been under NT the longest at 14 years; Tribune was in NT for six years, while Spearville was only in continuous NT for four years. After the change from CvT to NT management, there may be little to no increase in sequestered SOC in the first two to five years, but then reach peak sequestration rates in years five through ten (West and Post, 2002; Lal et al., 1998). Theoretically, relative to pre-NT SOC levels, Spearville would have sequestered the least amount of C and Wallace the most amount of C before our study. Much of the increase in SOC may have occurred as particulate organic matter (POM) that accumulated between microaggregates within macroaggregates (Six et al., 2002). Since there was no measurable change in aggregation after tillage at either site, it can be deduced that a single tillage event was unable to expose the accumulated intramicroaggregate POM to decomposition (Six et al., 2000a). One would expect the greatest change in SOC and aggregation to have occurred in the Wallace site, where the percent increase in aggregation and SOC would have been the greatest relative to pre-NT levels. Conversely, SOC accumulation relative to pre-NT levels would have been the lowest at Spearville, and thus tillage-induced changes in aggregation and SOC would be the least measurable. Since neither location experienced changes in SOC or aggregation, we conclude that a single tillage event in a semi-arid environment will not have a deleterious effect on SOC and aggregation regardless of how long the location has been under NT.

## Literature Cited

Angers, D.A. and M.R. Carter. 1996. Aggregation and organic matter storage in cool, humid agricultural soils. Pp. 193-211. *In:* D.A. Angers and M.R. Carter (eds.). *Structure and Organic Matter Storage in Agricultural Soils*. CRC Press, Boca Raton, FL.

Angers, D.A., S. Recous, and C. Aita. 1997. Fate of carbon and nitrogen in water-stable aggregates during decomposition of $^{13}C^{15}N$-labelled wheat straw *in situ*. Eur. J. Soil Sci. 48: 295-300.

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates on organic matter fractions in conventional- and no-tillage soils. Soil Sci. Soc. Am. J. 58: 777-786.

Blevins, R.L., M.S. Smith, and G.W. Thomas. 1984. Changes in soil properties under no-tillage. Pp.191-231. *In*: R.E. Phillips and S.H. Phillips (eds.). *No-tillage Agriculture: Principles and Practices*. Van Nostrand Reinhold, New York, NY.

Bossuyt, H., J. Six, and P.F. Hendrix. 2002. Aggregate-protected carbon in no-tillage and conventional tillage agroecosystems using Carbon-14 labeled plant residue. Soil Sci. Soc. Am. J. 66:1965-1973.

Bruce, R.R., G.W. Langdale, L.T. West, and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. Soil Sci. Soc. Am. J. 59: 654-660.

Cambardella, C.A. and E.T. Elliot. 1994. Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. Soil Sci. Soc. Am. J. 58: 123-130.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F.B. Dyck, F. Selles, and D. Curtin. 1995. Carbon sequestration in a Brown Chernozem as affected by tillage and rotation. Can. J. Soil. Sci. 75: 449-458.

Causarano, H.J., A.J. Franzluebbers, J.N. Shaw, D.W. Reeves, R.L. Raper, and C.W. Wood. 2008. Soil organic carbon fractions and aggregation in the Southern Piedmont and Coastal Plain. Soil Sci. Soc. Am. J. 72: 221-230.

Chen, Y., E. McKyes, and S. Tessier. 1994. Changes of soil bulk density during the growing season under three tillage systems. Can. Agric. Eng. 36: 45-49.

Chen, Y., S. Tessier, and J. Rouffignat. 1998. Soil bulk density estimation for tillage systems and soil textures. Trans. ASAE. 41: 1601-1610.

Collins, H.P., P.E. Rassmussen, and C.L. Douglas, Jr. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56: 783-788.

Coppens, F., P. Garnier, S. De Gryze, R. Merckx, and S. Recous. 2006a. Soil moisture, carbon, and nitrogen dynamics following incorporation and surface application of labeled crop residues in soil columns. Eur. J. Soil Sci. 57: 894-905.

Coppens, F., R. Merckx, and S. Recous. 2006b. Impact of crop residue location on carbon and nitrogen distribution in soil and water-stable aggregates. Eur. J. Soil Sci. 57: 570-582.

Cosentino, D., C. Chenu, and Y. Le Bissonnais. 2006. Aggregate stability and microbial community dynamics under drying-wetting cycles in a silt loam soil. Soil Biol. Biochem. 38: 2053-2062.

Denef, K., J. Six, K. Paustian, and R. Merckx. 2001. Importance of macroaggregate dynamics in controlling soil carbon stabilization: Short-term effects of physical disturbance induced by dry-wet cycles. Soil Biol. Biochem. 33:2145-2153.

Denef, K., J. Six, R. Merckx, and K. Paustian. 2004. Carbon sequestration in microaggregates of no-tillage soils with different clay mineralogy. Soil Sci. Soc. Am. J. 68: 1935-1944.

Ellert, B.H. and J.R. Bettany. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75: 529-539.

Elliot, E.T. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50: 627-633.

Gale, W.J. and C.A. Cambardella. 2000a. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. Soil Sci. Soc. Am. J. 64: 190-195.

Gale, W.J., C.A. Cambardella, and T.B. Bailey. 2000b. Root-derived carbon and the formation and stabilization of aggregates. Soil Sci. Soc. Am. J. 64: 201-207.

Golchin, A., J.A. Baldock, and J.M. Oades. 1998. A model linking organic matter decomposition, chemistry, and aggregate dynamics. Pp. 245-266. *In*: R.Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Grandy, A.S. and G.P. Robertson. 2006a. Aggregation and organic matter protection following tillage of a previously uncultivated soil. Soil Sci. Soc. Am. J. 70: 1398-1406.

Grandy, A.S. and G.P. Robertson. 2006b. Initial cultivation of a temperate-region soil immediately accelerates aggregate turnover and $CO_2$ and $N_2O$ fluxes. Glob. Change Biol. 12: 1507-1520.

Janzen, H.H., C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1998. Soil carbon dynamics in Canadian agroecosystems. Pp. 57-80. *In*: R. Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Jarecki, M., R. Lal, and R. James. 2005. Crop management effects on soil carbon sequestration on selected farmers' fields in northeastern Ohio. Soil Till. Res. 81: 265-276.

Jastrow, J.D., and R.M. Miller. 1997. Soil aggregate stabilization and carbon sequestration: feedbacks through organo-mineral associations. Pp. 207-224. *In*: R. Lal, J.M. Kimble, R.F. Follet, and B.A. Stewart (eds.), *Soil Processes and the Carbon Cycle*. CRC Press, Boca Raton, FL.

Jastrow, J.D., R.M. Miller, and J. Lussenhop. 1998. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. Soil Biol. Biochem. 30: 905-916.

Jenny, H. 1941. *Factors of Soil Formation*. McGraw Hill, New York, NY.

Kettler, T.A., D.J. Lyon, J.W. Doran, W.L. Powers, and W.W. Stroup. 2000. Soil quality assessment after weed-control tillage in a no-till wheat-fallow cropping system. Soil Sci. Soc. Am. J. 64: 339-346.

Kong, A.Y.Y., J. Six, D.C. Bryant, R.F. Denison, and C. van Kessel. 2005. The relationshipe between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Sci. Soc. Am. J. 69: 1078-1085.

Kukal, S.S., Y. Singh, S. Yadav, E. Humphreys, A.Kaur and S. Thaman. 2008. Why does grain yield of transplanted rice on permanent raised beds decline with time? Soil Till. Res. 99: 261-267.

Lal, R., A.A. Mahboubi, and N.R. Fausey. 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. Soil Sci. Soc. Am. J. 58: 517-522.

McCarty, G.W., N.N. Lyssenko, and J.L. Starr. 1998. Short-term changes in soil carbon and nitrogen pools during tillage management transition. Soil Sci. Soc. Am. J. 62: 1564-1571.

McGill, W.B., K.R. Cannon, J.A. Robertson, and F.D. Cook. 1986. Dynamics of soil microbial biomass and water-soluble organic C in Breton L after 50 years of cropping to two rotations. Can. J. Soil Sci. 66: 1-19.

Mikha, M.M., and C.W. Rice. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. Soil Sci. Soc. Am. J. 68: 809-816.

Miller, A.J., R. Amundson, I.C. Burke, and C. Yonker. 2004. The effect of climate and cultivation on soil organic C and N. Biogeochem. 67: 57-72.

Oades, J.M. 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil. 76: 319-337.

Olchin, G.P., S.D. Frey, T.R. Filley, K. Paustian, and J. Six. 2008. Residue carbon stabilization in soil aggregates of no-till and tillage management of dryland cropping systems. Soil Sci. Soc. Am. J. 72: 507-513.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51: 1173-1179.

Paustian, K., J. Six, E.T. Elliot, and H.W. Hunt. 2000. Management options for reducing CO2 emissions from agricultural soils. Biogeochem. 48: 147-163.

Perfect, E., B.D. Kay, W.K.P. van Loon, R.W. Sheard, and T. Pojasok. 1990. Rates of change in structural stability under forages and corn. Soil Sci. Soc. Am. J. 54: 179-186.

Pierce, F.J., M.-C. Fortin, and M.J. Staton. 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58: 1782-1787.

Plante, A.F. and W.B. McGill. 2002a. Soil aggregate dynamics and the retention of organic matter in laboratory-incubated soil with differing simulated tillage frequencies. Soil Till. Res. 66:79-92.

Plante, A.F. and W.B. McGill. 2002b. Intraseasonal soil macroaggregate dynamics in two contrasting field soils using labeled tracer spheres. Soil Sci. Soc. Am. J. 66: 1285-1295.

Plante, A.F., R.T. Conant, C.E. Stewart, K. Paustian, and J. Six. 2006. Impact of soil texture on the distribution of soil organic matter in physical and chemical fractions. Soil Sci. Soc. Am. J. 70: 287-296.

Purakayastha, T.J., D.R. Huggins, and J.L. Smith. 2008. Carbon sequestration in native prairie, perennial grass, no-till, and cultivated Palouse silt loam. Soil Sci. Soc. Am. J. 72: 534-540.

Six, J., E.T. Elliot, K. Paustian, and J.W. Doran. 1998. Aggregation and soil organic matter accumulation in cultivated and native grassland soils. Soil Sci. Soc. Am. J. 62: 1367-1377.

Six, J., E.T. Elliot, and K. Paustian. 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Sci. Soc. Am. J. 63: 1350-1358.

Six, J., E.T. Elliot, and K. Paustian. 2000a. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32: 2099-2103.

Six, J., K. Paustian, E.T. Elliot, and C. Combrink. 2000b. Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64: 681-689.

Six, J., C. Feller, K. Denef, S.M. Ogle, J.C. de Moraes Sa, and A. Albrecht. 2002. Soil organic matter, biota, an aggregation in temperate and tropical soils – Effects of no-tillage. Agronomie. 22: 755-775.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33: 141-163.

Tisdall, J.M. 1996. Formation of soil aggregates and accumulation of soil organic matter. Pp. 57-96. *In*: M.R. Carter and B.A. Stewart (eds.), *Structure and Organic Matter Storage in Agricultural Soils*. CRC Press, Boca Raton, FL.

Turchenek, L.W., and J.M. Oades. 1978. Organo-mineral particles in soils. Pp. 137-144. *In*: W.W. Emerson, R.D. Bond, and A.R. Dexter (eds.). *Modification of Soil Structure*. Wiley, London, England.

Utomo, W.H. and A.R. Dexter. 1982. Changes in soil aggregate water stability induced by wetting and drying cycles in non-saturated soil. J. Soil Sci. 33: 623-637.

VandenBygaart, A.J. and B.D. Kay. 2004. Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. Soil Sci. Soc. Am. J. 68: 1394-1402.

Weill, A.N., G.R. Mehuys, and E. McKyes. 1990. Effect of tillage reduction and fertilizer type on soil properties during corn (*Zea mays* L.) production. Soil Till. Res. 17: 63-76.

Wright, A.L. and F.M. Hons. 2005a. Soil carbon and nitrogen storage in aggregates from different tillage and crop regimes. Soil Sci. Soc. Am. J. 69: 141-147.

Wright, A.L. and F.M. Hons. 2005b. Tillage impacts on soil aggregation and carbon and nitrogen sequestration under wheat cropping sequences. Soil Till. Res. 84: 67-75.

Yang, Z., B.R. Singh, and S. Hansen. 2007. Aggregate associated carbon, nitrogen, and sulfur and their ratios in long-term fertilized soils. Soil Till. Res. 95: 161-171.

# CHAPTER 5 - Conclusions

No-tillage soil management is considered one option of sequestering atmospheric C into the soil and improving soil quality. An important question from producers and policy makers focuses on the effect of a single tillage event of long-term no-till fields on key soil properties. Our study found that a single tillage pass with a disk, sweep, or chisel did not affect SOC stocks compared to no-till under a dryland cropping system in a semi-arid environment. At the Wallace site, disking increased the soil C concentration relative to NT one year after tillage but there was no difference in soil C mass to a depth of 30 cm. The mass of whole soil C had inconsistent changes over time, increasing from nine to twelve MAT in the upper 0-15 cm for Wallace but decreasing over the same time period for Tribune for the lower 5-30 cm. The decrease in SOC over time below 5 cm for Tribune may have been the result of C respiration and reduced C inputs because of drought conditions during the growing season. The Spearville site did not change in SOC over time from Pre-Tillage to twelve MAT.

Aggregation was not significantly affected by a single tillage operation, and thus soil structure was not impacted by the tillage event. Aggregation changed over time from nine to 12 MAT as a result of aggregate turnover, cropping sequence, and changes in soil moisture. Macroaggregates decreased with time in the surface 0-5 cm depth at Wallace because of the influence of alternating wet/dry cycles. Macroaggregates decreased at 12 MAT at Spearville as a result of the loss of actively growing roots and hyphae. The increase in macroaggregates at Tribune may have been the result of the beneficial effects of soil drying on the cohesion of aggregates. At all three sites, there was a general trend for the amount of large microaggregates to decrease and small microaggregates to increase over time.

A single tillage operation did not alter the C concentration of any aggregate size fraction at any site, nor did it alter the mass of C associated with any aggregate size fraction at Tribune or Spearville. The mass of C associated with macroaggregates at Wallace in the surface 0-5 cm was greater for DP and SwP as compared to CP, and tended to be greater than NT. The trend for DP to have a greater mass of macroaggregate C may be indirectly related to the greater root mass afforded by the slightly lower bulk density. This increase in macroaggregate C mass for DP and SwP in the surface 0-5 cm depth was most likely due to recent additions of root-derived POM instead of the incorporation of surface residue from the previous year. The DP tillage also had a lower mass of large microaggregate C in the surface 0-5 cm depth at Wallace, which also parallels a trend for fewer large microaggregates at that depth. The DP tillage at Wallace also had a lower N concentration in all aggregate size classes as compared to the other tillage systems. Differences in aggregate-associated C and N did not consistently correlate to differences in whole soil C and N, however.

The greatest mass of aggregate-associated C existed in the large microaggregate fraction for all three soils. Therefore, it is this aggregate size fraction that has the greatest influence on whole soil C for these locations. A direct causal relationship does not exist between large microaggregate-associated C and whole soil C. However, the response in whole soil C was mixed when large microaggregates decreased over time. It is apparent that other pools of organic C contribute to the net accumulation or loss of whole soil organic C besides aggregate-protected C.

In summary a single tillage utilizing a low intensity implement in semi arid environments will not have a deleterious effect on sequestered C or aggregation when NT management is immediately reinstated after tillage.