ABSTRACT

Title of Document: WINTER ANNUAL RYE COVER CROPS IN NO-TILL GRAIN CROP ROTATIONS: IMPACTS ON SOIL PHYSICAL PROPERTIES AND ORGANIC MATTER

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Winter annual cover cropping (WCC) is a common management practice subsidized by Maryland to protect water and soil quality. The affect of long-term incorporation of WCC on soil physical properties (SPP) is not well established. We hypothesized by increasing organic inputs WCC would improve SPP. To evaluate the effect of WCC and wheel traffic (WT) on SPP, we studied two long term rotations (corn/rye and corn/fallow) at two locations on the Coastal Plain (CP) and one on the Piedmont. WCC improved SPP, but only during the winter at the CP. High levels of WT compacted soil in both rotations. WCC and wheel traffic had no effect on SPP or organic matter at the Piedmont. We conclude, only during the winter did WCC improve SPP; however, due to the drastic annual changes, we hypothesize this improvement is due to soil disturbance caused by the grain drill planting the rye.

WINTER ANNUAL RYE COVER CROPS IN NO-TILL GRAIN CROP ROTATIONS: IMPACTS ON SOIL PHYSICAL PROPERTIES AND ORGANIC MATTER

By

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Literature Review

The State of Maryland encourages the use of winter annual cover crops to improve the quality and purity of water moving from agricultural lands into the Chesapeake Bay and its tributaries. The state government has offered financial incentives to farmers who plant winter annual cereal cover crops through the Maryland Cover Crop Program, (Maryland Department of Agriculture, 2006). For the 2006-2007 planting season, the state Department of Agriculture's Maryland Agricultural Water Quality Cost-Share (MACS) program, provided $8 million in grants for farmers who planted winter cereal cover crops following maize (*Zea mays,* L)or soybean (*Glycine max*) grain harvest (Maryland Department of Agriculture, 2006). Farmers received $20 to $50 per acre, for a maximum of 1,000 acres of planted cover crops. Cover crops eligible for the grants program for fall of 2006 included barley (*Hordeum distychum* L), canola (*Brassica napus* L), rapeseed (*Brassica rapa* L), rye (*Secale cereale* L), ryegrass *(Lolium multiflorum L)*, spring oats (*Avena sativa*), triticale (*Triticosecale rimpani)*, kale (*Brassica oleracea L)* and wheat (*Triticum aestivum* L*)* (Maryland Department of Agriculture, 2006).

Winter cover crop use is encouraged because the practice provides several known benefits for both water quality and ecosystem health, including "planted after the fall harvest, cover crops help absorb unused plant nutrients remaining in the soil and prevent erosion over the winter months" (Maryland Department of Agriculture, "Cover crop program", 2006). Winter annual cereal grains, such as rye and wheat, are known to recover some residual soil nitrogen (N), left after harvest of summer annual crops, to help prevent nitrate leaching into shallow ground and nitrogen enrichment of surface waters (Shipley et al., 1992). However, the effects on soil quality, in general, and soil physical properties, in particular, of long-term inclusion of winter cereal cover crops into grain crop rotations are not well established.

Soil Quality

The concept and definition of soil quality are both ambiguous. Brady and Weil (2002) defines soil quality as, "The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation." In agriculture, the function of soil is to grow plants, either for the consumption by humans or animals, for fiber, or more recently, for fuel energy. In agriculture, the quality of soil is generally judged by utilitarian standards; the soil's quality is determined by the value of the crops it can produce and the net revenue generated by those crops. A specific soil may support more or less plant growth and harvestable product depending on its intrinsic properties and the requirements of the plant species. Specific intrinsic properties, such as texture, and certain more transient chemical and physical properties, such as levels of plant available nutrients and bulk densities are indicative of high quality agricultural soils. Generally, for each parameter used to quantify soil quality, an optimum range exists, above or below which the soil will be less productive.

Certain soil properties can be more easily altered to increase soil quality and crop production. These properties can be altered for varying periods of time; the length depends on the specific soil property being managed. Chemical properties, such as soil pH and concentrations of plant available nutrients, can require frequent management to be maintained in non-native condition for long periods of time. For example, increased soil pH resulting from liming a soil may only last a couple of crop years. It may take repeated limestone applications to maintain an optimum soil pH for an extended period of time. Certain physical properties are often easier to change and, depending on how the change in a physical property is achieved; the resulting change can persist for multiple crop years. Agriculture is an example of a human activity that relies both on the physical condition of the soil to maintain productivity and at the same time, influences it. Often, while trying to change one property, others soil properties are affected, as well. In no-till agriculture, there are minimum physical manipulations of the soil; however, soil physical properties can be affected by other crop management decisions.

Soil Physical Properties

Physical properties of the soil, according to Brady and Weil (2002) are "those characteristics, processes, and reactions of a soil that are caused by physical forces and that can be described by, or expressed in, physical terms or equations". There are many examples of physical properties, and human influences and natural conditions and forces can alter all of them. Natural conditions and forces are those humans have little or no influence over and include the parent material of the soil, pedogenic processes, and the climate.

Whether intended or not, most agricultural management practices alter soil physical properties. Management practices such as tillage are meant to breakup, mix, and granulate soil for the purpose of decreasing the bulk density, improving aeration, and incorporating plant residues. However, many management practices meant to improve the quality of soil for plant growth can also decrease soil fertility and destabilize the soil structure. For example, tillage has been shown to increase aeration, a characteristic that decreases the amount of soil organic matter, overtime. Tillage also can destabilize the soil structure, a characteristic that decreases the nutrient holding capacity, root penetration, and water infiltration. A field that is left fallow for the winter exposes the soil to increased forces of rainfall and wind, a characteristic that breaks down the soil structure and ultimately result in erosion and a loss of the nutrient holding topsoil (Dabney et al., 2001).

Most crop management activities require machinery, such as tractors and combines, to be driven through the field. The machine's weight converts to pressure on the soil through the wheels; heavier tractors and combines increase the pressure on the soil. Wheel traffic often results in soil compaction, the severity of which depends on the vehicle weight, speed, ground contact pressure, number of passes, and the existing physical properties of the soil, soil type, and water content (Swan et. al, 1987, Larson et al. 1994, Charmen et al. 2003). Hillel (1980) stated that in modern agriculture machine wheels and tracks were the most common cause of compaction. Often, compaction is measured in terms of physical properties, such as bulk density, air filled porosity, and air and water infiltration and permeability. Compaction can have significant impacts on both soil physical properties and plant productivity. Plant root systems grown under optimum soil physical conditions are generally deep and expansive, whereas plant roots grown in compacted soils are restricted and concentrate near the base of the plant (Trouse, 1977, Abu-Hamdeh, 2003).

The use of winter annual cereal grain cover crops in most management systems increases the wheel traffic. A minimum of one additional pass with a tractor is required to plant the cover crop; however, more passes may be required depending on how the cover crop is killed and how the residue is managed. As the number of management equipment passes increases, so does the potential for soil compaction (Trouse, 1977, Swan et. al, 1987, Larson et al. 1994, Charmen et al. 2003, Abu-Hamdeh, 2003). Therefore, because the use of cover crops increases the wheel traffic, long term use of cover crops may increase compaction in traffic rows.

Soil Physical Properties and the Environment

The physical condition of agricultural soil is important, not only to maintain agricultural crop productivity, but also to protect the health of surrounding waterways and ecosystems. Cover cropping is a common management practice; however, its ability to alter soil physical properties and improve soil quality is not well documented. As stated by MACS, the purpose for the Maryland Department of Agriculture's financial support of the use of winter cover crops is to protect the quality of water and the surrounding ecosystem (Maryland Department of Agriculture, "Cover Crop Program", 2006). Standards for water quality have been better established than standards for measuring soil quality (Doran and Parkin, 1994). However, because the potential revenue realized by farmers from adopting management practices that protect water quality is low or negative compared to the potential revenue realized by maintaining high soil productivity, government supported programs, such as Maryland's cover crop program, are used to encourage implementation of management practices that protect water and ecosystem quality.

Farmland is considered a non-point source for water pollution (Cunningham and Saigo, 1999). Reduced infiltration of water and the breakdown of the soil structure increase the amount of run-off water from fields and the quantity of soil carried with it. Soil and fertilizers, not incorporated into the soil or covered by vegetation, are exposed to rain and wind that can transport them into waterways. Soil washed off agricultural fields increases sedimentation of nearby waterways which reduces light penetration for submerged aquatic vegetation and other aquatic photosynthetic life that regulate the oxygen availability in the aquatic ecosystem (Cunningham and Saigo, 1999). When soil, mineral fertilizers or organic fertilizers are washed off fields through surface runoff, plant nutrients are transported into the waterways. These nutrients become food for aquatic life normally limited in an aquatic system by the availability of nutrients such as nitrogen and phosphorous. As a result, populations of algae, bacteria, and other species increase, ultimately resulting in decreased oxygen availability, which stresses aquatic organisms. This process, known as cultural eutrophication, reduces survival of fish and other larger forms of aquatic life that humans enjoy and depend on (Cunningham and Saigo, 1999).

The Chesapeake Bay is a large and diverse estuary that has approximately 16 million people population living in its watershed (Chesapeake Bay Program, 2006). The Bay provides both economic and recreational benefits. According to the Maryland Department of Natural resources, the Chesapeake Bay yields more fish and shellfish than any other estuary in the United States (Maryland Department of Natural Resources 2003). The Bay can be divided into four broad habitats: inland and island, fresh water tributaries, shallow water, and open water (Chesapeake Bay Program, 2004). Each habitat depends on levels of nutrients, sediment, and biotic populations. Changing conditions have altered the composition and function of some habitats. Many human activities, including agriculture, of the large population living in the Bay region affect the ecosystem balance. Agriculture is considered a major source of nutrient and sediment pollution to the Bay, as is urban water runoff, wastewater treatment, and industrial activity (Chesapeake Bay Program, 2004). Prevention of nutrient and sediment movement from agriculture lands depends on levels of fertilization, manure management, and soil erosion control. Soil's physical properties have a strong influence on water, nutrient, and sediment movement and therefore a significant influence on prevention of Bay pollution.

The physical condition of soil may also play an important role in both causing and preventing the rise of carbon dioxide (CO_2) in the atmosphere. Approximately 50% of global warming is attributed to increases in atmospheric CO_2 (Cunningham and Saigo, 1999). Many human and natural sources contribute to the increasing CO_2 levels. The combustion of hydrocarbons, and reducing the amount of carbon sinks are all ways that humans contribute to elevated atmospheric CO_2 levels (Cunningham and Saigo, 1999). Agriculture contributes to atmospheric CO_2 levels through the respiration of the tissues of annual plants grown for grain and forage. In addition, respiration of stored soil organic carbon caused by tillage and other soil management practices that disturb the soil release CO_2 into the atmosphere. However, agriculture can also be a method of removing CO_2 into carbon sinks.

Carbon sinks are an important part of the carbon cycle and the global warming issue. Carbon sinks act as long term storage for carbon (Cunningham and Saigo, 1999). There are many examples of carbon sinks, both inorganic and organic. A large amount of carbon is stored in the form of calcium carbonate ($CaCO_3$), which makes up shells and coral stored in the oceans and limestone stored in the land (Cunningham and Saigo, 1999). Coal and oil are sinks that contain large amounts of stable carbon resulting from deposits of decomposed animal and plant remains. Plant life is also an important carbon sink, because it removes CO_2 from the air directly through photosynthesis and stores it as cellulose, lignin, starches or other compounds which make up the majority of a plant's tissues. Perennial plant life, like tree stands, is valuable due to their long lives and long-term carbon storage capacity. Combustion of historic carbon sinks such as oil and forest products releases CO_2, thereby converting stored carbon to new sources of atmospheric CO2 (Cunningham and Saigo, 1999). Soil is gaining attention recently, because it also can act as both a source and a sink for atmospheric CO_2 through soil organic matter cycling (Kay, 1997).

One source of CO_2 evolution from a soil is soil organic matter (SOM). SOM is comprised primarily of carbon containing compounds in various stages of decomposition (Stevenson and Cole, 1999). Soil organisms consume these various compounds transforming them into organic residues, and respiring CO_2. Studies have shown that management practices that decrease soil organic matter, such as tillage which breaks down aggregates, also increase the amount of CO_2 released from the soil into the atmosphere (Drury et. al, 2004). However, SOM can also act as a carbon sink and sequester CO_2. Approximately one third of the carbon from plant residues is left in the soil after one year (Angers and Chenu, 1997). Agriculture contributes to atmospheric CO_2, for example, by emissions from tractors and increasing the release of CO_2 from the soil through tillage. Predictions have been made that over the next 30 years, converting large areas of agricultural land from conventional to conservation tillage will have the capacity to sequester all of the CO_2 emitted from agricultural practices and about 1% of the United States' fossil fuel emissions (Kern and Johnson, 1993).

Certain physical characteristics of soil are important in determining long term CO_2 storage because of the association of CO_2 with soil organic matter. Because many soil organisms require oxygen for respiration, the availability of oxygen is important. The amount of oxygen in the soil is influenced by both soil porosity and water content. Aggregation of soil particles is known to sequester carbon by physically entrapping SOM, occluding it from aerobic microorganisms, and preventing decomposition (Amelung and Zech, 1996; Bol et. al, 2004). One study found that crushing aggregates increased SOM decomposition as measured by C mineralization by 14-35% (Aoyama et. al, 1999). However, loss of soil organic carbon from cultivated soils is primarily due to accelerated soil erosion (Dabney et al, 2001). Since management techniques such as the use of cover crops, reduced tillage, and no tillage can change physical properties of soil to reduce erosion and protect SOM from decomposition, they could also be used to increase long-term storage of carbon in agricultural soils.

The following is a introduction to how winter annual cereal cover crops influence six related soil characteristics that influence the overall soil physical condition – bulk density, water infiltration rate, soil moisture characteristic, air permeability, and aggregation – as well as the changes in soil organic matter that result from long-term use of winter annual cereal cover crops.

Soil organic matter

Soil organic matter influences many of the soil's physical characteristics. Therefore, to understand why observed changes might have occurred, and how we might use this knowledge to optimize soil physical characteristics, it is important to determine how the use of winter annual cereal cover crops changes the components of soil organic matter. Conversely, a soil's physical properties will affect SOM accumulation and residence time in the soil. Because SOM is a heterogeneous dynamic entity within the soil, it is important to define SOM and identify its different components before discussion of the relation of SOM to soil physical characteristics.

When discussing SOM, authors generally create definitions or modify existing definitions to best suit the concepts they are presenting. Organic matter can be defined by both general and specific components as well as by how the components function in the soil. Brady and Weil (2002) broadly define soil organic matter (SOM) as "the organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cell and tissues of soil organisms, and substances synthesized by soil population". Stevenson and Cole (1999) define *in situ* SOM or humus according to the types of component compounds as "a complicated, intertwined network of humic and nonhumic substances adsorbed onto mineral components and containing complexed (chelated) metal ions". Since the two types of material can be bound together the boundary between humic and non humic substances is not distinct (Stevenson and Cole, 1999). Nonhumic substances are a relatively well defined class of compounds including lipids, carbohydrates, peptides, amino acids, and proteins. Humic substances consist of yellow to black colored, high molecular weight polyelectrolytes such as humic acid and fulvic acid (Stevenson and Cole, 1999).

Because organic matter is a complex and dynamic part of the soil system, researchers have grouped organic matter components by their state of decomposition and rate of decay into classification pools. The labile, or active, pool of SOM is characterized by relatively rapid turnover rates of less decomposed components of SOM (Schroth et al., 2003). The recalcitrant pool is comprised of stable compounds, mostly residues digested by microbes, which have slower rates of decay due to their chemical structure, mineral associations, or associations with aggregates (Schroth et al., 2003).

Organic matter also has been grouped into light and heavy fractions. The light fraction is comprised of organic residues within the soil at various stages of decomposition (Stevenson and Cole, 1999). The light fraction excludes soil litter, which is the macroorganic matter that lies on the soil surface. Crop residues are considered to be part of the soil litter, not the light fraction (Stevenson and Cole, 1999). The light fraction is comprised of similar material as the labile pool and can be used as an indicator of input or decomposition changes (Stevenson and Cole, 1999). This SOM fractionation scheme is determined through density separation in liquids with densities of 1.6-2.0. The light fraction is determined as SOM components with lower densities than these liquids and will, therefore, float. The heavy fraction consists of components that do not float (Stevenson and Cole, 1999).

The constituents of SOM may also be characterized by their relationship to water. Water soluble organics are those components which are released into the soil solution; whereas the non-water soluble component is the remainder (Stevenson and

Cole, 1999). Non-water soluble compounds, which are included in the heavy fraction of SOM, contain about 80% of the total SOM mass, but contain only approximately 40% of the soil organic carbon (Swanston et al., 2002). A second group of compounds which are non-water soluble, but extractable in hydrophobic solvents such as chloroform or methanol are known are the hydrophobic components or soil lipids (Dinel et al., 1990). This group is chemically very diverse, and though called *soil lipids,* not all compounds are actually lipids (Stevenson and Cole, 1999). The major components of the hydrophobic group are typically lipids, phospholipids, and long chain fatty acids (Dine et al., 1990). Compounds found in the hydrophobic component are also found as constituents of plant and microorganism lipids (Dinel et al., 1990).

Soil physical properties have complex relationships with each other and with the different types of organic matter. The following is a discussion of the six soil physical characteristics; bulk density, water infiltration rates, soil moisture characteristic, soil respiration, air permeability, and aggregate size distribution and stability. It is important to understand how they are related and their relationship to the different types of organic matter in order to understand how winter annual cover crops might affect each soil physical property.

Bulk density

Bulk density, is a physical property of the soil, which according to Hillel (2004) is "the mass of the soil solids per unit bulk volume of the soil" which includes the volume of the void space. The soil texture influences bulk density. For example, the bulk density of a sandy soil may be approximately 1.6g cm^{-3}, whereas the bulk density of a loam might be less than 1.2 g cm^{-3} (Hillel, 2004). Bulk density is also a function of the arrangement of particles with in a soil. A soil structure with particles packed closely together, containing less void space, will have a higher bulk density than a packing arrangement which increases void space. A decrease in bulk density, and the corresponding increase in porosity, is found with increasing soil organic carbon concentrations. This is due to the "dilution" of the soil solid matrix; where less dense, more porous materials increase the void space within the soil (Kay, 1997). Particle density is the mass of only the soil particles within a given volume without any void space. The average density of organic matter is 0.224 g cm^{-3} (Kay, 1997), where soils have an average particle density of 2.65 g cm^{-3} (Hillel, 2004).

Related to the bulk density is the macroporosity and microporosity of a soil. Macroporosity defines a class of larger size pores and includes biopores, cracks, interaggregate pores, and the largest pores within aggregates (Kay, 1997). No standard size ranges for macro-, meso-, and micropores exist; though several attempts have been made (Daniel and Sutherland, 1986). Macropores have been classified by Kay (1997) as those pores that drain at 0.01 MPa pressure, mesopores are pores that drain from 0.01 to 1.5 MPa pressure, and micropores are pores that drain at 1.5 MPa pressure or greater. According to Brewer (1964), macropores are those with diameters >75μm, mesopores are those with diameters 30 to 75μm, and micropores 5 to 30μm. Decreases in bulk density should result in increases in macroporosity. Macropores, much more so than micropores, are affected by changes in soil management (Kay, 1997). Macropores are the principle pathways for infiltration, water drainage, and aeration. Therefore decreases in bulk density due to increases in SOM may be correlated with increases in water infiltration rates and air permeability.

Effect of cover crops on bulk density

Winter annual cover crops have been shown to increase soil organic matter and macroporosity (Patrick et al., 1957). In a 17 year rye/vetch cover crop and cotton rotation on a fine-silty soil, bulk density of the cover crops treatment decreased for the 0-10cm depth compared to treatments without cover crops (Keisling et al., 1994). Villamil et al. (2006) found that drilled winter annual cereal grain cover crops in no-till corn and soybean rotations decreased surface soil bulk density compared to rotations with winter weeds. No significant differences in soil bulk density were found deeper than 10cm (Villamil et al 2006). However, in a three year study, cover crops did not affect bulk density; yet wheel traffic in the same rotations had a significant impact of increasing bulk density (Wagger and Denton, 1989). This might indicate that the longer a cover crop is in rotation the more likely it is to affect the bulk density. Testing bulk density gives an important estimate of overall extent of change in total soil properties.

Effect of wheel traffic on bulk density

Changes in bulk density due to increases in wheel traffic have been well established. Wheel traffic has been shown to increase bulk density by compacting soil in traffic rows (Swan et. al, 1987, Hill and Meza-Montalvo, 1990). The weight of a vehicle pressing on the wheels is known as axle load. The bulk density has been found to increase as the axle load increases. Abu-Hamdeh (2003) found a 3.5% increase in bulk density with an 8 Mg load and a 5% increase with a 19 Mg axle load for the 10 to 50cm portion of the soil profile on a clay loam soil. Similarly, Gysi et al. (1999) found a 7% and 6% increase in bulk density under 7.47 and 11.23 Mg wheel loads respectively for an untilled sandy loam. In addition to the axle load, the moisture content of the soil at the time the vehicle is driven can affect the change in bulk density. When exposed to the same axle load the bulk density of a wet soil will have larger increases in bulk density compared with the same soil with a lower moisture content (Gysi, 1999, Abu-Hamdeh, 2003, Yavuzcan et al. 2005).

Water infiltration, hydraulic conductivity, sorptivity, and soil-moisture retention

Water infiltration, hydraulic conductivity, sorptivity, and soil moisture characteristic are related soil physical properties. Water infiltration rate (i) is defined according to Hillel (2004) as "the volume flux of water flowing into the profile per unit of soil surface area". Closely related to infiltration (I) is hydraulic conductivity and sorptivity. Hydraulic conductivity (k_w) has been defined as "the ratio between the flux of water through a porous medium and the hydraulic gradient." Sorptivity (S) is infiltration into the soil profile dominated by the absorptive forces of capillarity (Clothier and Scotter, 2002).

The relationships between I, k_w, and S with time (t) were first established by Phillip (1957). He proposed this simple relationship to describe one dimensional infiltration:

$$I = St^{1/2} + At$$

where A is an estimate of k_w. At initial and short periods of time S is considered to dominate infiltration; however, at long times when gravity dominates downward movement of water so does k_w dominate the estimation of I (Clothier and Scotter, 2002).

Soil properties that affect infiltration also will affect the soil-moisture characteristic include texture, soil structure, pore size distribution, and entrapped air.

The soil-moisture characteristic, also known as the soil moisture retention curve or the soil moisture release curve, is the relationship between soil water content and soil water suction (Klute, 1986). Soil organic matter has a direct effect on soil moisture retention due to its dominant hydrophilic composition and indirectly by changing soil structure (Klute, 1986).

As stated, water infiltration rates and soil-moisture retention are dependent on the relative size of the pores. Base on Poiseuille's Law, at the same depth in the soil, if pore A has a diameter twice the diameter of pore B, pore A will carry approximately 16 times the quantity of water (Hillel, 2004). This implies that the number of macropores will have the largest impact on how quickly a soil can transmit water and will affect both the infiltration rate and the soil-moisture characteristic.

Effect of cover crops on water movement

Crop rotations have been shown to have an effect on water movement; however, no conclusive evidence on the effect of winter annual cover crops on water infiltration rates has been presented. In a 17 year rye/vetch cover crop and cotton rotation, hydraulic conductivity was shown to have increased with use of a cover crop compared to fallow (Keisling et al., 1994). Villamil et al (2006) found significant increases in total soil porosity and soil transmission pores (macropores), however did not find significant differences in hydraulic conductivity suggesting high variation and reductions in residue cover decreased the hydraulic conductivity. Carreker et al. (1968) concluded that water infiltration rates increased as the quantity of plant material returned to the soil increased. However, in a 3 year study conducted by Carreker et al. (1968) on a sandy loam there was no significant difference in infiltration of continuous corn rotations that used either a rye cover crop or winter fallow. Similarly, in another short term study, Wagger and Denton (1989) found no significant difference in soil porosity and hydraulic conductivity after only 3 years of rye cover crops in rotation with continuous corn. This could imply that longer periods of cover crop use are necessary before changes in characteristics affecting infiltration and the soil moisture curve are measurable.

Effect of wheel traffic on water movement and retention

Wheel traffic, however, has been proven to have a significant effect on infiltration rates. Kemper et al. (1982) found reductions in infiltration rate from 12 to 80% in traffic furrows compared to non-traffic furrows. Moderate compaction with 3 tractor passes decreased the number of large pores and increased the number of medium pores (Lipiec et al., 1998). Similarly, Hill and Meza-Montalvo (1990) at Maryland's lower eastern shore location found a similar effect of increased wheel traffic load on the water storage, decreased storage at 0 kPa offset by increased storage at mid-range (-3.9 to – 40 kPa) water potentials. However, infiltration rate depends on the size and number of large pores. If the largest pores are significantly affected, then increased compaction in trafficked rows can decrease the permeability of soil to air and water (Basher and Ross, 2001). In addition, water content at time of compaction had significant effect on measured water infiltration rates (Kemper, 1982).

Basher and Ross (2001) found when the soil went through wetting and drying cycles cracks opened and infiltration rates increased. They also found that increasing the rate of infiltration can significantly decrease erosion, which occurred along the edge and bed of wheel tracks. Most of the erosion occurred during the season with highest frequency and intensity of rainstorms and when infiltration was lowest. The eroded soil was comprised of stable aggregates, 75% of which were between 0.25 and 4mm (Basher and Ross, 2001). Because of the influence on water infiltration and erosion, understanding the influence of wheel traffic and cover crops on water infiltration, and water movement within an agricultural landscape is important to nutrient management, particularly management of phosphorous.

Effect of water infiltration on phosphorus mobility

Phosphorus (P) is an important plant nutrient and its availability to plants is often limited by the inability of soluble P to remain at adequate concentrations in the soil solution. Phosphorus ions form highly insoluble precipitates with calcium in alkaline soils, and with iron, aluminum, and manganese in acidic soils. However, because excess P is considered a pollutant in water bodies which can contribute to the eutrophication of surface waters, keeping phosphorous from being transported from agricultural fields to surface water is important to environmental quality (Cunningham and Saigo, 1999). Water runoff from agricultural fields can carry soil sediment, particulate-bound P, and dissolved P from land-applied organic and mineral fertilizers into waterways before they can be immobilized within the soil or taken up by plants. Increased infiltration rates can help reduce runoff and the quantity of P reaching waterways by increasing the quantity of water that can enter the soil during a given time. Cover crops may play a role in preventing P pollution of surface waterways by increasing soil infiltration rates.

Air permeability

Measurements of air permeability (k_a) quantify convective gas movement within the soil. Ball and Schjinning (2002) describe air permeability as a soil's ability to transmit convective flow of air through the soil in response to a pressure gradient. Because both water and air movement follow Darcy's Law, which relates the rate of flow to the pressure and the porous medium, the flow of air is comparable to the flow of water (Ball and Schjinning, 2002). Since air and water both occupy pore spaces among soil solids, water content has a strong influence on air permeability. Maximum air permeability values are attained when soil is dry and decreases as soil water contents increase (Ball and Schjinning, 2002). Macropores are the main conduits for airflow and the largest decreases in airflow occur when those pores fill with water (Ball and Schjinning, 2002). Another study found that though texture was relatively the same, air permeability decreased as organic matter decreased (Jalbert and Dane, 2003). Air permeability is useful in determining the "openness" of the soil surface to air entry (Hillel, 2004).

The ability of the soil to transmit air is important to soil respiration and aeration. Soil respiration requires oxygen, which is supplied to soil organisms through air filled pores. It is important to determine air permeability when measuring soil respiration to understand whether differences in soil respiration are due to decreased activity of soil organisms or by the inability of the air to penetrate through the soil. For example, if there are differences in the respiration of two soils but not in the air permeability, it can be assumed that the difference is due to microbial activity.

It has been established that wheel traffic can have a significant effect on the large pores in the soil. Because wheel traffic can affect the large pores it also will affect the air permeability. Gysi et al. (1999), found decreases in air permeability of 2.3% when a 7.47Mg load was applied and 27.5% when an 11.23 Mg load was applied under moist conditions for an untilled sandy loam soil. At three moisture contents, Yavuzcan et al. (2005) found wheel traffic decreased air permeability 85%, 48%, and 91% in conventional tillage plots compared to no wheel traffic conventional tillage is the most aggressive and usually causes the most soil disturbance. In the less aggressive chisel plowed plots soil air permeability decreased 95, 81, and 87% at 6kPa suction when compared to the control with no wheel traffic. Similar, results were found at 32kPa suction. When the soil was at a lower moisture content, wheel traffic caused less decrease in k_a for both suctions (Yavuzcan et al., 2005). Dry soil deforms the least, transmitting most of the stress lower in the profile. At the mid-level moisture, less stress was transferred to the lower profile, while the soil was dry enough to maintain structural integrity (Yavuzcan et al., 2005).

Aggregate size distribution and stability

Soil structure is an important aspect of the physical condition of the soil. There currently are only two methods available for indirectly quantifying soil structure. One method is measuring porosity, mentioned previously, and the other method is a measure of aggregation. Aggregation is defined as the manner in which primary and secondary soil particles are arranged together and become part of the broader soil structure (Hillel, 2004). Aggregates are an important aspect of the soil condition and may influence other processes.

The theory of hierarchical aggregation formation was developed by Tisdall and Oades in 1982. The theory describes how primary particles bind together by bacterial, fungal, and plant debris that form microaggregates. The microaggregates are then further bound together by transient and temporary binding agents, such as particulate organic matter and polysaccharides, into macroaggregates (Tisdall and

Oades, 1982). More highly aggregated soils will have larger proportion of macroaggregates to microaggregates. In 1984, Oades proposed an alternative to part of this theory, suggesting that macroaggregates are formed physically by roots and fungal hyphae, and microaggregates form and stabilize within the macroaggregates as a result of the break down of the debris and microbial by-products, clay, and organic molecules (Oades, 1984). There is support for both theories within the literature with no conclusive evidence giving preference to either theory.

Aggregates demonstrate the following characteristics. First, aggregates will break down into their constituent parts due to dispersive forces such as slaking, but not into primary particles such as clays and binding agents (Oades and Waters, 1991). Air slaking is the tendency for aggregates to burst due to positive pressure on air entrapped inside of aggregates (Hillel, 2004). Second, carbon concentrations will increase with aggregate size due to the addition of organic agents binding smaller aggregates (Elliot, 1986). And third, more labile materials are contained in macroaggregates than microaggregates (Elliot, 1986; Puget et al., 2000; Jastrow, 1996). This model has been confirmed for all soils in which organic materials are the dominant binding agents, which excludes soils such as metal oxisols where oxides are the dominant binding force (Oades and Waters, 1991).

The distribution of SOM in and among aggregates is heterogeneous in nature and results of characterization efforts are frequently affected by methods of analysis that are used (Angers and Chenu, 1997). In a study by Jastrow (1996), approximately 90% of SOM was located within soil aggregates. Similar findings by Puget et al. (2000) analyzed the distribution of particulate organic matter (POM), which contains a significant fraction of the labile pool (Angers and Chenu, 1997), and found that

87% of the POM was occluded within water stable aggregates. Additionally, POM within water stable aggregates contained 74% of the total POM carbon (Puget et al, 2000). The majority of POM was found in the 0.2mm – 1.0mm aggregate class size, and aggregates of this size occluded approximately 70% of both the POM and POM carbon (Puget et al, 2000). Approximately 13% of POM was free, not occluded within aggregates; however, it contained 26% of the POM carbon (Puget et al, 2000). POM is just one of the SOM fractions that have been found to be important for aggregate formation and stability.

Different types of organic matter have been found to affect aggregate formation and stability. Hydrophilic polysaccharides have been shown to be highly correlated with aggregate stability due to tendency to be strongly adsorbed onto mineral particles (Chaney and Swift, 1984; Haynes and Swift, 1990; Haynes et al., 1991; Angers et al., 1993a, b). The hydrophobic components of soil organic matter influence the formation and stability of aggregates. Hydrophobic components of SOM are more resistant to breakdown by soil microbes which may help protect the SOM holding the aggregates together from breaking down. In an incubation study, Piccolo and Mbagwu (1999) found that additions of a hydrophilic polysaccharide gum increased aggregate stability more than additions of a hydrophobic stearic acid. The aggregation-enhancing effect of hydrophilic gum addition was transient and diminished quickly, where as the hydrophobic stearic acid increased aggregate stability throughout the study. An interpretation of results in the literature indicated that hydrophobic compounds tend to increase aggregate stability by slowing water entry into aggregates and reducing slaking (Sullivan, 1990). When studying water repellant sands in New Zealand, Horne and McIntosh (2000) suggested that hydrophobic compounds were found on the outer layers of the organic matter. This supports findings by Piccolo and Mbagwu (1999), who suggested that hydrophobic compounds form protective coatings around aggregates. Therefore, quantifying the hydrophobic component may present a clearer picture of changes in organic matter and be more highly correlated with changes in aggregation.

Plant residues and the resulting microbial activity have been found to stimulate aggregate formation (Angers and Chenu, 1997). However, different plant residues decomposed at different rates and do not promote aggregation with the same efficiency, possibly due to the ability of soil organisms to break them down (Angers and Chenu, 1997). For example, non-water soluble components of winter cover crops have slower carbon mineralization rates at lower temperatures than the water-soluble compounds (Magid et al., 2004). Use of winter annual cereal cover crops could lead to a build-up in the soil of both the non-water soluble and hydrophobic fractions that are associated with aggregation. Therefore, analysis of the plant residue biomass added to the soil and their relative proportions remaining in the soil may also lead to a better understanding how winter annual cover crops affect aggregation and the types of compounds being built up in the soil over time.

Effect of cover crops on aggregate stability

Because aggregation is intimately tied to the quantity and quality of organic matter present in the soil, management practices that affect soil organic matter have been shown to affect aggregation. Several studies have shown that increases in organic matter from the addition of manure have resulted in the formation of macroaggregates (Aoyama et al., 1999; Bol et al., 2004). Cover crops also influence aggregate stability over time through the addition of organic residues. In a 25 year conventionally tilled cotton study, cover crops improved mean aggregate size as well as several other related characteristics (Patrick et al. 1957). In a continuous wheat rotation, cover crops are grown during the fallow period during the summer months, whereas in a continuous corn rotation a cover crop is grown during the winter months where the field would otherwise be left fallow. Switching to a rotation with a cover crop from a continuous wheat or corn rotation resulted in a 23% - 40% increase in aggregate stability over 100 year rotation study on the Sanborn Field, University of Missouri – Columbia (Rachman et al., 2003). In another study, compared to winter fallow a significant increase was found in the percent of soil in aggregates in a winter wheat cover crop following maize rotation (Kabir and Koide 2000). Villamil et al (2006) found significant increase in water aggregate stability in corn/soybean rotation. Cover crops also have been shown to increase aggregate size distribution by protecting aggregates from the impact of raindrops (Delgado et al, 1999).

Not all studies have shown that cover crops increase average aggregate size. Mendes et al. (1999) found no significant difference in aggregate size distribution with or without a cover crop in a vegetable crop rotation; he did, however, find significant increases in soil microbial carbon and enzymatic activity in the cover crop treatment. Wright et al. (1999) found that several compounds produced by fungi, glycoproteins including glomalin, are essential to the stability of aggregates, however, active root growth and no-till management are necessary for maximum effect. In addition, several studies have confirmed that tillage homogenizes aggregate size distributions (Beare, 1994). In the vegetable rotation study by Mendes et al. (1999), cover crops were incorporated by rototilling, which could explain why, despite the increase in soil microbial biomass carbon and enzyme activity, no increase in the mean aggregate size was found.

Effect of wheel traffic on aggregate stability

The effect of wheel traffic on the stability of aggregates has not been extensively investigated. Wheel traffic and compaction lead to larger aggregates in the 0 –7.5 cm layer (Liebig et al., 1993). Compression caused by wheel traffic forces soil particles closer together, which may help increase aggregate stability without an increase in organic matter. Similarly, traffic was found to increase aggregate stability (Voorhees 1979, Voorhees 1984). However, several studies have shown that wheel traffic has no significant effect on OM (Hill and Meza-Montalvo 1990, Pierce et al. 1994, Lal 1999). Therefore, an increase in aggregate stability would depend on other soil factors.

Cover crops and physical properties

Soil's physical properties: bulk density, water infiltration, air permeability, and aggregate stability, all influence the total soil physical characteristic and how plants grow in the soil. If cover crops have a positive influence on the soil physical properties by increasing oxygen availability and decreasing bulk density, then farmers may benefit from better root growing conditions for cash crops. In addition increases in soil organic matter from cover crops may help maintain soil quality and plant available nutrients. However, the primary goal of Maryland's cover crop program is to prevent nutrient and sediment movement from agricultural soils to ground and surface water. Since soil physical properties influence the movement of nutrients by determining water movement and erosion. Understanding how cover crops affect physical properties is important for evaluating the program's effectiveness at preventing sediment and phosphorus movement into waterways, which in the Chesapeake Bay may become pollutants and alter the current ecosystem.

Experiment objectives

This experiment has three objectives. First, determine the influence of long term winter annual cover crops use in corn rotations on soil physical properties: bulk density, water infiltration, the soil moisture release characteristic, air permeability, and aggregate stability. Second, evaluate the effect of winter annual cover crops on physical properties in high and low wheel traffic areas. Lastly, determine the influence of winter annual cover crops and wheel traffic on soil organic matter. Understanding how winter annual cover crops and wheel traffic affect physical properties and soil organic matter is important for evaluating the program's effectiveness at preventing sediment and nutrient movement into the Chesapeake Bay and maintaining soil quality in the state of Maryland.

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Chapter Two: The effect of winter annual cover crops on soil physical properties and organic matter

Introduction

The State of Maryland encourages the use of winter annual cover crops (WCC) to improve the quality and purity of water moving from agricultural lands into the Chesapeake Bay and its tributaries. WCC use is encouraged because the practice provides several known benefits for both water quality and ecosystem health (Maryland Department of Agriculture, 2006). However, the effects on soil quality, in general, and soil physical properties, in particular, of long-term incorporation of WCC into grain crop rotations are not well established. Since soil physical properties partially determine the off-field movement of nutrients by influencing water movement and erosion, understanding how WCC affect soil physical properties is important for evaluating the potential effectiveness of cover crops at preventing sediment and nutrient transport into waterways, which may become pollutants and alter the aquatic ecosystem.

Physical properties of the soil, according to Brady and Weil (2002) are "those characteristics, processes, and reactions of a soil that are caused by physical forces and that can be described by, or expressed in, physical terms or equations". A soil's individual physical properties: bulk density, water movement, air permeability, and aggregate stability; all influence the total soil physical characteristic and have the potential to be influenced by the use of WCC. WCC has been shown to affect soil C and the rate of soil C accumulation compared to winter weeds (Sainju 2006), and through the accumulation of soil C WCC may directly affect soil physical properties (Reeves 1994). Macropores, much more so than micropores, are affected by changes in soil management (Kay, 1997). An inverse relationship exists between bulk density and the number and/or size of macropores, as bulk density decreases macropores can increase in both size and number. Macropores are the principle pathways for infiltration, water drainage, and aeration. Macropores are the main conduits for airflow and the largest decreases in airflow occur when those pores fill with water (Ball and Schjinning, 2002). Therefore decreases in bulk density due to increases in SOM and porosity may be correlated with increases in water infiltration rates, air permeability, and aggregate stability.

Evidence of the positive effect of winter annual cover crops on soil physical properties is found in past studies. In a 17 year rye/vetch cover crop and cotton rotation on a fine-silty soil, bulk density of the cover crops treatment decreased for the 0-10cm depth and hydraulic conductivity, which is the ability of the soil to transmit water, was shown to have increased with use of a cover crop compared to winter fallow (Keisling et al., 1994). Similarly, in a short term study, Villamil et al. (2006) found that drilled WCC in no-till corn and soybean rotations decreased surface soil bulk density compared to rotations with winter weeds; however, no significant differences in soil bulk density were found deeper than 10cm. In the same study, though significant increases in total soil porosity and soil transmission pores (macropores) were found, there were no significant differences in hydraulic conductivity between rotations with cover crops and winter weeds (Villamil et al 2006).

However, several studies provide evidence that cover crops have no affect on soil physical properties. In a three year study, cover crops were not found to affect bulk density and no significant difference in soil porosity and hydraulic conductivity were found after 3 years of rye cover crops in rotation with continuous corn (Wagger and Denton, 1989). Carreker et al. (1968) concluded that water infiltration rates increased as the quantity of plant material returned to the soil increased. However, in a 3 year study conducted by Carreker et al. (1968) on a sandy loam there was no significant difference in water infiltration rate when a rye cover crop was included in a continuous corn rotation.

Soil organic matter has effects on the soil physical properties directly due to its dominant hydrophilic composition and indirectly by changing soil structure (Klute, 1986). Puget et al. (2000) analyzed the distribution of particulate organic matter (POM), which contains a significant fraction of the labile pool (Angers and Chenu, 1997), and found that 87% of the POM was occluded within water stable aggregates. Additionally, POM within water stable aggregates contained 74% of the total POM carbon (Puget, 2000).

In a 25-year conventionally tilled cotton study, cover crops improved mean aggregate size as well as several other related characteristics (Patrick et al., 1957). Similarly, Rachman et al.(2003) reported a 23 to 40% increase in aggregate stability when continuous wheat or corn rotations in the historic100-year rotation study on the Sanborn Field at the University of Missouri where modified to include a winter cover crop. In another study, a significant increase in the percent of soil in aggregates was found in a winter wheat cover crop following maize compared to winter fallow (Kabir and Koide 2000). Villamil et al. (2006) found a significant increase in water aggregate stability with the use of winter annual cover crops in a corn/soybean rotation.

Not all studies have shown that WCC increase the average size of soil aggregates. Mendes et al. (1999) found no significant difference in aggregate size distribution with or without a cover crop in a vegetable crop rotation; he did, however, find significant increases in soil microbial carbon and enzymatic activity in the cover crop treatment. Wright et al. (1999) found that several compounds produced by fungi (glycoprotein and glomalin) are essential to the stability of aggregates and the presence of these aggregate stability promoters are related to active root growth and are more prevalent under no-till management conditions. In addition, several studies have confirmed that tillage homogenizes aggregate size distributions (Beare et al., 1994). In the vegetable rotation study by Mendes et al. (1999), cover crops were incorporated by rototilling, which could explain why, despite the increase in soil microbial biomass carbon and enzyme activity, no increase in the mean aggregate size was found.

Experiment objectives

Understanding how winter annual cover crops and wheel traffic affect physical properties is important for evaluating the ability of cover crops to prevent sediment and nutrient movement into surface waters and maintaining soil quality. Our research has two objectives. First, we set out to determine the influence of long term use of winter annual cover crops in corn rotations on primary soil physical properties: bulk density, water infiltration, the soil moisture release characteristic, air permeability, and aggregate stability. Our second objective was to determine the influence of winter annual cover crops on soil organic matter.

Materials and methods

Experimental Design

A long-term row-crop rotation study was established in 1994 with field plots at three locations; 1) the Wye Research and Education Center (Wye), 2), the Lower Eastern Shore Research and Education Center, Poplar Hill Facility (Poplar Hill), and 3) the Central Maryland Research and Education Center, Clarksville Facility (Clarksville). The Wye and Poplar Hill are located on the Delmarva Peninsula on the coastal plain of Maryland, USA. Wye was located at 38°59' N and 76'09'W, and has a Matapeake silt loam soil with fine-silty, mixed, semiactive, mesic Typic Hapludults surface texture and <1% slope. Poplar Hill was located at 38°37' N and 76°44' W, and has a Mattapex loam soil, a fine silty, mixed, active, mesic Aquic Hapludults surface texture and <1% slope. Clarksville is located at 39°14'N and 76°55' W', and includes portions of both a Manor loam soil with a Coarse-loamy, micaceous, mesic Typic Dystrudepts and a Chester fine-loamy, mixed, semiactive, mesic Typic Hapludults with a 5 to 8% slope. See Appendix B for additional soil properties. Though Poplar Hill location is generally wetter than Wye, the Wye and Poplar Hill locations, both located on the coastal plain, are similar soils compared to the soil at Clarksville. The three locations will therefore be grouped into two locations where possible: Coastal Plain, which will include Wye and Poplar Hill locations, and the Piedmont, which will include the Clarksville location.

The field experiment design was a randomized complete split-block design where the main-plot treatments are two, two-year crop rotations that were established at the three research locations in 1994. The crop rotation treatments were: 1) corn/winter fallow/corn/winter fallow; and 2) corn/cereal rye winter cover crop/corn/cereal rye winter cover crop. There were four replications of the two crop rotation treatments at each of the three research locations. The 2005 corn and 2006 corn growing seasons were the twelfth and thirteenth consecutive years for the crop rotations, respectively. All three locations have been in no-till row crop management since the initiation of the study in 1994.

Management of the experiment varied slightly among the three locations. Corn planting and harvest dates varied by a one to two weeks from site to site and year to year (Table 2.1). Corn was no-till planted and fertilized according to Maryland Cooperative Extension recommendations for the expected yield goals. The rye cover crop was planted after corn harvest with a Great Plains 1510P (Wye) and Great Plains 1006NT (Poplar Hill), no-till seed drill, with fluted disk row openers. Rye was planted at Clarksville with a John Deere 1560 no-till drill with beveled edge disk row openers. No fertilizer was applied to the rye cover crop. Rye was killed with an herbicide at approximately the early boot stage (Feekes growth stage:9) prior to corn planting with residues left on the soil surface.

Soil Sample Collection and Processing

Sampling for bulk density, air permeability, water infiltration, soil moisture content, aggregate stability, total organic matter, and labile organic matter occurred May through January of 2005 and 2006, but categorized into two seasonal sampling periods: “corn” and “rye” (Appendix A). The corn sampling period was defined as the period between corn planting and rye cover crop planting. The rye season sampling period was defined as the period between rye cover crop planting and corn planting.

Water infiltration, the soil moisture release curve and aggregate stability were determined for the 0 to 7cm soil depth. Bulk density was determined for 1 to 7 cm soil depths, due to construction of the core sampler which excluded the top 1cm of soil. The surface layer of the soil was chosen because studies have shown that these soil physical parameters were most likely to be affected by no-till crop management in the surface layers of the soil (Blevins et al. 1985). The choice to use the 0 to 7 cm depth was based on compromise between soil morphological features, the need for a uniform sampling depth for all sites, and equipment limitations. Air permeability and soil water content were sampled at the 0 to 3 cm soil depth. This shallower depth was selected based on preliminary sampling and the limitations of the sampling equipment which indicated a consistent, but shallow sampling depth would be required to facilitate reliable sample collection under both high and low soil moisture conditions. Total organic matter and labile carbon were determined for the 0-7 cm layer. Samples were immediately air dried after field removal. After drying a sub-sample of soil was ground, passed through a 2 mm sieve, and stored at room temperature for organic matter and labile carbon analysis.

Bulk Density

Bulk density soil samples were collected by removing an undisturbed soil core 5.5 cm diameter, 1 to 7 cm deep, with an Unland core sampler (Blake and Hartge, 1986). At each sampling date, six cores were collected from each replicate of each treatment from the three research sites. Sets of bulk density cores were collected during the corn and rye season sampling seasons for both 2005 and 2006. Cores were oven dried at 105ºC for 24 hours and then weighed. Bulk density was calculated as the mass of the soil divided by the total volume of the core (Blake and Hartge, 1986).

Soil-moisture retention

A subset of the bulk density cores were used for determination of soil moisture retention. Two cores from each replicate of each treatment from the three experimental sites were used. Soil moisture release curves were determined from cores collected from Wye and Poplar Hill in the corn and rye seasons of 2006. For the Clarksville location, soil moisture release curves were determined from cores that were collected corn 2005 and rye 2006 sampling periods. The soil moisture characteristic was constructed using the drainage curve of the undisturbed cores according to the methods presented by Klute (1986) and Dane and Hopmans (2002). A combination of three levels of suction and pressure conditions were applied to the cores and the water content measured at each level. The 0 to -0.3 kPa range was determined using a suction sand table with a hanging water column the - 10.0 to -60 kPa range was done using low pressure plates, and for the –500 to -1500 kPa range, high pressure plates were used on smaller ground sub-samples of the original cores (Dane and Hopmans, 2002).

Water infiltration rate and cumulative water infiltration.

A modified Marriot-type infiltrometer was used to measure water infiltration rates at all three locations (van Es, et al., 1999). Water infiltration rate was determined from each replicate four times in rye season 2005 and six times in corn and rye seasons 2006. No pre-wetting procedure was used; instead measurements were taken within 48 hours of a significant rainfall event, except for the May 2006 measurements at Wye. A significant drought occurred during the first 6 months of 2006. Soil moisture content measurements were made at the time of sampling with a Campbell Scientific "HydroSense ^{TM}" two prong time-domain reflectrometer (TDR) to assure that soil was at or near field capacity for the when sampled. The infiltrometer was mounted on a 20 cm diameter metal ring was driven into the surface soil to a depth of 7 cm. The Marriot-type infiltrometer maintained a constant 10cm hydraulic head above the surface of the soil and water evacuation from the reservoir was used to determine the flow of water (Q) into the soil. Infiltration measurements were recorded every five minutes for at least 30 minutes and until the flow was constant. Infiltration rate (length (L), time $^{-1}$ (t)) was calculated by:

$$i = q/t,$$

Where q is the amount of water, t is time and i is the infiltration rate. Cumulative water infiltration (I) for a given measurement was considered to be the amount of water infiltrated after 30 minutes.

Hydraulic conductivity and sorptivity

Hydraulic conductivity (k_w) and sorptivity (S) were calculated based on the methods by Clothier and Scotter (2002) using water infiltration data: the cumulative infiltration (I) and time (t). According to Phillip (1957) the relationship between cumulative infiltration, hydraulic conductivity, and sorptivity can be described by:

$$I = At + St^{-1/2},$$

where A is an estimate of hydraulic conductivity and S an estimate of sorptivity. Analysis was performed using Excel's "solver" (Microsoft Corporation, Redmond, WA), a non-linear parameterization according to the methods of Wraith and Or (1998) which estimates the value of A and S by minimizing error between the observed cumulative infiltration (I_{ob}) and the cumulative infiltration predicted by the Phillips equation (I_m).

Air Permeability

Air permeability (k_a) field measurements were made at all Wye and Poplar Hill plots for both corn and rye seasons of 2005 and 2006. Air permeability was determined at Clarksville corn and rye seasons of 2005 and rye season of 2006. A hand held air permeameter (Soil Measurement System, Tucson, Arizona) based on the design by Jalbert and Dane (2003) was used to collect field data. The air permeameter used a battery powered, constant, low-flow air pump, a low pressure differential pressure transducer, and a voltmeter. Air flow of the pump was calibrated for a range of pressures by the manufacturer. To reduce the disturbance of the plots, surface plant residue was gently removed from the measurement area and PVC rings (10.16 cm diameter, 12.70 cm height) were inserted 3cm into the soil. The plant residue that was previously removed was placed back inside the PVC ring prior to air permeability measurement. Tygon tubing connected the air permeameter and a sealed PVC chamber fit over the inserted rings. Changes in air pressure in the chamber above the soil were detected by the pressure transducer and translated into a voltage and recorded by the voltmeter and converted to a back-pressure in cm H_2O units.

It was assumed that Darcy's Law is applicable, which will be used in determining air permeability. Jalbert and Dane (2003) used:

$$k_a = (\mu/DG)\ (Q/\Delta P),$$

where k_a is the permeability (L^2), μ is the dynamic air viscosity (mass (M) $L^{-1}\ t^{-1}$), Q is the air flow rate provided by the pump ($L^3\ t^{-1}$), D is the inside diameter (L) of the rings inserted into the soil, G is the geometric factors based on the shape and diameter of the rings, and ΔP is the pressure differential between the air inside the pump chamber above the soil and the atmosphere ($M\ L^{-1}\ t^{-2}$). Air viscosity is determined by the equation:

$$\mu = (1717 + 4.8T) * 10^{-8}\ \text{Pa s}.$$

Air viscosity, while ignoring humidity, is mainly dependent on temperature (T, ºC). Air temperature was recorded simultaneous with the pressure reading to determine viscosity (Jalbert and Dane, 2003). Water content has been shown to have a significant effect on air permeability (Ball and Schjinning, 2002). To decrease variability due to water content between 1 and 3 air permeability measurements were recorded during the corn and rye seasons sampling periods at various soil water contents without removing the PVC rings from the soil. In addition, 3 TDR measurements of the volumetric water content of the soil were taken surrounding each ring, so the water content might be measured without disturbing the soil in the ring. The PVC rings were removed at the end of each of the corn and rye season sampling periods.

Aggregate stability

The procedure for aggregate stability was adapted from methods by Kemper and Rosenau (1986) and Bryant et al. (1948). Four soil samples from each replicate at the three study locations were collected. Soil was air dried and large clods gently broken apart. About 20 g of 2.0 to 6.0 mm aggregates was placed on a nest of two sieves, including a 10 and 35-mesh (2 and 0.5 mm) and vertically oscillated 3.8 mm inside of a can filled with water, 30 times a minute for 3 minutes. The soil retained on each sieve was oven dried for 3 hours at 105ºC and weighed. After weighing, soil was returned to its sieve, re-wet, and aggregates were dispersed by smearing it across the sieve so that only sand or gravel remained on the sieve, sand and gravel was re-dried and weighed. The fraction of water stable aggregates (WSA_C) corrected for gravel/sand by subtracting gravel/sand from the fraction of soil left on the sieve before sand was removed before dividing by the original sample weight.

Residue

The percent of soil covered by residue was determined by laying a 48 cm by 48 cm grid of 4 cm^2 squares between corn rows. A digital image was taken of the grid, at four locations in the plot. Later the grid was analyzed by counting the squares with residue and divided by the total number of squares.

Total organic matter

Four ground samples from each experimental unit were taken from each site and analyzed for total organic matter (OM_t) by the loss on ignition method using a "Blue M" oven according to methods by Schulte (1995), adapted from the methods of Storer (1984). Approximately 1.5 to 2 g of ground soil was exposed to 360°C for two hours to incinerate organic compounds. The loss on ignition (LOI) was calculated:

$$LOI = [\ (S_d - S_f) / S_d)\ ]$$

Where S_d is the weight of dry soil in grams, and S_f is the weight of soil after combustion. A subset of samples was analyzed for total organic carbon using a Leco CHN 2000 (Leco Corporation, St Joseph, MI) high-temperature induction furnace (Nelson and Sommers 1982). An estimate of OM_t was calculated as:

$$\%OM_T = (\%\ \text{total C} * 1.72) / 0.58,$$

recommended by Schulte (1995). The resulting estimates of OM_t were regressed upon LOI and the resulting equation:

$$\%OM_T = ((LOI*1.1408) + 0.0098)*100,$$

was used to estimate $\%OM_T$ for all samples.

Concentration of labile pool of SOM.

Methods developed by Weil et al. (2003) were used to quantify the amounts of labile carbon through $KMnO_4$ oxidizable carbon. Exactly 2.5 g of oven dried, ground soil were hand shaken in a 20 ml solution of 0.020 M $KMnO_4$ in 0.1 M $CaCl_2$ for 2 minutes. The solution was then allowed to sit for 10 minutes to settle the soil particles. The resulting supernatant was analyzed at 550 nm with an UV-1201 UV-VIS Spectrophotometer (Shimadzu Scientific Instruments Inc., Kyoto, Japan) and compared to a standard curve of known $KMnO_4$ concentrations. It is assumed, that one mol of Mn^{7+} gain 3 mole electrons when reduced to Mn^{4+}, while C0 loses 4 mol electrons when oxidized to C^{4+}. Therefore one mol MnO_4^- oxidizes 0.75 mole (9000mg) of C. Based on these assumptions labile carbon (C_L) was calculated by:

$$C_L\ (\text{mg C kg}^{-1}) = [0.02\text{M} - (a + b * \text{ABS})] * 9000\ (\text{mg C/mol}) * (0.02\text{L} / 0.0025\text{kg soil})$$

where *a* is the standard curve y-intercept, *b* is the standard curve slope, ABS is the absorbance at 550 nm, 0.02L is the volume of the solution and 0.0025 kg is the weight of the soil reacted.

Statistics

Analysis of variance procedures were used to analyze data from all sites and seasons. Analysis of variance was performed using the PROC MIXED procedure on soil physical properties and organic matter using SAS version 9.1 (SAS Institute Inc. 2002). Main plot replicates were arranged in a randomized complete block design. The main plots were the rotation treatment (cover crop vs. winter fallow), which were replicated 4 times at each location, for a total of 8 experimental units at each site. All ANOVA assumptions were evaluated prior to final analysis. For all models, air permeability and all water parameter data were log-transformed. Given the highly variable nature of soil physical properties, significance levels for main effect and mean comparisons using LSD were evaluated at $p = 0.10$.

The analysis of variance model utilized both a repeated measures procedure and blocked data by location to combine sites. The repeated measures procedure allowed comparisons to be made between corn and rye sampling seasons from a single year by designating the season as the repeated unit. There are a couple exceptions where the repeated measures procedure was not used due to data for an entire season missing for a year. This includes all 2006 Clarksville data and 2005 water parameter data for all locations. Data from the Coastal Plain locations, Poplar Hill and Wye, were combined by designating the two sites as blocks to increase the scope of inference from the individual site to the Coastal Plain. Prior to blocking, the results from the combined sites were evaluated for site level interactions. The data from the Piedmont, because there was a single location, was not blocked by site. Water parameter data could also not be blocked by site due to multiple site level interactions.

Results and discussion

Bulk Density

Results of the soil bulk density (D_b) measurements showed the effect of both crop rotations. However, because the results varied by location, soil bulk density at the Piedmont and Coastal Plain locations were evaluated independently.

For the Coastal Plain, the season*rotation interaction was significant both in 2005 ($F = 32.75$, $p<0.0001$) and 2006 ($F = 34.50$, $p<0.0001$), therefore rotations were compared within a year and season. During the corn 2005 season, soil bulk density did not differ from winter annual cereal cover crops and fallow treatments (Figure 2.1). By the rye 2005 sampling period, the D_b for the cover crop treatment (1.26 Mg m^{-3}) was significantly less compared to the fallow plots (1.40 Mg m^{-3}). The following corn 2006 sampling period, soil D_b was less in the cover crop (1.38 Mg m^{-3}) compared to the fallow treatments (1.41 Mg m^{-3}); however, had increased 0.12 Mg m^{-3} compared to the previous rye 2005 sampling period. The following rye season 2006, soil D_b in cover crop treatment (1.26 Mg m^{-3}) was decreased compared to the preceding corn sampling period and significantly decreased compared to the winter fallow treatment (1.40 Mg m^{-3}). The seasonal changes in D_b created an annual cycle within the cover crop rotation: decreased D_b during the rye season and increased D_b during the corn seasons. Non-significant variations in D_b over the seasons in the fallow plots were likely caused by the inherent spatial variability, sampling at various water contents, and other weather related changes in the soil physical characteristic.

Though the observed annual cyclic fluctuation in D_b had not been established previously; however, evidence of similar changes in D_b can be found in the literature when the results are grouped by sample timing. Keisling (1994) collected D_b data post-rye planting from a 17-year rye/vetch cover crop and cotton rotation on a fine-silty soil and found D_b of the cover crops treatment decreased for the 0-10 cm depth compared to treatments without cover crops. Similarly, when sampled in the spring prior to corn or soybean planting, Villamil et al (2006) found significantly decreased soil D_b in corn/soybean rotations including winter cover crops compared to rotations with winter fallow. However, Wagger and Denton (1989) sampled during the corn summer growing season and compared D_b for three years in a corn/wheat rotation versus a corn/fallow rotation and concluded that winter cereal cover crops did not affect D_b.

When annual changes in D_b at the Coastal Plain locations were examined in relationship with time, the change in D_b in the cover crop plots was found to be very rapid and closely associated with cover crop planting (Figure 2.2). The decrease in D_b from summer 2005 (June 2005) to winter 2005/2006 (February 2006) appears to occur gradually over the eight month period of time between the corn and rye sampling seasons (Figure 2.2). For the 2006/2007 season, sampling dates were changed to decrease the time period between the corn and rye sampling seasons. Observed seasonal changes in D_b occurred rapidly during the six-week period between the corn 2006 (November 2006) and rye 2006 (January 2007) sampling (Figure 2.2). Rye cover crop planting occurred during the time between corn and rye sampling in both years. Because of the magnitude of the shift in $D_{b,}$ and the relatively short period of time over which the D_b decrease occurred, we propose that the physical action of the grain drill planting the rye seed was the most likely cause of the substantial and rapid decrease in D_b, not the growth of the cover crop rye plant.

In the Piedmont, significant differences in D_b were found in rye season 2005, but were not present corn season 2005 or rye season 2006 and no consistent seasonal annual pattern was observed (Figure 2.1). During the three sampling seasons the winter fallow rotation maintained a bulk density of approximately 1.20 Mg m^{-3}, while the cover crop rotation averaged a D_b of 1.22 during corn 2005 and rye 2006 sampling periods and decreased to 1.16 Mg m^{-3} during the rye 2005 sampling period. Bulk density samples were not collected at the Piedmont location during corn 2006 sampling period.

Several confounding factors may contribute to the lack of significant differences in soil D_b at the Piedmont location. First, the Manor loam soil is highly structured and maintained a relatively low D_b throughout the year. Second, the small grain drill used at the Clarksville (Piedmont) location to plant the rye was a John Deere 1560 no-till drill. This type of grain drill has beveled edge disk row openers, whereas the Great Plains grain drills used at both Coastal Plain locations had fluted disk row openers. The soil disturbance caused by beveled edge disk row openers used at the Piedmont location was substantially less than the disturbance caused by the fluted disks on the grain drills used at the Coastal Plain locations. Both a stronger soil structure and use of less aggressive disk row openers at the Piedmont location combined to minimize change in D_b.

The effect of the annual decrease in D_b at the Coastal Plain locations following the planting winter cereal cover crops on the following summer's corn crop is not clear. Decreases in D_b have been shown to increase the volume and density of corn roots (Abu-Hamdeh, 2003). However, the corn crop may not directly benefit from enhanced root growth in less dense soil conditions because the reduction in D_b is temporary and does not persist throughout the corn growing season. Since sampling during the spring and early summer was limited and the timing of the changes in D_b is unclear, it is possible that very young corn plants do get a direct benefit from decreased D_b following winter cereal cover crops. However, it is more likely that the cover crop rye plants may directly benefit from the decrease in D_b and produce larger root biomass; therefore the corn might receive an indirect secondary benefit from increased rye root production. Increased rye root production may increase organic matter in the soil and the number of soil macropores, which may benefit the following corn crop.

As previous experiments have shown, measured changes in D_b often correspond with changes in other soil physical properties (Kay, 1997, Hillel, 2004). Such related physical changes include changes in the size distribution of soil pores. Decreased D_b has been correlated with an increased number of macropores, which are the primary conduits for air and water flow through a well-structured soil (Kay, 1997).

Air Permeability

Similar to the bulk density observations, annual fluctuation in air permeability (k_a) were observed at the Coastal Plain locations. However, because the results varied by location, k_a at the Piedmont and Coastal Plain locations were evaluated independently.

k_a results are discussed by year and season for the Coastal Plain locations. The data indicated that during the corn sampling periods of 2005 and 2006, use of WCC had no effect on measured k_a of the soils studied and maintained a k_a of approximately 4.0 μm^2 during both sampling periods, while the winter fallow rotation maintained an average k_a of approximately 4.5 μm^2 (Figure 2.3). However, during both the rye season 2005 and rye season 2006 sampling periods, k_a was significantly increased in the cover crop treatment (Figure 2.3). While the winter fallow rotation maintained an average k_a of 1.5μm^2 during both rye sampling periods, the k_a measured in the cover crop rotation increased to 10.7μm^2 during rye 2005 and 4μm^2 during rye 2006. At the Coastal Plain locations, seasonal changes in k_a followed an annual cycle of increased k_a in the cover crop compared to the fallow treatment during the rye season and decreased k_a during the summer season compared to fallow conditions (Figure 2.3).

The seasonal differences in k_a measured in the cover crop and fallow treatment at the Piedmont location were inconsistent with k_a observations at the two Coastal Plain locations. In rye season 2005 was k_a increased in the cover crop treatment compared to the winter fallow rotation; however, in the rye 2006 sampling period k_a of the cover crop treatment was decreased compared to the fallow treatment (Figure 2.3). Soil k_a of both crop rotations was not significantly different during corn 2005. Because of the different results found in the rye sampling period of 2005 and 2006, an annual pattern of k_a changes could not be established.

The lack of seasonal change at the Piedmont location may be due to several factors. First, a different type of grain drill was used at the Piedmont location. The coulter of this drill was smooth, beveled, and less aggressive compared to the fluted coulters of the grain drills used at the Coastal Plain locations. Second, the overall bulk density is much lower at the Piedmont location than at the two Coastal Plain sites which may have resulted from differences in soil texture and parental material. The higher concentration of iron oxides and organic matter content also may have helped resist disturbance by the grain drill. Due to the resistance to change in D_b observed at the Piedmont location by CC indicates that both air permeability and water movement are less likely to be affected by crop rotation.

The large variation in measured k_a between seasons is likely caused by changes in water content (Ball and Schjinning, 2002). For all locations, the effect of water content on k_a was observed throughout multiple samplings within a season at various volumetric water contents (VWC) (Figure 2.4). To help reduce variation in data, k_a was analyzed at the highest VWC available for each sampling season. In both 2005 and 2006, at the Coastal Plain and Piedmont locations sampling season had a significant effect on VWC. The significant differences in VWC occurred over the season and can account for some of the k_a variation; however, no significant differences in VWC were found between the cover crop and fallow treatments within a single sampling season (Table 2.2). Therefore the increased k_a measured in the cover crop rotation cannot be attributed to differences in VWC, but are better explained by changes in porosity and soil structure.

A thorough review of the literature indicated that previous studies have not compared k_a under winter cover crop and winter fallow conditions. Increased k_a may increase the availability of oxygen to plant roots. However, because the increase in k_a does not last through the summer, the corn plants following the winter cover crop probably do not benefit from increased availability of oxygen to roots compared to corn planted after winter fallow conditions. However, increased oxygen availability may increase the respiration of aerobic soil microorganisms responsible for the breakdown of fresh plant residues and transitional soil organic matter (Sylvia et al. 2005). The build up of stable soil organic matter is also influenced by available oxygen and the activity of soil microorganisms, which is inversely related to the volumetric water content of the soil (Sylvia et al. 2005). During the winter, cover crops effect on soil oxygen availability is also related to water content and rate of water infiltration.

Water Infiltration Parameters

I - Water infiltration rate**,** cumulative infiltration, and hydraulic conductivity,

The results for water infiltration rate (i_{rate}), cumulative water infiltration (I), and hydraulic conductivity (k_w) were similar in 2005 and 2006 for both Poplar Hill and Wye. Because i_{rate} and I were based on measurements taken after a significant period of time, these three parameters are all based on the gravitational downward movement of water into the soil. Therefore results are expected to be similar for all three water parameters.

The effect of cover cropping on i_{rate}, I, and k_w was similar to the effect on air permeability and bulk density for both Poplar Hill and Wye. A seasonal cycle of increased water infiltration rates during the rye season and decreased rates during the corn sampling season were observed at both Coastal Plain locations, Poplar Hill and Wye; however, the response of the water movement parameters to cover crop management varied amongst all locations (Table 2.3). Similar observations were not made at the Piedmont location.

Similar to bulk density and air permeability, at Poplar Hill (Coastal Plain) seasonal trends in i_{rate}, I, and k_w were significantly different in the cover crop rotation compared to fallow conditions (Table 2.3). At the Poplar Hill (Coastal Plain) location, in rye season 2005 and rye season 2006, i_{rate}, I, and k_w of the cover crop treatments found to be significantly greater than i_{rate}, I, and k_w were under winter fallow conditions. However, during corn 2006 sampling period no significant differences were found between cover crop and winter fallow rotation for any of the three parameters.

At the Wye (Coastal Plain) location, only in rye season 2006, was i_{rate}, I, and k_w in cover crop plots greater than infiltration rates under winter fallow conditions (Table 2.3). Though the mean i_{rate}, I, and k_w in the cover crop was greater than for the fallow condition rye season 2005, high data variability resulted in no significant differences. In rye season 2006, when data variability was reduced differences in i_{rate}, I, and k_w were found to be significantly different.

Like D_b and k_a we suggest that the observed increase in water infiltration parameters under the cover crop treatment during the rye sampling season is likely due to the disturbance of the upper soil layers at the time of planting, similar to the effect of tillage. Similar to D_b, past studies conducted during either sampling season reported results consistent with the observed changes were found for water movement parameters. In a 3 year study conducted by Carreker et al. (1968) on a sandy loam soil measured in the spring, there was no significant difference in water infiltration rates between rotations with a rye winter cover crop and the winter fallow rotation. Studies that sampled during the fall after a rye cover crop was planted found increased water infiltration. Wagger and Denton (1989), in a three year study compared hydraulic conductivity in a corn/wheat rotation with a corn/fallow rotation; cover crops did not affect hydraulic conductivity when sampled during the corn growing season. In a 17-year rye/vetch cover crop and cotton rotation on a fine-silty soil, sampled in the fall following rye planting, Keisling (1994) found hydraulic conductivity of the cover crops treatment increased for the 0-10 cm depth compared to treatments without cover crops.

Most changes in soil management are less likely to affect i_{rate}, I, and k_w. We hypothesize that the ring of the infiltrometer was not inserted deep enough into the soil to pass into the undisturbed soil beneath the layer disturbed by the grain drill. As the water percolated downward through the soil and reached a layer with higher density, water moved laterally, increasing the k_w and subsequently i_{rate} and I. We suggest further study is needed to determine the exact cause of increased infiltration. Increased water movement during the winter months may have a significant impact on nutrient and sediment movement from fields with a drilled cover crop. Increases in infiltration rates have been shown to reduce water runoff (Basher and Ross, 2001). Reducing runoff also decreases movement of sediment and nutrients, such as phosphorus, into adjacent surface water where they may become pollutants.

At the Clarksville (Piedmont) location no consistent differences were found in i_{rate}, I, and k_w in rye 2005 and 2006 seasons (Table 2.3). Significant increases in i_{rate} were found between cover crop and fallow plots only in the rye 2005 season. Because Clarksville was not sampled either corn season it is not possible to make any conclusions about the presence or absence of an annual cycle, however, no differences were found during the rye sampling period.

II – Sorptivity

No significant differences were found between soil sorptivity of cover crop plots and fallow plots at any of the locations (Table 2.3). Water infiltration was measured when the soil was near field capacity and may have negated the ability to measure sorptivity (Table 2.3). The method used to measure water infiltration, from which sorptivity was calculated is not a sensitive measure of sorptivity. In addition, measurements of water infiltration were started five minutes after applying water to soil surface. Missing the first few minutes of infiltration may have further hindered our ability to accurately measure sorptivity.

Soil Moisture Retention

WCC effect on soil moisture retention reflected the seasonal changes found Db, k_a, and the water movement parameters at the Coastal Plain locations. During rye season 2006, WCC significantly increased moisture retention at 0 kPa compared to winter fallow at both the Wye and Poplar Hill locations; however, no significant differences were found during corn 2006 sampling period (Table 2.4). No other significant differences were found at any other water potential. The moisture retention at zero and the lowest measured water potentials correspond to the number of macropores which have the largest impact on how quickly a soil can transmit water and will affect both the water infiltration and air permeability (Hillel, 2004). Macropores, much more so than micropores, are affected by changes in soil management (Kay, 1997).

Results for the Piedmont location varied from both Coastal Plain sites. We observed no significant differences in moisture retention between the cropping system treatments at the lower water potentials. However, during rye season 2006, soil moisture retention was significant increased by the cover crop rotation compared to winter fallow for 10 and 30 kPa water retention measurements (Table 2.4). This range of water potentials often corresponds to the presence of meso-pores (Kay 1997). Given the Piedmont results for the other physical properties, it is unclear why

WCC would be causing an increase in the frequency of meso pores and further investigation is required.

Aggregate Stability

WCC had a significant effect on the fraction of water stable aggregates (WSA); however, this effect did not reflect the same annual cycle response observed in D_b, k_a, and water movement parameters. At the Coastal Plain locations, the effect on aggregate stability of using WCC into the grain crop rotation was consistent in both the corn and rye sampling seasons of 2005 and 2006. Regardless of season and changes in other physical properties, cover crops significantly increased WSA >2.0 mm by an average of 35% during 2005 and 41% during 2006 (Figure 2.5). Similarly, cover crops also maintained significantly increased WSA >0.5mm during both 2005 and 2006 corn and rye seasons.

The results of the aggregate stability analysis for the Piedmont location were similar to those of the Coastal Plain locations. WCC significantly increased the fractions of water stable aggregates >2 mm by 20% during the corn 2005 sampling period and 37% during the rye 2005 sampling period at the Piedmont location compared to winter fallow (Figure 2.7). However, though the WSA was increased in the cover crop rotation, WSA of the cover crop and winter fallow rotations was not significantly different during rye 2006. For WSA >0.5 mm only during the 2005 rye sampling season was WSA increased in the cover crop plot.

The increased aggregate stability due to the use of WCC consistent with previous studies that have shown rotations including cover crops increase aggregate stability (Patrick et al. 1957 Delgado et al., 1999, Rachman et al., 2003, Villamil et al

2006). At both the Piedmont and Coastal Plain locations, in both crop rotations, aggregate stability decreased during the rye sampling period compared to the corn sampling period (Figure 2.7). This seasonal variation is often documented irregardless of treatments and attributed to fluctuations in climate, soil moisture, and organic matter (Perfect et al., 1990; Angers et al. 1999; Cosentino et al. 2006). Results of this study suggest that the use of WCC in crop rotations does not influence this annual occurrence.

Aggregate stability results did not reflect the annual changes in other physical properties. Due to the lack of congruent results between aggregate stability and the rest of the physical properties, we suggest aggregate stability may be a poor indicator of changes in soil structure and other soil physical properties. However, the connection between aggregate stability and organic matter has been well established (Tisdall and Oades, 1982 Elliot, 1986 Puget et al., 2000; Jastrow et al. 1996). In a study by Jastrow (1996), approximately 90% of soil organic matter (SOM) was located within soil aggregates. Similar findings by Puget et al. (2000) analyzed the distribution of particulate organic matter (POM), which contains a significant fraction of the labile pool (Angers and Chenu, 1997), and found that 87% of the POM was occluded within water stable aggregates. Additionally, POM within water stable aggregates contained 74% of the total POM carbon (Puget, 2000). Therefore, as the fraction of water stable aggregates increases, so should labile C increase.

Grain yield and crop residue

After 13 years of including WCC in a continuous corn rotation, WCC did not significantly impact grain yield during either sampling year (data not shown). There is no evidence that the observed improvements in soil physical properties due to use of WCC resulted in higher grain yields.

Residue was significantly impacted by the use of WCC during the rye sampling period. In the rye sampling period of both 2005 and 2006, residue cover in cover crop plots was significantly less than residue of winter fallow plots (Table 2.5). At the Clarksville location, residue cover was measured only during the rye 2006 sampling period, in which residue cover of cover crop plots was significantly decreased compared to fallow plots (Table 2.5). However, at its largest, the decrease in residue cover was only 12%, leaving at least 88% of the soil surface covered. Though significantly different, the difference between residue cover of the winter fallow and cover crop rotations will likely not impact physical properties. Because residue was not measured while the corn was growing, only after harvest, the benefits of WCC during the corn growing season cannot be evaluated.

Though the reduction in residue likely does not impact physical properties directly, the reduction in residue may have an effect on carbon sequestration in the cover crop plots. The reduced proportion of residue found at the soil surface during the rye sampling period was probably due to the tilling action of grain drill. The grain drill likely incorporated a portion of residue into the soil surface. Increased soil-residue physical contact may increase the accumulation of SOM.

Total Organic Matter

Including a winter annual cover crop in grain crop rotations increases the carbon input into the system through biomass produced by the rye plant. Estimations based on previously measured biomass produced by the rye at the study locations, an additional 2.02 Mg ha^{-1} (Clarksville), 1.80 Mg ha^{-1} (Poplar Hill), and 1.46 Mg ha^{-1} (Wye) of total dry mass was added annually to the system by the WCC (data not shown). Carbon constitutes approximately 45% of the total biomass (data not shown). However, the sequestration of that additional carbon into soil organic matter depends on factors beyond how much carbon is added.

Total organic matter (OM_T) was calculated based on both a concentration and a mass per area basis. In no-till systems, soil organic matter tends to be highly stratified, having the largest accumulations in the layers closest to the surface and quickly diminishing with depth. As demonstrated previously, surface soil bulk density changed significantly over the year, likely due to the effect of the grain drill. The decrease in surface soil bulk density observed for the WCC treatment likely influenced the portion of the upper soil horizons sampled during the rye sampling period, resulting in the upper most layers of the soil comprising a larger proportion of the volumetric soil sample. To compensate for the annual changes in soil bulk density, OM_T was analyzed on both a mass per area basis and by concentration. In order to conclude OM changed due to the rotation treatment, both OM_T based on concentration (OM_{TConc}) and OM_T based on mass per area (OM_{TArea}) would have to be significantly different. Applications for evaluating OM_T by mass per area and by concentration are different. Mass per area indicates how much OM is present in the surface soil and better indicates accumulation or loss of soil carbon from the system. However, when comparing changes in carbon with changes in physical properties, such as aggregate stability, the concentration of OM_T is more useful. To maximize utility of data we present total organic matter and labile carbon in both a mass per area and concentration basis.

Analysis of the OM_{TConc} for the Coastal Plain locations resulted in significant main effect of rotation in 2005 (F = 6.17, p = 0.042) and in 2006 (F = 10.92, p = 0.013). Comparisons of fallow and cover crop OM_{TConc} for each season shows larger increases during the rye sampling periods compared to the corn sampling periods; likely due to the changes in bulk density (Figure 2.6). No significant differences in OM_{TConc} were found for the Piedmont location (Figure 2.6).

Analysis of the OM_{TArea} for the Coastal Plain locations resulted in significant main effect of rotation in 2005 (F = 3.92, p = 0.0883), but not in 2006 (F = 1.70, p = 0.233). Comparisons of fallow and cover crop treatments for the Coastal Plain sites indicated that only in corn 2005 sampling period was the cover crop soil OM_{TArea} significantly greater than the fallow treatment (Figure 2.6). No significant differences in OM_{TArea} were found for the Piedmont location (Figure 2.6).

At the Coastal Plain locations there was a more consistent increase OM_{TConc}, however, when examined on a mass per area basis OM_T was not consistently significantly different from winter fallow. At the Piedmont locations no significant differences were found in any sampling season. Therefore, in this continuous corn rotation, after 13 years, there were no consistent significant increases in total soil organic matter due to cover crop use at either Coastal Plain or Piedmont locations. Similarly, Villamil et al. (2006), found no significant increase in soil OM_T with use of rye as a cover crop alone. They suggested, though rye produces significantly more biomass than vetch, without the additional N input, rye residues could not be transformed into soil OM_T (Villamil et. al 2006). We suggest that further studies consider potential changes in bulk density when sampling for OM_T.

Labile Carbon

Similar to OM_T, labile carbon (C_L) was also calculated both on a concentration and on a mass per area basis to compensate for the annual changes in bulk density. And like OM_T, in order to conclude C_L changed due to the rotation treatment, both C_L based on concentration (C_{LConc}) and C_L based on mass per area ($C_{L\ Area}$) would have to be significantly different.

Analysis of the C_L based on concentration for the Coastal Plain locations resulted in significant season*rotation interaction in 2005 ($F = 13.99$, $p<0.0008$) and 2006 ($F = 2.97$, $p< 0.0959$); therefore treatment effect was evaluated for both years by mean comparison within a sampling period. In 2005, for the Coastal Plain, cover crop soil C_{LConc} was significantly increased compared to winter fallow during both the rye sampling period and the corn sampling period (Figure 2.7). In 2005, the largest difference between soil C_{LConc} of cover crop and fallow plots was found during the rye sampling period, where C_{LConc} was 0.64 and 0.46 g kg^{-1} respectively. In 2006, for the Coastal plain, cover crop C_{LConc} was again significantly increased compared to winter fallow during the rye sampling period; however there were no differences in CL_{Conc} during the corn sampling period (Figure 2.7). No significant differences were found for the Piedmont location either year.

Similar to the results for CL_{Conc}, analysis of the $C_{L\ Area}$ resulted in significant increases in soil $C_{L\ Area}$ of the cover crop rotation compared to the winter fallow. Due to a significant season*rotation interaction in 2005 ($F = 4.74$, $p <0.038$) corn and rye sampling season were evaluated individually; however, in both the corn 2005 and rye 2005 sampling periods, cover crop soil $C_{L\ Area}$ was significantly greater than fallow soil $C_{L\ Area}$ by 0.0046 and 0.013 Ma ha^{-1} respectively (Figure 2.7). In 2006, there were significant effects of sampling season ($F = 11.64$, $p = 0.002$) and rotation ($F = 3.84$, $p<0.091$) on C_{Larea}, where the cover crop rotation significantly increased soil $C_{L\ Area}$ by 0.002 Ma ha^{-1} in the corn sampling season and 0.0036 Ma ha^{-1} in the rye sampling season. No significant differences in C_{LArea} were found for the Piedmont location either year.

At the Piedmont location, though the mean soil C_L was general higher for cover crop plots than fallow plots, long term use of cover crop in corn rotation did not significantly impact soil C_L. At the Coastal Plain locations, given that cover crop soil C_L was significantly greater than and fallow soil $C_{L,}$ both on a concentration and mass per area; we conclude that corn rotations including winter annual cereal cover crops will likely maintain more soil labile carbon compared to corn rotations with winter fallow.

The difference between C_L in cover crop and fallow rotations is most prevalent during the rye sampling period. As previously stated, given the design of this experiment we were unable to determine the exact cause of the C_L increase due to the inclusion of a winter cover crop in the rotation. However, given the effect of the grain drill on soil physical properties of the cover crop plots, we hypothesize that the action of the grain drill disturbing the soil incorporated a portion of the corn residue into the soil and increased the presence of C_L. During the corn season, additional organic residue from the dead rye cover crop is introduced, maintaining an increased level of C_L throughout the year.

Conclusion

The practice of using a winter annual cereal cover crop in a continuous corn rotation significantly affected physical properties of the Atlantic Coastal Plain soils more than the Piedmont soil. When measured during the period between rye planting and corn planting cover crop use decreased bulk density and increase air permeability, water infiltration rate, cumulative infiltration, and hydraulic conductivity in the surface soil layer (0 to 7 cm) compared to winter fallow. When soil physical properties were measured during the summer corn season, no differences in these parameters were observed. After 13 years of cover crop use, no consistent differences in total soil organic matter were observed between the winter cover crop and winter fallow treatments. However, cover crops did cause an increase in the amount of labile C present in the surface soil, due to the additional C introduced by the growth of the rye plants and the partial incorporation of corn residues into the surface soil by the cover crop planting drill compared to the no-till fallow condition.

The rapid decrease in bulk density that was observed after the rye cover crop was planted and the subsequent return to summer bulk density levels due to settling of the soil indicated that the annual change in soil physical properties was likely due to the grain drill disturbing the soil surface when planting the rye cover crop. We do not attribute changes in soil bulk density to the growing rye plant, increased carbon inputs from the growing rye plant, or better soil structure resulting from the growing rye plant's root system. There were two probable reasons that a similar annual fluctuation in the soil's physical condition was not observed at the Piedmont location: the Piedmont soil was very highly structured compared to the soil at the Coastal Plain locations, and the grain drill used to plant the cover crop at the Piedmont location cause substantially less aggressive soil surface disturbance. The timing of measurements and sample collection had significant impact on the results of this study. Future research of this nature should carefully consider operational activities that can potentially alter results when scheduling measurements and sample collection.

The annual changes observed at the Coastal Plain locations have both positive and negative implications for the effectiveness of cover cropping to protect water quality. Increased water infiltration during the late fall, winter and spring decreased the potential for nutrient runoff and erosion of sediments into waterways. However, because the soil is disturbed by the action of planting the cover crop, the potential for erosion increases during the heaviest of rainfall events immediately following cover crop planting. Because the changes to the measured soil physical properties are transient, we expect planting a cover crop would have little influence in soil erosion potential during the summer corn growing season.

The annual changes in soil physical properties observed at the Coastal Plain locations have both positive and negative implications for the effectiveness of cover cropping to maintain soil quality. Though the soil physical properties were improved during the rye sampling season, after 13 years of cover cropping, the increase in aggregate stability and labile soil carbon were found to have improved enough to influence soil quality so that growers may see a benefit during the summer corn growing season. No consistent increases in total organic matter were observed for cover crop use, possibly due to the increased soil disturbance, increased aeration and accelerated decomposition of organic compounds following rye planting. These factors may limit the potential use of cover crops as a method of sequestering carbon dioxide from the atmosphere. Certainly, the relationship between carbon sequestration and optimum management of winter cereal cover crops must be determined in future studies.

Further studies are needed to understand the seasonal changes observed at the Coastal Plain locations and their implications for maintaining water and soil quality. First, because this study was designed to test the cover crop management system as it might be implemented by a producer, not isolate the effect caused by the rye plant, we must determine the exact cause of the observed changes in physical properties following rye planting. Studies should be designed to distinguish between the act of planting and the growth of the cover crop. In addition we need to examine the effect of alternative planting methods, such as broadcast or aerial seeding, and the effect of various crop management equipment on soil physical properties and soil quality indicators. Further experimentation is necessary, so that society might receive the most benefit from our large financial investment in cover crop implementation programs.

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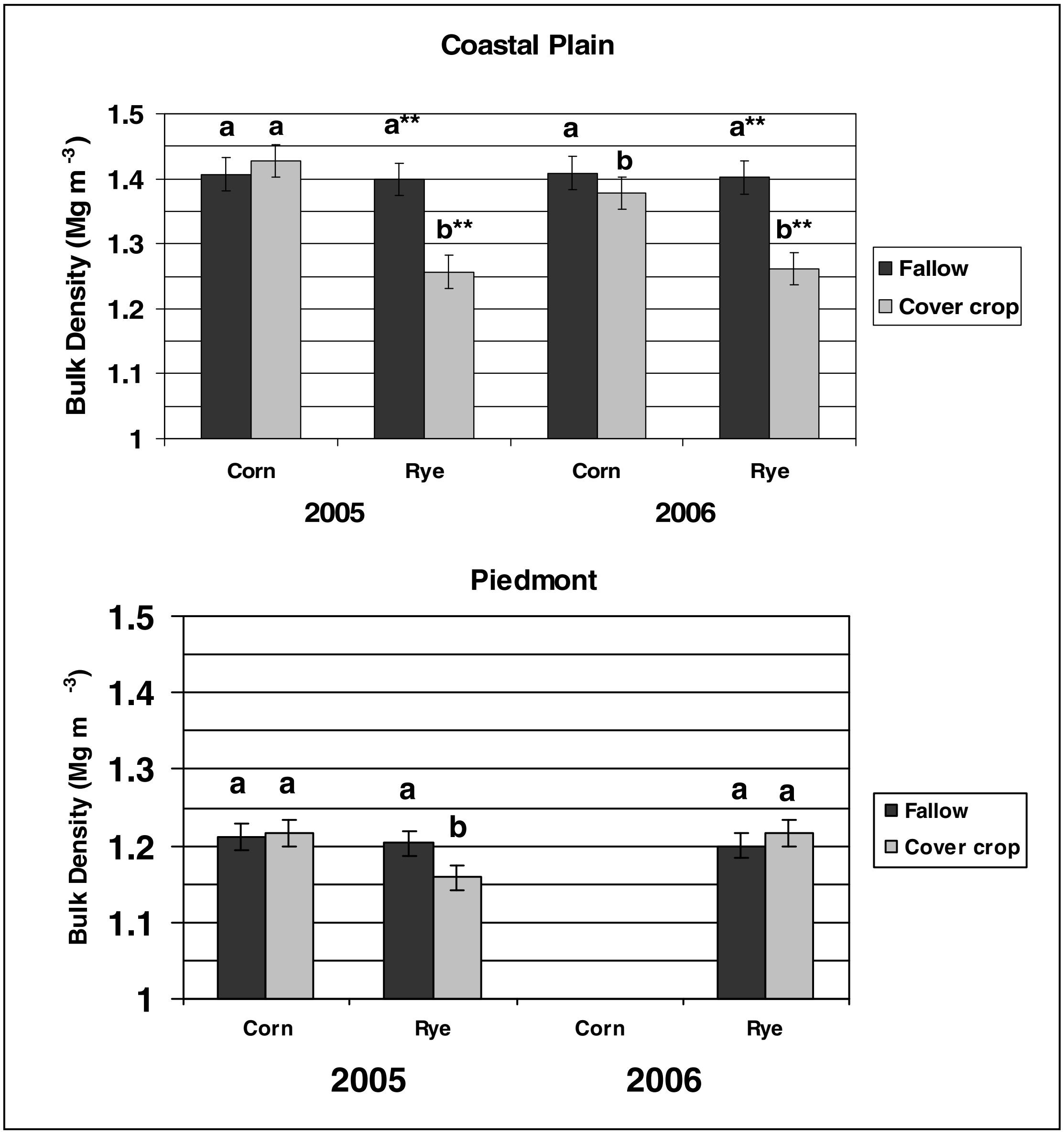
Figures and Tables

Figure 2.1: Bulk density of fallow and cover crop treatments for all seasons at the Coastal Plain and Piedmont locations. Sampling period means, within a year and sampling season, with different letters are significantly different by LSD mean comparison (p<0.10). Error bars represent average standard error of the mean for both years.



** Means are significantly different p<0.01

Figure 2.2: The change in soil bulk density of fallow and cover crop plot at the Coastal Plain locations over time. Each date represents a measurement taken within a sampling period, corn 2005, rye 2005, corn 2006, and rye 2006 respectively.

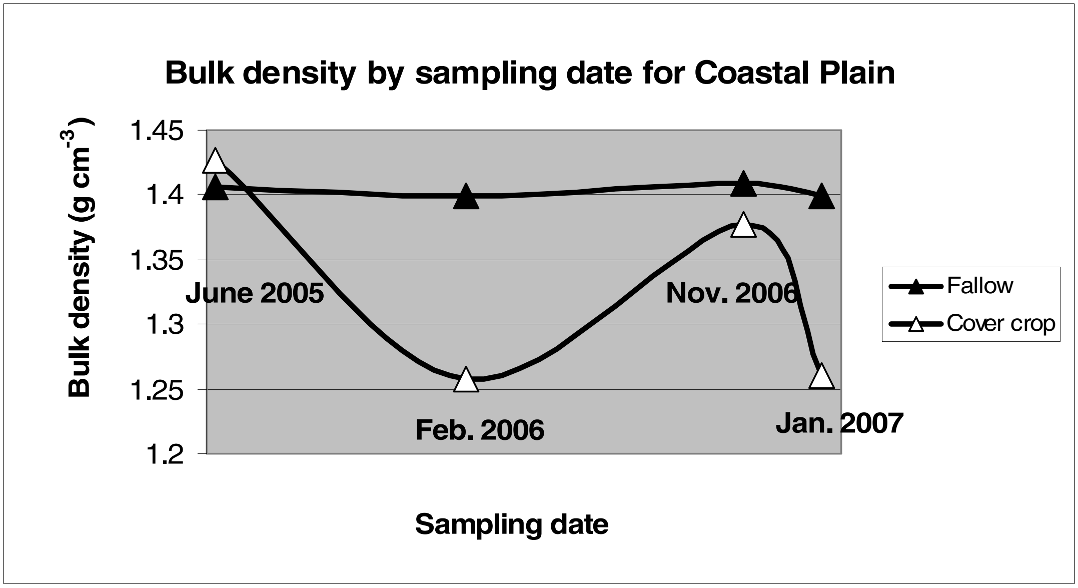
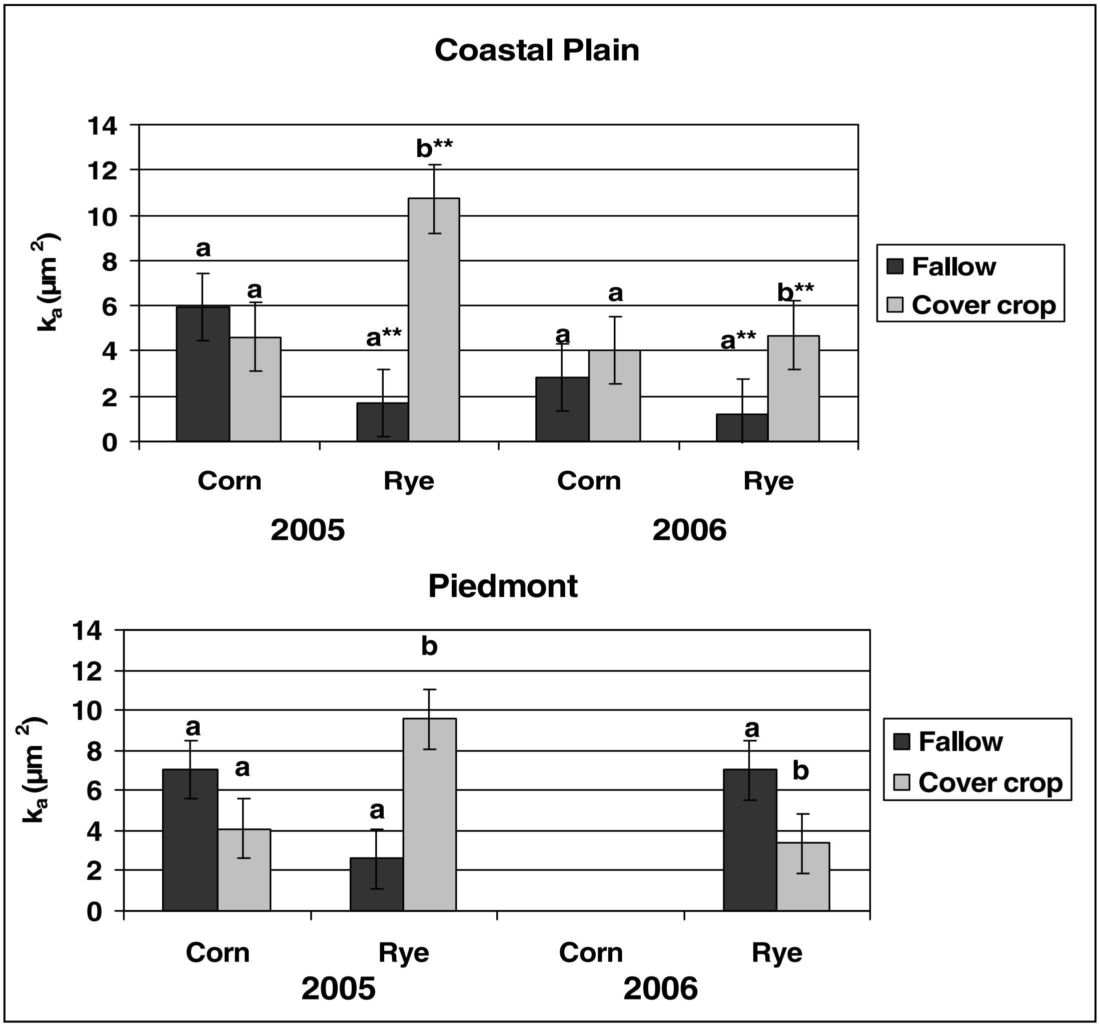


Figure 2.3: Air permeability (k_a) of fallow and cover crop treatments for all seasons at the Coastal Plain and Piedmont locations. Sampling period means, within a year, with different letters are significantly different by LSD mean comparison ($p<0.10$). Error bars represent average standard error of the mean for both years.



** Means are significantly different $p<0.01$

Figure 2.4: The air permeability (k_a) of Coastal Plain and Piedmont locations during corn 2005 sampling season compared to soil volumetric water content (VWC) during measurement.

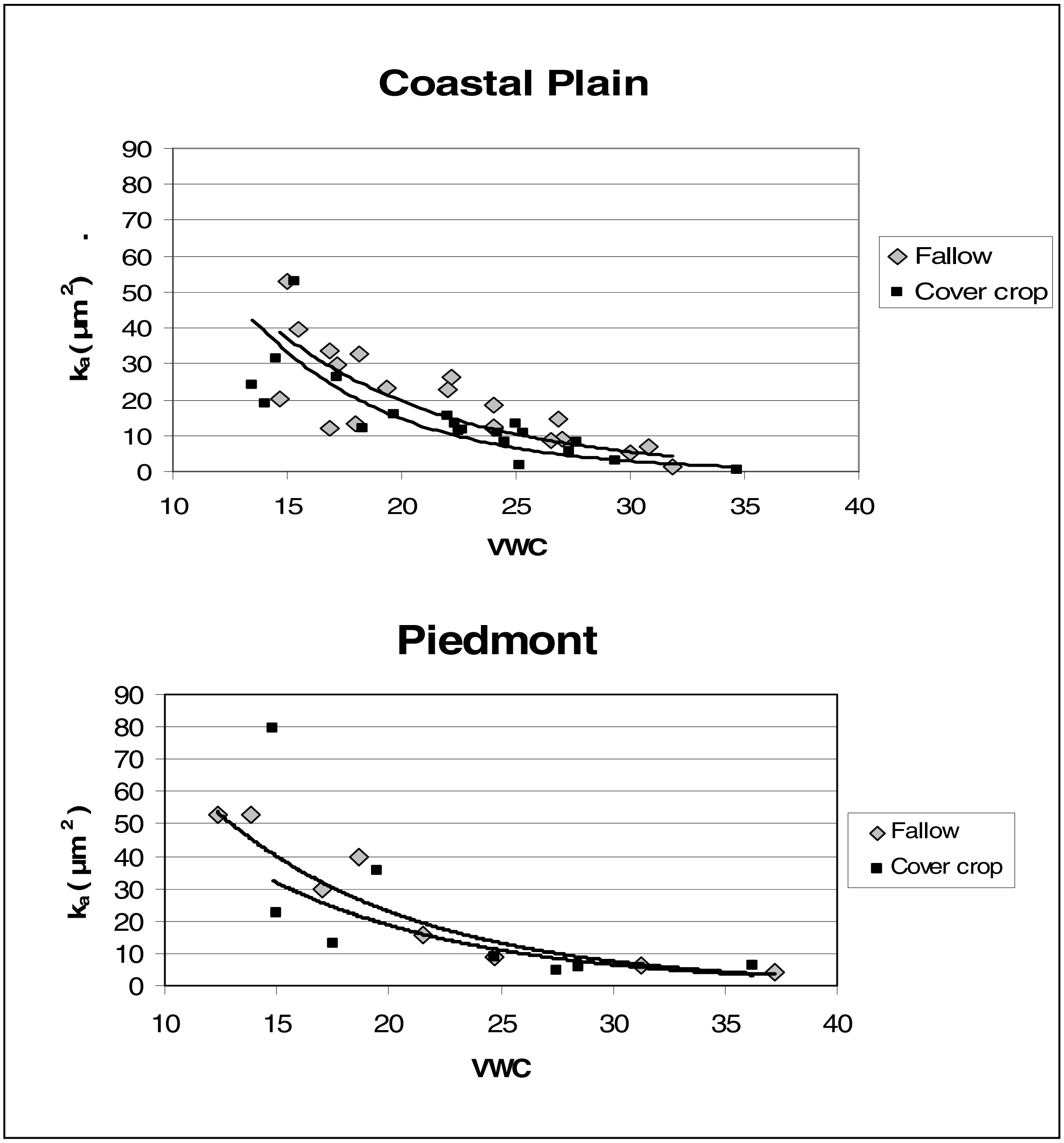


Figure 2.5: Proportion of water stable aggregates (WSA) > 2.0 mm and >0.5 mm at the Piedmont and Coastal Plain locations in 2005 and 2006 for winter fallow and cover crop treatments for Corn and Rye sampling seasons. Within a year, sampling period means with different letters are significantly different by LSD mean comparison (p<0.10). Error bars represent average standard error of the mean for both years.

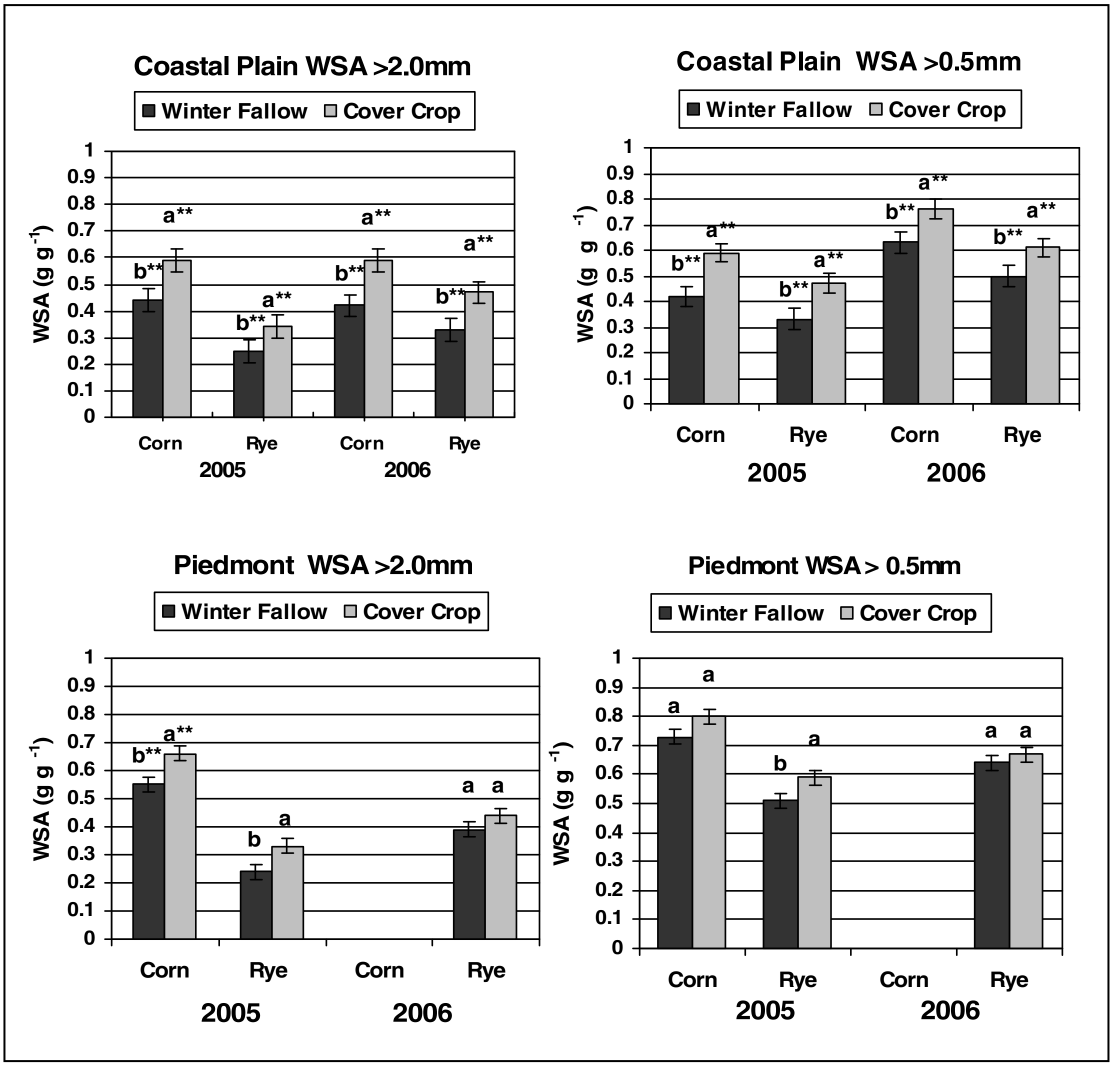


Figure 2.6: Soil total organic matter concentration (OM_{TConc}, right) and expressed as mass per area (OM_{TArea}, left) of fallow and cover crop treatments for all seasons at the Coastal Plain and Piedmont locations. Sampling period means, within a year, with different letters are significantly different by LSD mean comparison (p<0.10). Error bars represent average standard error of the mean for both years.

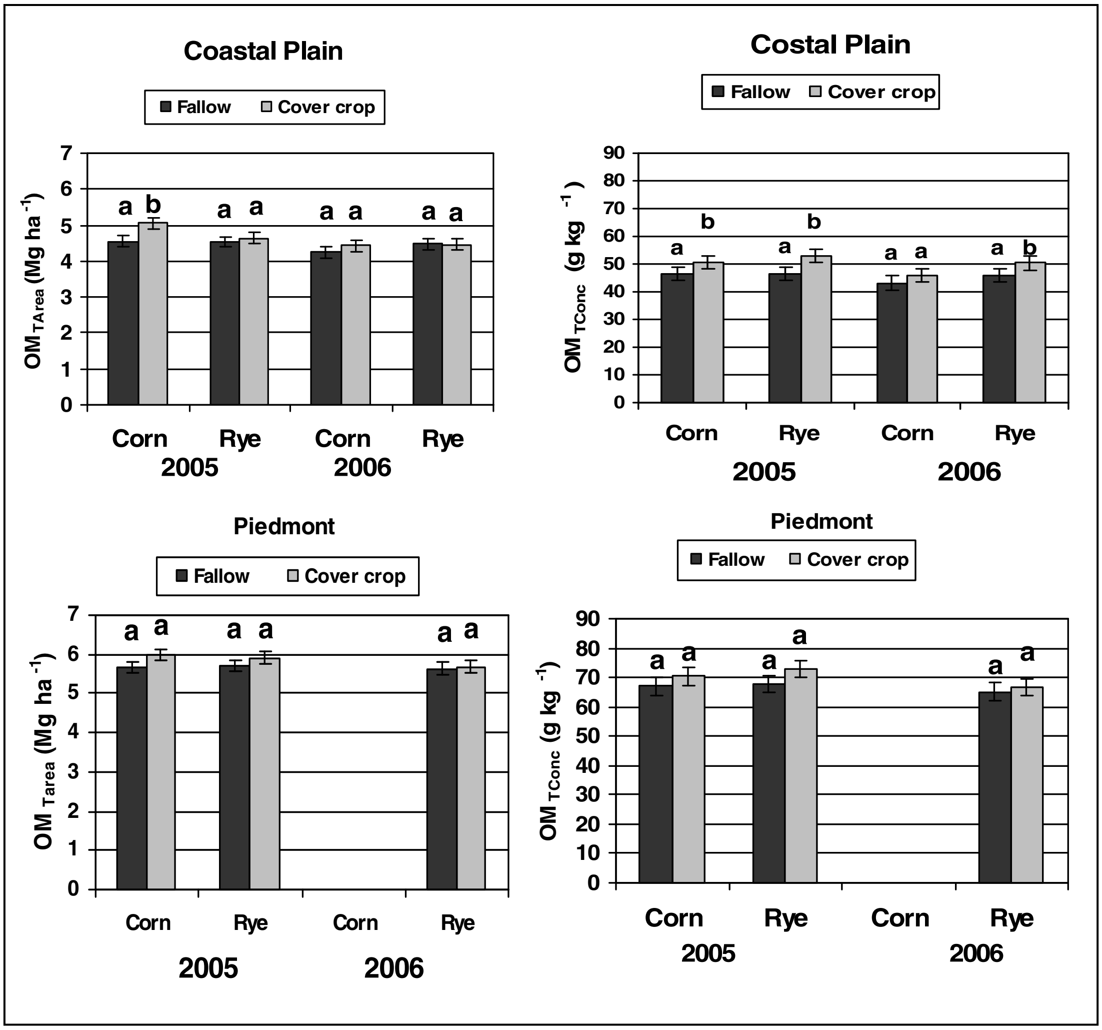
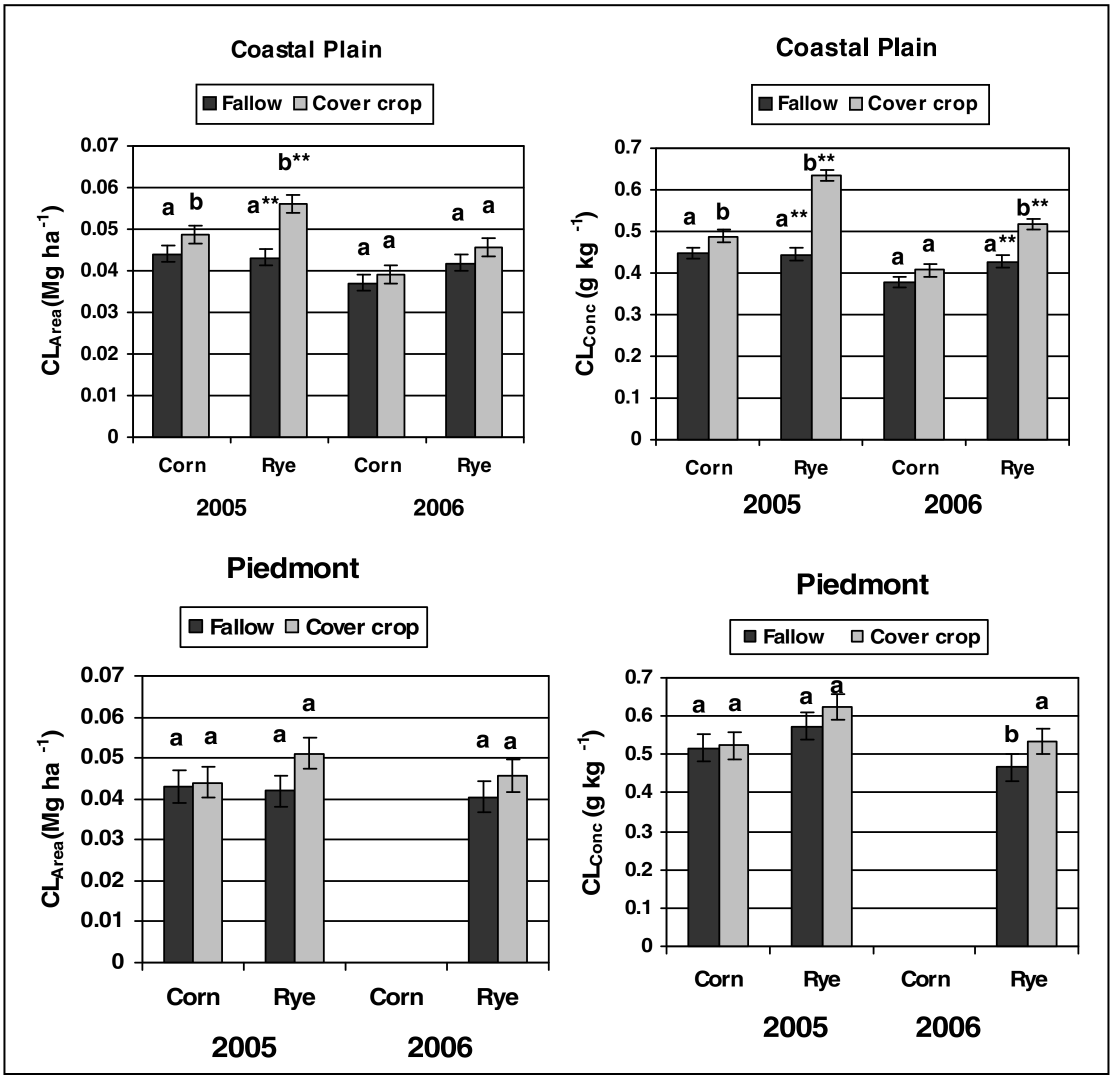


Figure 2.7: Soil labile carbon concentration (CL_{Conc}, right) and soil labile carbon as mass per area (CL_{Area}, left) of fallow and cover crop treatments for all seasons at the Coastal Plain and Piedmont locations. Sampling period means, within a year, with different letters are significantly different by LSD mean comparison ($p<0.10$). Error bars represent average standard error of the mean for both years.



** Means are significantly different $p<0.01$

Table 2.1: Dates of the management operations for 2005 and 2006 for Coastal Plain (Poplar Hill and Wye) and Piedmont (Clarksville) locations.

Rotation study management				
		Kill rye	Planted corn	Seeded rye
Clarksville	2005	May 9	May 9	Oct. 31
	2006	May 1	May 1	Oct. 11
Wye	2005	April 29	May 9	Oct. 8
	2006	April 28	May 3	Oct. 27
Poplar Hill	2005	April 30	May 8	Nov.7
	2006	April 26	May 6	Oct. 24

Table 2.2: Volumetric water content of cover crop and winter fallow rotations at Coastal Plain and Piedmont locations.

			Crop rotation	
Site	Year	Season	Fallow	Cover crop
Coastal Plain	2005	Corn	25.7	26.04
		Rye	34.8	34.1
	2006	Corn	29.7	29.6
		Rye	35.3	33.1
Piedmont	2005	Corn	28.6	29.9
		Rye	35.3	36.4
	2006	Corn	---	---
		Rye	33.8	33.8

Table 2.3 – Water infiltration rate (i_{rate}), hydraulic conductivity(k_w), sorptivity(S), and cumulative infiltration (I) of fallow and cover crop treatments at three locations, Poplar Hill, Wye, and Clarksville for corn 2005, rye 2006, and corn 2006 sampling seasons. Letters compare fallow and cover crop treatments for each parameter, within a year, season, and location. Means are significantly different at $p< 0.10$. See Appendix E for standard errors.

Year	Season	Water movement parameter	Poplar Hill (Coastal Plain)		Wye (Coastal Plain)		Clarksville (Piedmont)	
			Fallow	Cover	Fallow	Cover	Fallow	Cover
2005	Rye	i_{rate} (m s^{-1})	$1.41*10^{-3}$ **a**	$4.02*10^{-3}$ **b**	$8.68*10^{-4}$ **a**	$2.30*10^{-3}$ **a**	$8.70*10^{-4}$ **a**	$2.30*10^{-3}$ **b**
		k_w (m s^{-1})	$6.44*10^{-5}$ **a**	$1.75*10^{-4}$ **b**	$1.31*10^{-5}$ **a**	$1.34*10^{-5}$ **a**	$8.36*10^{-5}$ **a**	$9.75*10^{-5}$ **a**
		S (m s$^{-1/2}$)	$3.58*10^{-6}$ **a**	$7.56*10^{-6}$ **a**	$5.69*10^{-6}$ **a**	$3.25*10^{-4}$ **a**	$1.79*10^{-6}$ **a**	$1.00*10^{-5}$ **a**
		I (m)	0.237 **a**	0.301 **b**	0.0192 **a**	0.0883 **a**	0.156 **a**	0.207 **a**
2006	Corn	i_{rate} (m s^{-1})	$1.85*10^{-4}$ **a**	$9.33*10^{-5}$ **a**	$3.00*10^{-4}$ **a**	$3.07*10^{-4}$ **a**	+	+
		k_w (m s^{-1})	$6.71*10^{-6}$ **a**	$3.18*10^{-6}$ **a**	$8.41*10^{-6}$ **a**	$4.41*10^{-6}$ **a**	+	+
		S (m s$^{-1/2}$)	$8.30*10^{-5}$ **a**	$3.50*10^{-4}$ **a**	$4.27*10^{-4}$ **a**	$9.96*10^{-4}$ **a**	+	+
		I (m)	0.0474 **a**	0.0325 **a**	0.0230 **a**	0.0285 **a**	+	+
2006	Rye	i_{rate} (m s^{-1})	$3.17*10^{-4}$ **a**	$1.78*10^{-3}$ **b**	$2.33*10^{-5}$ **a**	$8.33*10^{-5}$ **b**	$2.32*10^{-3}$ **a**	$4.51*10^{-3}$ **a**
		k_w (m s^{-1})	$1.76*10^{-5}$ **a**	$7.63*10^{-4}$ **b**	$3.77*10^{-7}$ **a**	$2.38*10^{-6}$ **b**	$1.09*10^{-4}$ **a**	$1.19*10^{-4}$ **a**
		S (m s$^{-1/2}$)	$2.35*10^{-4}$ **a**	$5.12*10^{-4}$ **a**	$3.80*10^{-5}$ **a**	$4.40*10^{-5}$ **a**	$1.16*10^{-3}$ **a**	$1.18*10^{-3}$ **a**
		I (m)	0.103 **a**	0.188 **b**	0.00352 **a**	0.0198 **b**	0.271 **a**	0.273 **a**

+ Data was not collected for corn 2006 at the Clarksville location.

Table 2.4: Comparison of soil moisture retention of cover crop and winter fallow rotations at three locations Poplar Hill, Wye, and Clarksville for rye and corn seasons of 2006. Letters compare rotation treatment within a water potential, site, and sampling season. Means are significantly different at p<0.10.

		Crop	Water Potential (kPa)				
Site	Season	Rotation	0	-0.1	-0.2	-0.3	-10
Poplar Hill	Corn	Fallow	0.400 **a**	0.382 **a**	0.370 **a**	0.362 **a**	0.319 **a**
		Cover	0.413 **a**	0.384 **a**	0.370 **a**	0.362 **a**	0.329 **a**
	Rye	Fallow	0.391 **a**	0.374 **a**	0.354 **a**	0.352 **a**	0.293 **a**
		Cover	0.426 **b**	0.366 **a**	0.345 **a**	0.341 **a**	0.299 **a**
Wye	Corn	Fallow	0.437 **a**	0.404 **a**	0.396 **a**	0.388 **a**	0.356 **a**
		Cover	0.435 **a**	0.409 **a**	0.400 **a**	0.390 **a**	0.359 **a**
	Rye	Fallow	0.403 **a**	0.389 **a**	0.376 **a**	0.371 **a**	0.319 **a**
		Cover	0.419 **b**	0.399 **a**	0.377 **a**	0.373 **a**	0.318 **a**
Clarksville	Rye	Fallow	0.462 **a**	0.442 **a**	0.410 **a**	0.411 **a**	0.328 **a**
		Cover	0.465 **a**	0.451 **a**	0.42 3**a**	0.422 **a**	0.343 **b**
		Crop	Water	Potential	(kPa)		
Site	Season	Rotation	-30	-60	-500	-1000	-1500
Poplar Hill	Corn	Fallow	0.273 **a**	0.256 **a**	0.100 **a**	0.084 **a**	0.081 **a**
		Cover	0.294 **b**	0.282 **b**	0.081 **a**	0.079 **a**	0.079 **a**
	Rye	Fallow	0.267 **a**	0.247 **a**	0.104 **a**	0.081 **a**	0.078 **a**
		Cover	0.274 **a**	0.242 **a**	0.096 **a**	0.081 **a**	0.075 **a**
Wye	Corn	Fallow	0.316 **a**	0.300 **a**	0.106 **a**	0.089 **a**	0.081 **a**
		Cover	0.319 **a**	0.300 **a**	0.101 **a**	0.084 **a**	0.080 **a**
	Rye	Fallow	0.291 **a**	0.263 **a**	0.115 **a**	0.095 **a**	0.075 **a**
		Cover	0.292 **a**	0.258 **a**	0.097 **b**	0.085 **a**	0.079 **a**
Clarksville	Rye	Fallow	0.295 **a**	0.288 **a**	0.125 **a**	0.113 **a**	0.112 **a**
		Cover	0.310 **b**	0.293 **a**	0.129 **a**	0.116 **a**	0.114 **a**

Table 2.5: Percentage of soil covered by residue for fallow and cover crop rotations for Clarksville, Wye, and Poplar Hill for rye 2005, corn 2006, and rye 2006 sampling periods. Letters compare means within sampling season and site. Means are significantly different at $p<0.10$.

			Percent area residue covered	
year	Season	site	Fallow	Cover crop
2005	Rye	Poplar Hill	99.4 **a**	92.1 **b**
		Wye	99.5 **a**	95.0 **b**
2006	Corn	Poplar Hill	99.7 **a**	99.6 **a**
		Wye	99.8 **a**	100.0 **a**
	Rye	Clarksville	99.1 **a**	97.4 **b**
		Poplar Hill	97.8 **a**	88.2 **b**
		Wye	99.9 **a**	92.3 **b**

Chapter Three: The effect of winter annual cover crop and wheel traffic on soil physical properties

Introduction

The State of Maryland encourages the use of winter annual cover crops (WCC) to improve the quality and purity of water moving from agricultural lands into the Chesapeake Bay and its tributaries. Winter cover crop use is encouraged because the practice provides several known benefits for both water quality and ecosystem health (Maryland Department of Agriculture, 2006). However, the effects on soil quality, in general, and soil physical properties, in particular, of long-term incorporation of winter cereal cover crops into grain crop rotations are not well established.

Whether intended or not, most agricultural management practices alter soil physical properties. Most crop management activities require machinery, such as tractors and combines, to be driven through the field. The machine's weight converts to pressure on the soil through the wheels and, in general, heavier machinery increases the pressure on the soil. Machinery wheel traffic often results in soil compaction, the severity of which depends on the vehicle weight, speed, ground contact pressure, number of passes, and the existing physical properties of the soil, soil type, and water content (Swan et. al, 1987, Larson et al. 1994, Charmen et al. 2003). Compaction can have significant impacts on both soil physical properties and plant productivity. Plant root systems grown under optimum soil physical conditions are generally deep and expansive, whereas plant roots grown in compacted soils are restricted and concentrated near the base of the plant (Trouse, 1977, Abu-Hamdeh, 2003).

The use of WCC in most management systems increases the wheel traffic. A minimum of one additional pass with a tractor and grain drill is required to plant the cover crop; however, more passes are likely required depending on the equipment used, how the cover crop is killed, and how the residue is managed. Wheel traffic has been shown to increase bulk density by compacting soil in traffic rows (Swan et. al, 1987, Hill and Meza-Montalvo, 1990). Moderate compaction created with 3 tractor passes decreased the number of large pores and increased the number of medium pores compared to no traffic in a silt loam soil tilled with a moldboard plow the previous season (Lipiec et al., 1998). Gysi et al. (1999), found decreases in air permeability of 2.3% when the soil is exposed to a 7.47 Mg load and 27.5% when exposed to an 11.23 Mg load for an untilled sandy loam soil under moist conditions. Therefore, because the use of cover crops increases the wheel traffic, cover crops may increase compaction in traffic rows.

Though WCC increases the amount of wheel traffic, it also has the potential to decrease compaction and improve physical properties. WCC have been shown to affect soil C and rates of soil C accumulation compared to winter weeds (Sainju et. al 2006), and through the accumulation of soil C WCC may directly affect soil physical properties (Reeves 1994) and potentially mitigate the effect of wheel traffic compaction. Macropores, much more so than micropores, are affected by changes in soil management, such as incorporating WCC into rotations (Kay, 1997), and macropores are the principle pathways for infiltration, water drainage, and aeration (Hillel, 2004). Basher and Ross (2001) found that erosion, which occurred along the edge and bed of wheel tracks, decreased significantly as the rate of infiltration in the wheel traffic rows increased. Therefore, even though WCC increases the number of traffic passes and potentially compaction, WCC also has the potential to mitigate compaction in these rows by increasing soil C and improving physical properties.

Evidence of the positive effect of winter annual cover crops on soil physical properties is found in past studies. In a 17 year rye/vetch cover crop and cotton rotation on a fine-silty soil, bulk density of the cover crops treatment decreased for the 0 to 10 cm depth and hydraulic conductivity, which is the ability of the soil to transmit water, was shown to have increased with use of a cover crop compared to winter fallow (Keisling et al., 1994). Similarly, in a short term study, Villamil et al. 2006, found that drill-planted winter annual cereal grain cover crops in no-till corn and soybean rotations decreased surface soil bulk density compared to rotations with winter weeds; however, no significant differences in soil bulk density were found deeper than 10 cm. In the same study, though significant increases in total soil porosity and soil transmission pores (macropores) were found, there were no significant differences in hydraulic conductivity (Villamil et al 2006).

However, several studies provide evidence that cover crops have no effect on soil physical properties. In a three year study, cover crops did not affect soil bulk density and no significant differences in soil porosity or hydraulic conductivity were found after 3 years of rye cover crops in rotation with continuous corn (Wagger and Denton, 1989). Carreker et al. (1968) concluded that water infiltration rates increased as the quantity of plant material returned to the soil increased. However, in a 3 year study conducted by Carreker et al. (1968) on a sandy loam soil there was no significant difference in water infiltration rates between treatments that included winter rye cover crops verses winter fallow in a continuous corn rotation.

Soil organic matter affects soil physical properties directly due to its dominant hydrophilic composition and indirectly by changing soil structure (Klute, 1986). Rachman et al. (2003) reported a 23 to 40% increase in aggregate stability when continuous wheat or corn rotations in the historic100-year rotation study on the Sanborn Field at the University of Missouri were modified to include a winter cover crop. In another study that compared winter fallow to winter cover crop use, a significant increase was found in the percent of soil aggregates in a winter wheat cover crop following maize (Kabir and Koide 2000). Villamil et al (2006) found significant increase in water aggregate stability with the use of winter annual cover crops in a corn/soybean rotation. Several studies have shown that wheel traffic has no significant effect on soil organic matter (Pierce et al. 1994, Lal 1999). However, increased wheel traffic and compaction have been shown to lead to larger aggregates in surface soil (0 to 7.5 cm depth) (Liebig et al., 1993).

Not all studies have shown that growing cover crops results in an increase average soil aggregate size. Mendes et al. (1999) found no significant differences in aggregate size distribution with or without a cover crop in a vegetable crop rotation; he did, however, find significant increases in soil microbial carbon and enzymatic activity in the cover crop treatment. Wright et al. (1999) found that several compounds produced by fungi (glycoprotein and glomalin) were essential to the stability of aggregates and the presence of these aggregate stability promoters were related to active root growth and were more prevalent under no-till management conditions. In addition, several studies have confirmed that tillage homogenizes aggregate size distributions (Beare et al., 1994). In the vegetable rotation study by Mendes et al. (1999), cover crops were incorporated by rototilling, which could explain why, despite the increase in soil microbial biomass carbon and enzyme activity, no increase in the mean aggregate size was found.

Experiment objectives

Understanding how winter annual cover crops and wheel traffic affect physical properties is important for evaluating the effectiveness of WCC at preventing sediment and nutrient movement into the Chesapeake Bay and maintaining soil. Our research had two objectives: first, evaluate the effect of increased wheel traffic due to cover crop management on physical properties associated with compaction, second, evaluate the cover crop's potential for ameliorating existing compaction.

Materials and methods

Experimental Design

A long-term row-crop rotation study was established in 1994 with field plots at three locations; 1) the Wye Research and Education Center (Wye), 2), the Lower Eastern Shore Research and Education Center, Poplar Hill Facility (Poplar Hill), and 3) the Central Maryland Research and Education Center, Clarksville Facility (Clarksville). The Wye and Poplar Hill are located on the Delmarva Peninsula in the Coastal Plain physiographic region of Maryland, USA. Wye was located at 38°59’ N and 76’09’W, had a Matapeake silt loam soil with fine-silty, mixed, semiactive, mesic Typic Hapludults surface texture and <1% slope. Poplar Hill was located at 38°37’ N and 76°44’ W, had a Mattapex loam soil with fine silty, mixed, active, mesic Aquic Hapludults surface texture and <1% slope. Clarksville is located at 39°14’N and 76°55’ W’, and includes portions of both a Manor loam soil with a coarse-loamy, micaceous, mesic Typic Dystrudepts and a Chester loam soil with a fine-loamy, mixed, semiactive, mesic Typic Hapludults with a 5 to 8% slope. See Appendix B for additional soil properties. Though the Poplar Hill location is generally wetter than Wye, the Wye and Poplar Hill locations, both located on the Coastal Plain, are similar soils and distinctively different to the soil at Clarksville. The three locations will therefore be grouped into two physiographic categories, where possible: Coastal Plain, which will include Wye and Poplar Hill locations, and Piedmont, which will include the Clarksville location.

At all three locations, the field experiment design was a randomized complete split-block design where the main-plot treatments are two crop rotation treatments: 1) corn/winter fallow/corn/winter fallow; and 2) corn/cereal rye winter cover crop/corn/cereal rye winter cover crop. There were four replications of the two crop rotation treatments at each of the three research locations. The sub-plot treatments are two levels of commercial-scale production machinery traffic, High Traffic (HT) and Low Traffic (LT), which occurred as a result of standard crop management activities over 13 years. The HT subplots had the most number of equipment passes with a tractor and a combine, while LT subplots had fewer passes with a tractor and zero passes with a combine (Table 3.2). Data was collected during the 2005 and 2006 growing seasons, which represent the twelfth and thirteenth consecutive years for the crop rotation treatments, respectively.

Management of the experiment varied slightly among the three locations. Corn planting and harvest dates varied by one to two weeks from site to site and year to year (Table 3.1). Corn was planted using no-till planting practices and fertilized according to soil testing and Maryland Cooperative Extension recommendations for the expected yield goals. At the Wye and Poplar Hill, the rye cover crop was planted immediately following corn grain harvest with a Great Plains 1510P and Great Plains 1006NT respectively, no-till drill with fluted disk row openers. Rye was planted at Clarksville with a John Deere 1560 no-till drill with beveled edge disk row openers. No fertilizer was applied to the rye cover crop. The following spring, the rye cover crop was killed with an herbicide at approximately the boot stage (Feekes growth stage:9) of growth prior to corn planting. Cover crop residues were left on the soil surface.

Sample Collection and Processing

Sampling for bulk density, air permeability, water infiltration, soil moisture content, and aggregate stability occurred May through January of 2005 and 2006, but it was categorized into two seasonal sampling periods: "corn" and "rye" (Appendix A). The corn sampling period was defined as the time period between corn planting and rye cover crop planting. The rye sampling period was defined as the time period between rye cover crop planting and corn planting.

Water infiltration, the soil moisture release curve and aggregate stability were determined for the 0 to 7 cm soil depth. Bulk density was determined for 1 to 7 cm soil depths, due to the design of the core sampler which excluded the top 1cm of soil. The surface 7 cm layer of the soil was selected for study because previous research has shown that field management practices were most likely to affect the soil physical parameters in the surface layers of the soil (Blevins et al. 1985). The choice to use the 0 to 7 cm depth was based on compromise between soil morphological features, the need for a uniform sampling depth for all sites, and equipment limitations. Air permeability and soil moisture content were sampled at the 0 to 3 cm soil depth. This shallower depth was selected based on preliminary sampling which indicated a consistent, but shallow sampling depth would be required to facilitate reliable sample collection under both high and low soil moisture conditions.

Bulk Density

Bulk density soil samples were collected by removing an undisturbed soil core 5.5 cm diameter, 1 to 7 cm deep, with an Unland core sampler (Blake and Hartge, 1986). At each sampling date, six cores were collected from each replicate of each treatment from the three research sites. Sets of bulk density cores were collected during the corn and rye season sampling seasons for both 2005 and 2006. Cores were oven dried at 105ºC for 24 hours and then weighed. Bulk density was calculated as the mass of the soil divided by the total volume of the core (Blake and Hartge, 1986).

Soil-moisture retention

A subset of the bulk density cores were used for determination of soil moisture retention. Two cores from each replicate of each treatment from the three experimental sites were used. Soil moisture release curves were determined from cores collected from Wye and Poplar Hill in the corn and rye seasons of 2006. For the Clarksville location, soil moisture release curves were determined from cores that were collected corn 2005 and rye 2006 sampling periods. The soil moisture characteristic was constructed using the drainage curve of the undisturbed cores according to the methods presented by Klute (1986) and Dane and Hopmans (2002). A combination of three levels of suction and pressure conditions were applied to the cores and the water content measured at each level. The 0 to -0.3 kPa range was determined using a suction sand table with a hanging water column the - 10.0 to -60 kPa range was done using low pressure plates, and for the –500 to -1500 kPa range, high pressure plates were used on smaller ground sub-samples of the original cores (Dane and Hopmans, 2002).

Water infiltration rate and cumulative water infiltration.

A modified Marriot-type infiltrometer was used to measure water infiltration rates at all three locations (van Es, et al., 1999). Water infiltration rate was determined from each replicate four times in rye season 2005 and six times in corn and rye seasons 2006. No pre-wetting procedure was used; instead measurements were taken within 48 hours of a significant rainfall event, except for the May 2006 measurements at Wye. A significant drought occurred during the first 6 months of 2006. Soil moisture content measurements were made at the time of sampling with a Campbell Scientific "HydroSense ™" two prong time-domain reflectrometer (TDR) to assure that soil was at or near field capacity for the when sampled. The infiltrometer was mounted on a 20 cm diameter metal ring was driven into the surface soil to a depth of 7 cm. The Marriot-type infiltrometer maintained a constant 10 cm hydraulic head above the surface of the soil and water evacuation from the reservoir was used to determine the flow of water into the soil. Infiltration measurements were recorded every five minutes for at least 30 minutes and until the flow was constant. Infiltration rate (length (L), time $^{-1}$ (t)) was calculated by:

$$i = q/t,$$

Where q is the amount of water, t is time and i is the infiltration rate. Cumulative water infiltration (I) for a given measurement was considered to be the amount of water infiltrated after 30 minutes.

Hydraulic conductivity and sorptivity

Hydraulic conductivity (k_w) and sorptivity (S) were calculated based on the methods by Clothier and Scotter (2002) using water infiltration data: the cumulative infiltration (I) and time (t). According to Phillip (1957) the relationship between cumulative infiltration, hydraulic conductivity, and sorptivity can be described by:

$$I = At + St^{-1/2},$$

where A is an estimate of hydraulic conductivity and S an estimate of sorptivity. Analysis was performed using Excel's "solver" (Microsoft Corporation, Redmond, WA), a non-linear parameterization according to the methods of Wraith and Or

(1998) which estimates the value of A and S by minimizing error between the observed cumulative infiltration (I_{ob}) and the cumulative infiltration predicted by the Phillips equation (I_m).

Air Permeability

Air permeability (k_a) field measurements were made at all Wye and Poplar Hill plots for both corn and rye seasons of 2005 and 2006. Air permeability was determined at Clarksville corn and rye seasons of 2005 and rye season of 2006. A hand held air permeameter (Soil Measurement System, Tucson, Arizona) based on the design by Jalbert and Dane (2003) was used to collect field data. The air permeameter used a battery powered, constant, low-flow air pump, a low pressure differential pressure transducer, and a voltmeter. Air flow of the pump was calibrated for a range of pressures by the manufacturer. To reduce the disturbance of the plots, surface plant residue was gently removed from the measurement area and PVC rings (10.16 cm diameter, 12.70 cm height) were inserted 3cm into the soil. The plant residue that was previously removed was placed back inside the PVC ring prior to air permeability measurement. Tygon tubing connected the air permeameter and a sealed PVC chamber fit over the inserted rings. Changes in air pressure in the chamber above the soil were detected by the pressure transducer and translated into a voltage and recorded by the voltmeter and converted to a back-pressure in cm H_2O units.

It was assumed that Darcy's Law is applicable, which will be used in determining air permeability. Jalbert and Dane (2003) used:

$$k_a = (\mu/DG)\ (Q/\Delta P),$$

where k_a is the permeability (L^2), μ is the dynamic air viscosity (mass (M) L^{-1} t^{-1}), Q is the air flow rate provided by the pump (L^3 t^{-1}), D is the inside diameter (L) of the rings inserted into the soil, G is the geometric factors based on the shape and diameter of the rings, and ΔP is the pressure differential between the air inside the pump chamber above the soil and the atmosphere (M L^{-1} t^{-2}). Air viscosity is determined by the equation:

$$\mu = (1717 + 4.8T) * 10^{-8} \text{ Pa s.}$$

Air viscosity, while ignoring humidity, is mainly dependent on temperature (T, ºC). Air temperature was recorded simultaneous with the pressure reading to determine viscosity (Jalbert and Dane, 2003). Water content has been shown to have a significant effect on air permeability (Ball and Schjinning, 2002). To decrease variability due to water content between 1 and 3 air permeability measurements were recorded during the corn and rye seasons sampling periods at various soil water contents without removing the PVC rings from the soil. In addition, 3 TDR measurements of the volumetric water content of the soil were taken surrounding each ring, so the water content might be measured without disturbing the soil in the ring. The PVC rings were removed at the end of each of the corn and rye season sampling periods.

Aggregate stability

The procedure for aggregate stability was adapted from methods by Kemper and Rosenau (1986) and Bryant et al. (1948). Four soil samples from each replicate at the three study locations were collected. Soil was air dried and large clods gently broken apart. About 20 g of 2.0 to 6.0 mm aggregates was placed on a nest of two sieves, including a 10 and 35-mesh (2 and 0.5 mm) and vertically oscillated 3.8 mm inside of a can filled with water, 30 times a minute for 3 minutes. The soil retained on each sieve was oven dried for 3 hours at 105ºC and weighed. After weighing, soil was returned to its sieve, re-wet, and aggregates were dispersed by smearing it across the sieve so that only sand or gravel remained on the sieve, sand and gravel was re-dried and weighed. The fraction of water stable aggregates (WSA_C) corrected for gravel/sand by subtracting gravel/sand from the fraction of soil left on the sieve before sand was removed before dividing by the original sample weight.

Statistics

Analysis of variance procedures were used to analyze data from all sites and seasons. Analysis of variance was performed using the PROC MIXED procedure on soil physical properties using SAS version 9.1 (SAS Institute Inc., 2002). The data was analyzed as a split-plot design at each location. The main plots were the crop rotation treatments (cover crop vs. winter fallow), which were replicated 4 times at each location, for a total of 8 experimental units at each site. Main plot replicates were arranged in a randomized complete block design. The wheel traffic condition (high traffic vs. low traffic) was the subplot treatment. Each subplot treatment was replicated once within each main plot for a total of 16 subplot experimental units at each site. The subplot treatments were not randomized within a main plot due to the necessity of the farm machinery wheel tracks to be located at a consistent location within the main plot; it is the consistent location of the wheel tracks which cause the differences in the HT and LT subplots. However, given the random placement of the main plots within a given site, subplots were effectively randomized throughout the field. All ANOVA assumptions were evaluated prior to final analysis. For all models, air permeability and all water parameter data were log-transformed. Given the highly variable nature of soil physical properties, significance levels for main effect and mean comparisons using LSD were evaluated at $p = 0.10$.

The analysis of variance model utilized both a repeated measures procedure and blocked data by location to combine sites. The repeated measures procedure allowed comparisons to be made between corn and rye sampling seasons from a single year by designating the season as the repeated unit. There were a couple of exceptions where the repeated measures procedure was not used due to data for an entire season being missing for a year. This includes all 2006 Clarksville data and 2005 water parameter data for all locations. Data from the Coastal Plain locations, Poplar Hill and Wye, was combined by designating the two sites as blocks to increase the scope of inference from the individual sites to the Coastal Plain. Prior to blocking the results from the combined sites were evaluated for site level interactions. The data from the Piedmont, because there was a single location, was not blocked by site. Water parameter data could also not be blocked by site due to multiple site level interactions.

Results and discussion

Bulk density

Results of the soil bulk density (D_b) measurements showed the effect of both crop rotation and wheel traffic compaction. However, because the results varied by location, soil bulk density at the Piedmont and Coastal Plain locations were evaluated independently.

For the Coastal Plain, the season*rotation interaction was significant both in 2005 ($F = 32.75$, $p<0.0001$) and 2006 ($F = 34.50$, $p<0.0001$), therefore rotation effect and wheel traffic effect on soil bulk density (D_b) were compared within a year and season. For both the winter fallow (WF) and cover crop (CC) rotations at the Coastal Plain sites during the corn sampling periods, soil D_b in high traffic (HT) subplots was significantly greater compared to low traffic (LT) subplots (Figure X). While the winter fallow rotation maintained D_b of approximately 1.46 Mg m^{-3} in HT subplots and 1.35 Mg m^{-3} the LT treatments during all sampling seasons, during both 2005 and 2006, during rye sampling period, soil D_b significantly decreased to 1.30 and 1.22 Mg m^{-3} in the HT and LT treatments of the CC rotation were compared to both traffic conditions in the WF rotation (Figure 3.1).

It appeared that for both HT and LT conditions, the D_b of the WF treatment at all three locations showed little change from season to season. However, CC decreased soil D_b in both the HT and LT conditions during the rye sampling period. Given how dramatically D_b decreased in the short period of time we suggest that the decrease was not caused by the growing rye plant but by the grain drill that disturbed the soil when planting the rye seed. The mechanical action of the grain drill reduced the bulk density of the surface soil layers (0 to 7 cm), however, even though both HT and LT rows are affected by rye planting, the soil bulk density of HT rows remains higher than the LT rows. These results are similar to other studies that have shown that increased wheel traffic increased soil D_b compared to less wheel traffic (Swan et. al, 1987, Hill and Meza-Montalvo, 1990, Gysi et al., 1999, Abu-Hamdeh, 2003). Increased D_b in the HT rows may counteract the effect of the grain drill openers cutting into and disturbing the soil. By summer, the soil had resettled and re-compacted, the result of the increased wheel traffic during the late spring and early summer, so that there was no difference between the two crop rotations for either traffic condition. The significant decrease in D_b will likely increase water infiltration and air permeability with use of a CC during the winter months. However, there is no evidence to suggest CC permanently improve D_b, and the subsequent benefits do not extend into the corn growing season. Conversely, there is no evidence that the increased wheel traffic that accompanies the use of CC increases compaction.

Soil D_b results for the Piedmont location differed from these observed at the Coastal Plain locations (Figure 3.1). Overall, soil D_b of the Piedmont soil was less than at the Coastal Plain locations. In addition, both HT and LT wheel traffic had less impact on bulk density. During corn 2005 sampling period, the HT treatment of the WF rotation was significantly greater than the LT treatment; however, no difference between the two traffic treatments was found for the cover crop treatment (Figure 3.1). During the rye 2005 sampling period, soil D_b of the CC- LT was less than WF-HT, but no other differences were found (Figure 3.1). During rye sampling periods of 2006, Piedmont soil D_b of CC- HT and CC- LT were not different than either respective WF traffic level.

The lack of seasonal change at the Piedmont location may be due to several factors. First, a different type of grain drill was used at the Piedmont location. The coulter of this drill was smooth, beveled, and less aggressive compared to the fluted coulters of the grain drills used at the Coastal Plain locations. Second, the overall bulk density is much lower at the Piedmont location than at the two Coastal Plain sites which may have resulted from differences in soil texture and parental material. The higher concentration of sand size particles and organic matter content (Appendix B) also may have helped reduce compaction caused by wheel traffic at the Piedmont location compared to the Coastal Plain. Because there was little change in D_b observed at the Piedmont location for either CC or wheel traffic, it is surmised that both air permeability and water movement are less likely to be effected by either rotation or traffic condition.

Air Permeability

The effect of cover cropping and wheel traffic on soil air permeability (k_a) was similar to the effect on soil D_b. Overall, as the soil D_b increased, the soil k_a decreased. Results for Piedmont and Coastal Plain locations were evaluated independently.

The results of the soil k_a measurements on the Coastal Plain were, as expected, similar to those observed for soil D_b. Data collected during both years on the Coastal Plain indicated soil k_a was significantly less where there was increased wheel traffic in both corn and rye sampling periods (Figure 3.2). Soil k_a also was affected by the use of winter cover crops, but the cover crop effect on k_a was only discernable during the rye sampling periods. In 2005, there was a significant season*rotation interaction (F = 21.14, $p<0.0001$) and a significant interaction between rotation and wheel traffic condition (F = 5.97, $p<0.0284$), therefore data for individual treatment combinations were analyzed within each sampling season for 2005. During the corn sampling period 2005, soil k_a in the HT treatment was significantly less compared to LT treatment in the WF rotation, but not the CC rotation (Figure 3.2). During the rye 2005 sampling period, soil k_a for each traffic condition was greater in the cover crop rotation compared to the same traffic condition in the fallow rotation (Figure 3.2). In 2006, the rotation*season interaction was not significant. In 2006, there was an overall main effect of rotation (F = 28.49, $p<0.0011$) and traffic condition (F = 96.96, $p< 0.0001$) on soil k_a. By the corn sampling period of 2006, similar soil k_a measurements were observed for HT treatment regardless of crop rotation. Similarly, soil k_a for the LT treatment was not different between the two crop rotation treatments. During the rye 2006 sampling period the cover crop, CC-LT treatment had the highest k_a compared to all other treatment combinations.

As expected, results for k_a were similar to previous studies which showed a decrease in k_a due to high levels of wheel traffic (Gysi 1999, Yavuzcan 2005). However, there was no indication that increased wheel traffic due to management of the CC decreased k_a. Likely due to the action of the grain drill disturbing the soil surface, k_a in both traffic conditions of the CC rotation increased, but like D_b, only during the rye sampling season. Increased k_a may significantly increase the soil oxygen during the rye sampling period which may increase aerobic respiration and break down of organic matter during this time. However, because there is no evidence that the increased k_a is a permanent condition caused by better soil structure, there is no indication that corn plants benefit from increased oxygen during the corn growing season.

Trends in soil k_a at the Coastal Plain locations were not found at the Piedmont location. For the Piedmont location, the season*rotation*traffic condition interaction was significant in 2005 ($F = 3.55$, $p<0.0840$), therefore crop rotation and machinery traffic effects on soil k_a were compared within a season. In corn sampling period of 2005, soil k_a was less under high levels of wheel traffic for both crop rotations but was not significantly different (Figure 3.2). Soil k_a in the rye 2005 sampling season WF- LT was significantly less compared to all other treatment combinations, however, in the rye 2006 sampling season WF- LT was greater than all other treatment combinations, between which no other differences were found.

The inconsistent results of soil k_a at the Piedmont may be due to differences in weather conditions between 2005 and 2006. Beginning in mid summer 2005, a significant drought began which lasted through most of the fall. In addition, the soil surface froze briefly during December before soil k_a could be measured. In 2006, the rainfall was more evenly distributed during this period and no soil freeze took place before sampling. In 2005, due to the extreme dry weather conditions followed by soil freezing, larger cracks and pores opened in the soil surface. It is possible that the WF-LT, which was not disturbed either by compaction or CC planting, resisted the formation of large cracks and pores and therefore had a significantly lower k_a. In 2006, with the soil k_a unaffected by drought and freezing, the result was increased soil k_a in WF-LT. In the rye 2005 sampling period, the k_a did not follow the same treatment pattern as bulk density; however, in 2006 higher bulk density resulted in lower k_a.

Water Infiltration Parameters

I. Water infiltration rate, cumulative water infiltration, and hydraulic conductivity

The results for water infiltration rate (i_{rate}), cumulative water infiltration (I), and hydraulic conductivity (k_w) are similar in 2005 and 2006 for both Poplar Hill and Wye. These three parameters are all based on the gravitational downward movement of water into the soil. Therefore results are expected to be similar for all three water parameters.

The effect of cover cropping and wheel traffic on i_{rate}, I, and k_w was similar to the effect on air permeability and bulk density for both Poplar Hill and Wye. There was evidence of a seasonal cycle of increased i_{rate}, I, and k_w during the winter and decreased rates during the corn sampling period at both Coastal Plain locations, Poplar Hill and Wye (Table 3.3). A similar observation was not made at the Piedmont location. However, the response of the water movement parameters to cover crop management and increased wheel traffic varied among the locations.

Results for i_{rate}, I, and k_w the Poplar Hill (Coastal Plain) site reflect the seasonal changes found in soil both bulk density and k_a. During the rye 2005 sampling period, i_{rate}, I, and k_w of WF- HT were significantly decreased compared to all other treatment combinations; however, no differences were found among any other treatment combinations (WF-LT, CC-HT, CC-LT) (Table 3.3). During the corn 2006 sampling season, the HT subplots of the WF and CC rotations were not different from each other; however, i_{rate}, I, and k_w were decreased for the HT treatments compared to the LT treatment of both rotations. During rye sampling season 2006, i_{rate}, I, and k_w of WF- HT were decreased compared to all other treatment combinations, however, as in 2005, no differences were found between any other treatment combinations (Table 3.3).

Seasonal differences were also found at the Wye (Coastal Plain) location, but varied from the other two study locations. During the rye sampling season 2005, results for i_{rate}, I, and k_w varied slightly. For i_{rate} and I in 2005, the CC-LT was significantly increased compared to the CC-HT. For i_{rate} no differences were found between any other treatment combinations; however, for I, CC-LT was greater compared to both HT-WF and LT-WF. For k_w there were no differences between any of treatment combinations. In the corn 2006 sampling period, neither rotation nor wheel traffic had a significant impact on i_{rate}, I, or k_w. During the rye sampling season 2006, all three parameters, i_{rate}, I, and k_w, of the CC-LT treatment was increased compared to all other treatment combinations, however, no other differences were found between other treatment combinations. Variations in the results of i_{rate}, I, and k_w during the rye 2005 sampling period was likely due to sampling variation and human error. This site (Wye) was the first location sampled during the study and inconsistent sampling technique may have contributed to the random error. Results of all three parameters were in agreement during the rye 2006 sampling period.

Soil disturbance, caused by the action of the grain drill planting the cover crop, is the likely source of seasonal variation in i_{rate}, I, and k_w of the Coastal Plain soils at Poplar Hill and Wye. At the Poplar Hill location, i_{rate} of both the HT and LT treatments of the CC rotation were impacted during the rye sampling season, however, at the Wye location only in the LT treatment of the cover crop rotation was i_{rate} significantly impacted by cover crop planting. Improvement in water movement through the soil surface is limited at the Wye location compared to Poplar Hill, because only the LT area was affected by the grain drill. At both locations soil settling after disturbance and wheel traffic re-compacting the soil surface layer may contribute to the return to summer i_{rate} levels. We hypothesize that the ring of the infiltrometer was not inserted deep enough into the soil to pass into the undisturbed soil beneath the layer disturbed by the grain drill. As the water percolated downward through the soil and reached a layer with higher density, water moved laterally, increasing the k_w and subsequently i_{rate} and I. We suggest further study is needed to determine the exact cause of increased infiltration.

Increases in i_{rate}, I, and k_w increased the capacity of water to flow through the soil surface and percolate downward through the profile after long periods of rainfall. Increasing the amount of water that can flow into the soil decreases the potential for runoff and erosion of sediment and nutrients. Water runoff from agricultural fields can carry soil sediment, particulate-bound P, and dissolved P from land-applied organic and mineral fertilizers into waterways before they can be immobilized within the soil or taken up by plants. Most applications of fertilizer and pesticides are applied during the summer corn sampling season, however, the increased capacity for water flow into the profile is limited to the rye sampling period, before corn planting, and there is no evidence that the cover crop effects on i_{rate}, I, and k_w would provide environmental benefits by limiting nutrient and/or sediment runoff during the corn sampling season.

The results for i_{rate}, I, and k_w of the Piedmont, like k_a and Db, were not consistent with those of Coastal Plain sites. However, infiltration was measured only in rye 2005 and rye 2006 sampling periods at the Piedmont location, decreasing our ability to determine if an annual cycle in water infiltration was present. During rye

2005 sampling period, soil i_{rate} of both wheel traffic treatments of the cover crop rotation was increased compared to the winter fallow treatment (Table 3.3). Similarly, soil I of CC-LT was increased compared to WF-LT. k_w was not affected during this sampling period. Level of wheel traffic did not influence water movement parameters during this period, however, in rye 2006 sampling period, wheel traffic had a significant impact on i_{rate}, I, and k_w. During this rye 2006 sampling season, soil i_{rate}, I, and k_w for WF-LT were less than for WF-HT. No other consistent significant differences were found for the three parameters (Table 3.3).

The results for soil k_a and water infiltration show the same inconsistency between rye 2005 and rye 2006 sampling seasons. As previously discussed (see k_a results section), the differences in weather conditions between the two years likely caused large cracks in the soil which influenced both the k_a and water infiltration. Since infiltration measurements in 2005 were made before the soil froze, the drought is identified as the primary factor influencing water infiltration measurements.

II. Sorptivity

Results for the effect of cover crop use and wheel traffic on sorptivity (S) were similar to the results of the other three water movement parameters. At the Piedmont location, neither cover crop nor the traffic level had a significant impact on S. However, at both Poplar Hill and Wye S did fluctuate in the cover crop rotation in a seasonal pattern similar to the other three water movement parameters.

At Poplar Hill (Coastal Plain), S showed a similar response to the other three parameters. In 2005, during the rye sampling periods the traffic level*rotation interaction was significant ($F = 5.49$, $p<0.0576$). For this period, WF- HT had sorptivity that was decreased compared to all other treatment combinations (Table 3.3). In 2006, the season*rotation interaction was significant ($F = 10.41$, $p = 0.0321$). During the corn 2006 sampling season, soil S of the WF-LT was greater compared to the soil S of all other treatment combinations (Table 3.3). In 2006, results for rye 2006 were similar to rye 2005 sampling period, with the S of WF- HT decreased compared to all other treatment combination (Table 3.3).

At the Wye (Coastal Plain) location, S showed a similar response to the other three parameters. In 2005, during the rye sampling period no differences were found among treatment combinations. In corn 2006 sampling season, the soil S of CC- LT was significantly increased compared to that of WF- HT (Table 3.3). In the rye 2006 sampling season, the S of the CC- LT was again increased compared to that of the CC- HT; no other differences between treatment combinations were found (Table 3.3).

III. Water Movement

As per the discussion above the four parameters, overall water movement, as effected by the use of winter annual cover crop and wheel traffic level varied among the locations. The four parameters each described a component of the water movement, which is illustrated by water infiltration curves (see Appendix D,a through D,c). Water infiltration curves graphically demonstrate the seasonal trends and the effects of crop rotation and wheel traffic at the three sites.

Little evidence of similar seasonal trends that were observed at the two Coastal Plain sites (Poplar Hill and Wye) was observed at the Piedmont location

(Clarksville). The Manor loam Piedmont soil was very different compared to the soils at the Coastal Plain locations. The Piedmont soil was very well structured, with even the WF- HT treatments showing increased water infiltration rates compared to water infiltration rates of LT condition at the two Coastal Plain sites. However, because measurements were not taken during the corn seasons at Clarksville, it is not possible to draw any conclusions about possible seasonal changes in water movement due to the use of winter annual cover crops. There is a trend for high levels of wheel traffic to impair water movement (Table 3.3); however, this trend only was supported with significant data in the rye 2006 sampling period.

Despite the increased traffic that accompanies management of cover crops, water movement was not decreased. First, the increased tractor passes may not influence compaction as much as heavier equipment; such as the combine which passed an equal number of times in both the cover crop and fallow rotation. Second, the increased organic matter additions or the growing cover crop may have increased root channels and large pores. Lastly, the planting of the rye seed caused soil disturbance that resulted in a winter increase in water movement into the soil, and helping to prevent further compaction. We suggest further studies are needed that isolate the effect of the grain drill and other management activities to better understand the exact cause of the annual cycle and the interaction with wheel traffic.

Soil Moisture Retention

At the Coastal Plain locations (Poplar Hill and Wye) the results of the soil moisture retention reflect both the annual changes caused by use of WCC and the effect of the HT treatment. At the Coastal Plain locations, during the corn sampling season, there was evidence of soil compaction caused by HT, but no significant effect caused by crop rotation. During the corn sampling season for both the CC and WF crop rotations, water storage was increased in the LT treatment compared to the HT treatment when determined at the lowest water potential (0 kPa) (Table 3.4). However, at mid-range water potentials (-10 to -30 kPa), HT treatment contained more water compared to LT treatment, within each crop rotation. No other significant differences were found during this sampling period (Table 3.4).

During the rye 2006 sampling period, soil moisture retention at the Coastal Plain locations was affected by both crop rotation and level of wheel traffic. At the Poplar Hill location, soil moisture retention measured at 0 kPa in CC was increased compared to the WF rotation. At the mid range water potentials (-10 to -30, kPa), HT increased soil moisture retention compared to LT treatment. At the Wye, there was a significant wheel traffic effect (F = 12.28, p = 0.012) and soil moisture retention measured at 0 kPa water retention was greater for CC-LT than WF-HT (Table 3.4). Similar to Poplar Hill, at the mid range water potentials (-10 to -30, kPa), HT increased soil moisture retention compared to LT at Wye.

These results are in agreement with findings in past studies. Hill and Meza-Montalvo (1990) generated similar data from a similar Atlantic Coastal Plain soil and found a similar effect of increased wheel traffic load on the water storage with decreased storage at 0 kPa offset by increased storage at mid-range (- 20 to - 40 kPa) water potentials.

At the Piedmont location, crop rotation did not impact soil moisture retention (Table 3.4). However, there was an impact of increased wheel traffic on soil moisture retention. Similar to Coastal Plain sites, at the mid-range water potentials (-10 to -60 kPa) the soil moisture retention was increased in the WF-HT treatment compared to WF-LT treatment. However, a similar traffic-induced increase in soil moisture retention was not found in the CC rotation.

Results of the soil moisture retention analysis for the Coastal Plain and Piedmont sites have several implications for water movement in these cropping systems. The increase in moisture retention at the lowest water potentials (0 kPa) indicates an increase in macropores, which will likely increase water movement into the soil surface. However, during both rye and corn sampling seasons in the HT treatment there was greater moisture retention in the mid-range water potentials, correlating with an increased presence of mesopores associated with increased compaction. Therefore, the use of WCC did not help to ameliorate the compaction from HT, even during the rye sampling period. However, we reiterate the fact that planting WCC did not increase soil compaction on the Coastal Plain.

Aggregate Stability

At both the Coastal Plain and Piedmont locations WCC increased water stabile aggregates (WSA) during both the 2005 and 2006 corn and rye sampling periods (Figure 3.3). However, wheel traffic had an inconsistent effect at either the Coastal Plain or Piedmont locations. At the Coastal Plain in the corn 2006 sampling period, the proportion of WSA > 2.0 mm was greater in the CC-LT compared to the CC-HT. No other differences were found due to traffic for WSA > 2.0mm. For WSA >0.5 mm, though there was a trend for increased WSA in the CC-HT compared to CC-LT, only at the Coastal plain rye 2005 sampling period was the difference significant. No other differences in WSA due to wheel traffic were found.

The lack of consistency and significance leads us to conclude increased wheel traffic had no consistent effect on WSA. These findings are consistent with the results found by Hill and Meza-Montalvo (1990), where there was no evidence of increased aggregate stability due to wheel traffic as suggested by Voorhees (1979).

Conclusions

The practice of winter annual cereal cover crop use accompanied with increased levels of wheel traffic affected physical properties of the Atlantic Coastal Plain soils. Cover crop use decreased bulk density and increase air permeability, water infiltration rate, cumulative infiltration, and hydraulic conductivity in the surface soil layer (0 to 7 cm) compared to winter fallow only during the period between rye planting and corn planting. During the summer corn growing season no differences in these soil physical properties were found for cover crop use and winter fallow. Compaction in high traffic areas leads to increased bulk density and decreased air permeability, water infiltration rate, cumulative infiltration, and hydraulic conductivity in the surface soil layer in both the winter fallow and cover crop rotation during the corn growing season. During the rye growing season in the cover crop rotation, compaction of the surface layers decreased compared to the previous corn sampling period, but remained more compacted than the low traffic areas of the same rotation.

Due to the rapid decrease in bulk density after the rye cover crop was planted and the subsequent settling in both the high traffic and low traffic rows, the annual change in soil physical properties is likely due to the grain drill disturbing the soil surface layers when planting the rye cover crop rather than from the growing rye plant and increased carbon inputs helping build better soil structure and mitigating compaction in high traffic areas. This annual fluctuation in the soil’s physical condition was not observed at the Piedmont location, where the highly structured soil and differences in the small grain drill possibly muted or resisted annual changes and compaction due to wheel traffic, observed at the two Coastal Plain locations.

Though the management of the winter cover crop did increase the amount of wheel traffic, there was no indication that cover crop management increased soil compaction. Given the limitations of this study the exact cause of this outcome can not be determined; however three factors are suggested as contributing to the lack of increased compaction. First, cover crop management increased the number of tractor passes, however the tractor is a relatively light vehicle compared to equipment such as a combine. A tractor may not impact high traffic areas compared to a heavier vehicle. Second, the additional carbon provided by the rye cover crop increased the soil's structure and helped resist further compaction. Lastly, the hypothesized annual soil disturbance during rye planting alleviated soil conditions in the high traffic row so that they resisted the further compaction due to increased wheel traffic.

The annual changes observed at the Coastal Plain locations have positive implications for the effectiveness of cover cropping to maintain water quality. Increases in water infiltration within the high traffic rows during the late fall, winter, and spring, can result in a decrease in the runoff potential, minimize erosion of sediments, and reduce nutrients that flow into waterways compared to high traffic rows of a winter fallow rotation. However, because the improvement is transient, having grown a winter cereal cover crop provides no nutrient runoff reduction benefits during the corn growing season.

Figures and Tables

Figure 3.1: Bulk density of fallow and cover crop treatments and high traffic (HT) and low traffic (LT) rows for all seasons at Coastal Plain and Piedmont locations. Sampling period means, within a year, with different letters are significantly different by LSD mean comparison ($p<0.10$). Error bars represent average standard error of the mean for both years.

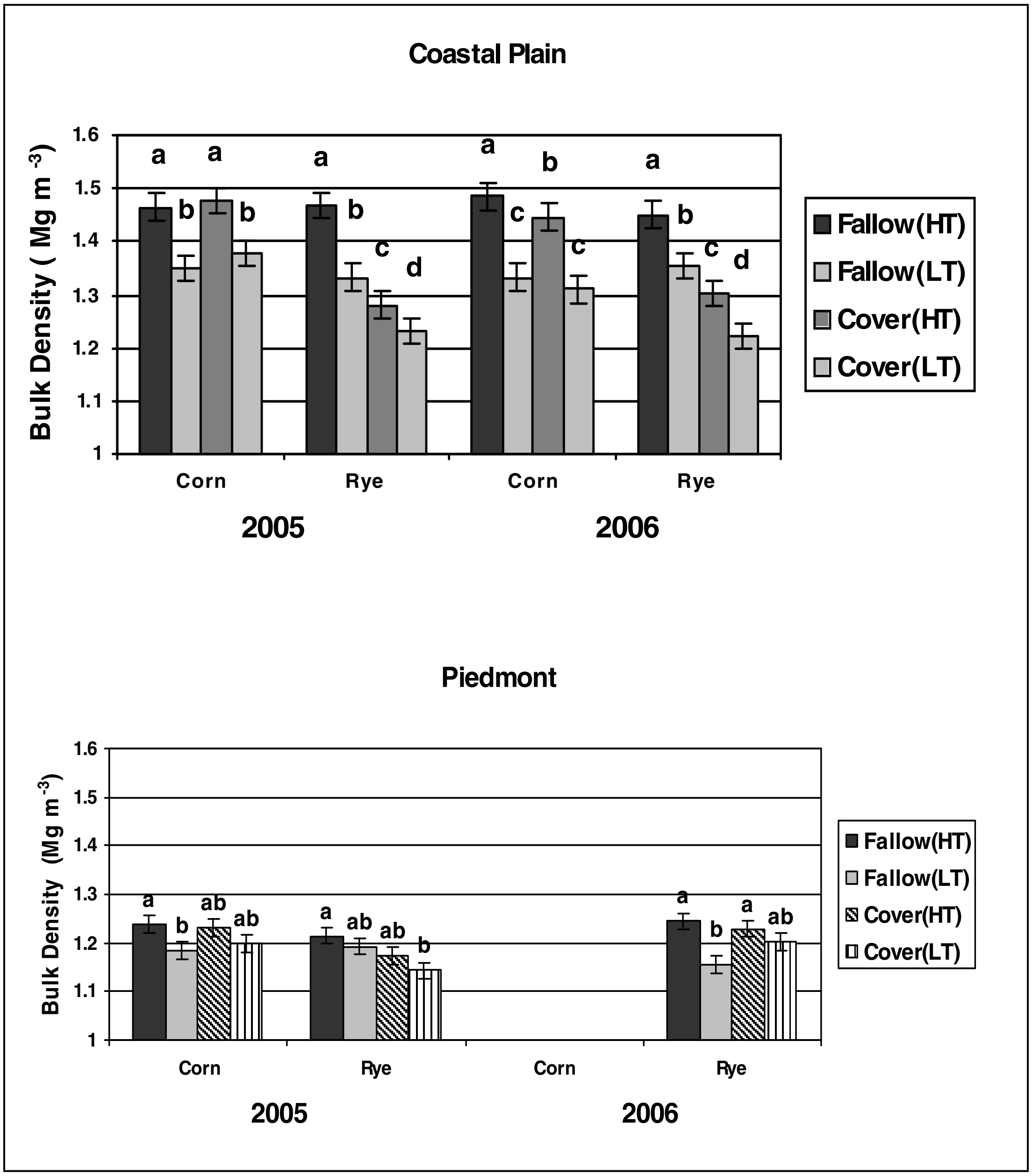


Figure 3.2: Air permeability (k_a) of fallow and cover crop treatments and high traffic (HT) and low traffic (LT) for all seasons at Coastal Plain and Piedmont locations. Sampling period means, within a year, with different letters are significantly different by LSD mean comparison ($p<0.10$). Error bars represent average standard error of the mean for both years.

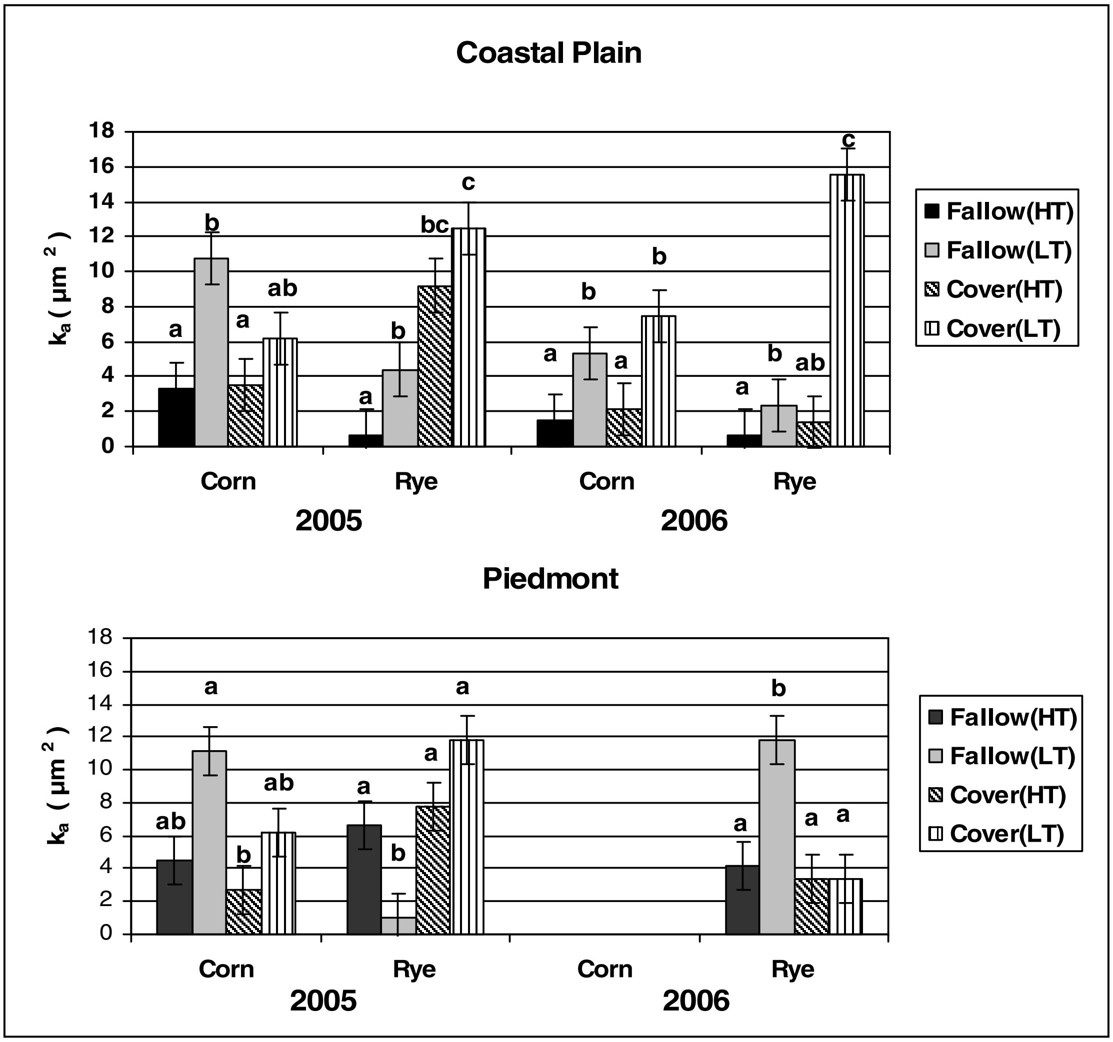


Figure 3.3a: Proportion of water stable aggregate (WSA) > 2mm of fallow (WF) and cover crop (CC) treatments and high traffic (HT) and low traffic (LT) rows for 2005 at Piedmont and Coastal Plain locations. Within a sampling season, sampling period means with different letters are significantly different by LSD mean comparison (p<0.10). Error bars represent average standard error of the mean for both years.

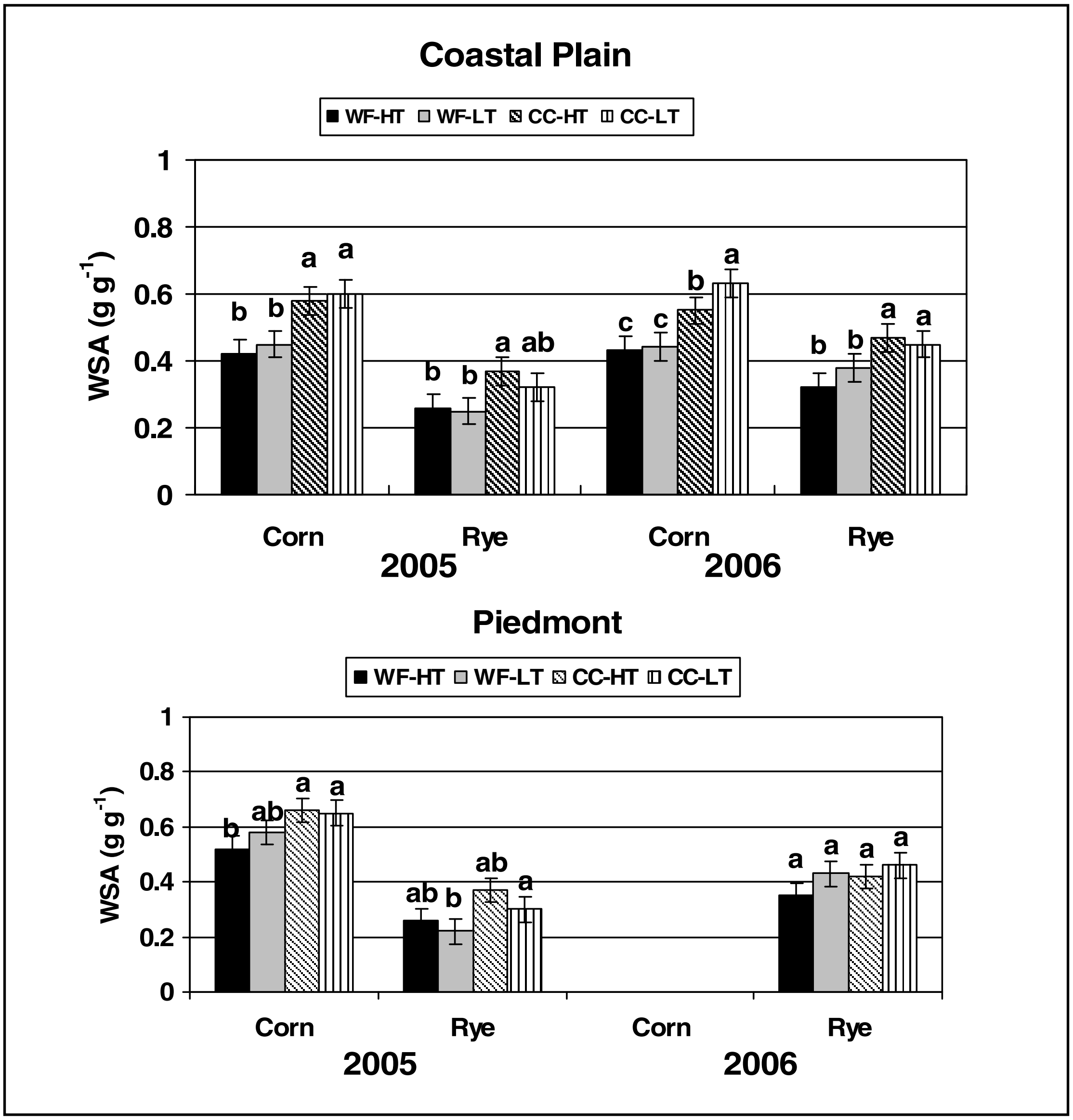


Figure 3.3b: Proportion of water stable aggregate (WSA) > 0.5 mm of fallow (WF) and cover crop (CC) treatments and high traffic (HT) and low traffic (LT) rows for 2005 at Piedmont and Coastal Plain locations. Within a sampling season, sampling period means with different letters are significantly different by LSD mean comparison (p<0.10). Error bars represent average standard error of the mean for both years.

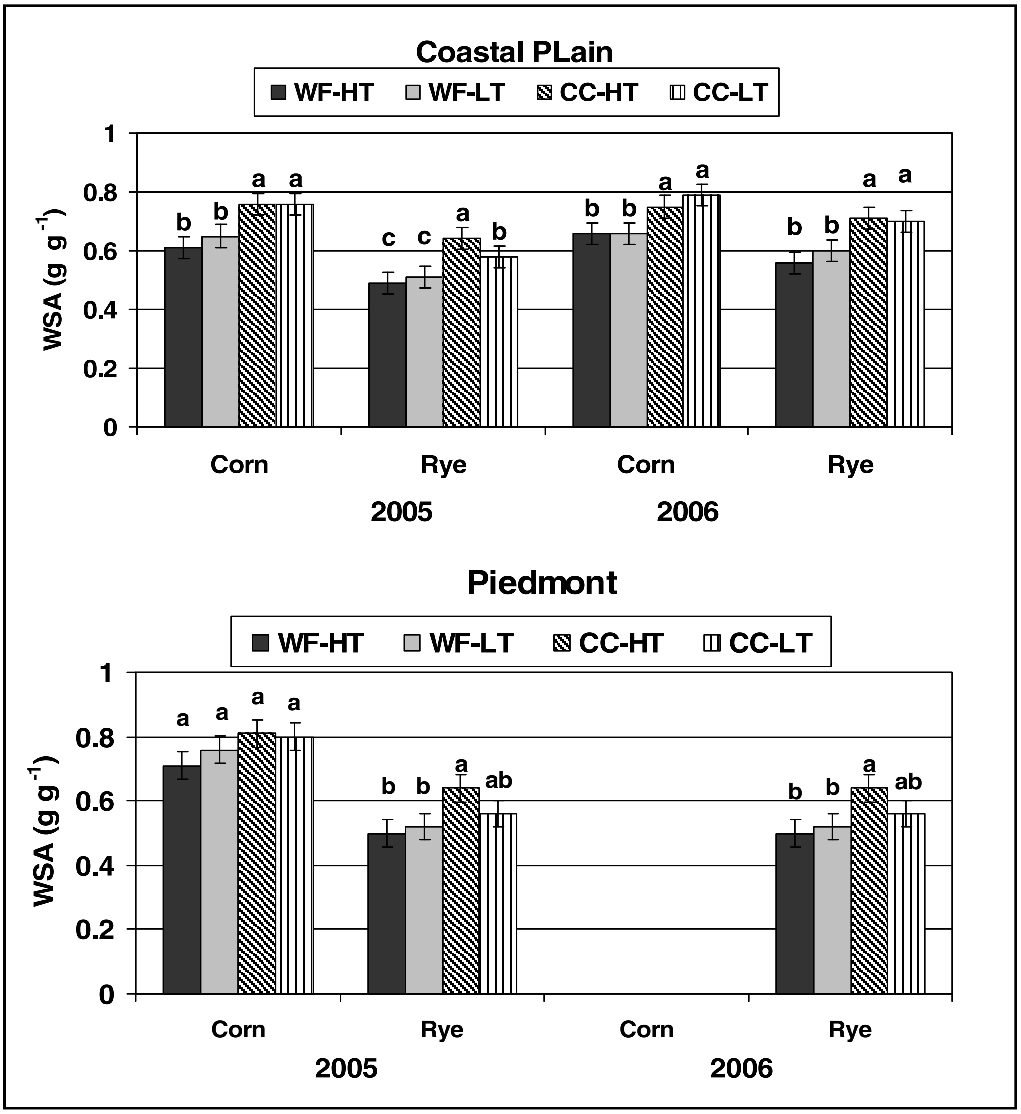


Table 3.1: Dates of the management operations for 2005 and 2006 for Coastal Plain (Poplar Hill and Wye) and Piedmont (Clarksville) locations.

Rotation study management				
		Kill rye	Planted corn	Seeded rye
Clarksville	2005	May 9	May 9	Oct. 31
	2006	May 1	May 1	Oct. 11
Wye	2005	April 29	May 9	Oct. 8
	2006	April 28	May 3	Oct. 27
Poplar Hill	2005	April 30	May 8	Nov.7
	2006	April 26	May 6	Oct. 24

Table 3.2: Average distribution of farm machinery (combine and tractor) wheel traffic over 13 years in high traffic (HT) and low traffic (LT) subplots of Coastal Plain and Piedmont locations.

		Poplar Hill (Coastal Plain)		Wye (Coastal Plain)		Clarksville (Piedmont)	
		Fallow	Cover	Fallow	Cover	Fallow	Cover
Combine passes	HT	2	2	2	2	2	2
	LT	0	0	0	0	0	0
Tractor passes	HT	2	3	3	4	2	3
	LT	1	3	1	2	1	3

Sampling Season	Water movement parameters	Traffic Level	Poplar Hill (Coastal Plain)		Wye (Coastal Plain)		Clarksville (Piedmont)	
			Fallow	Cover	Fallow	Cover	Fallow	Cover
2005 Rye	i_{rate} (m s^{-1})	HT	4.30 E-04 **a**	3.57 E-03 **b**	1.6 E-03 **b**	9.00 E-05 **a**	1.01E-03 **a**	2.42E-03 **b**
		LT	4.58 E-03 **b**	4.50 E-03 **b**	4.00E-04 **ab**	8.10E-04 **b**	7.50E-04 **a**	2.20E-03 **b**
	k_w (m s^{-1})	HT	2.34E-05 **a**	1.32E-04 **b**	8.00E-06 **a**	1.07E-05 **a**	9.04E-05 **a**	8.63E-05 **a**
		LT	1.77E-04 **b**	2.31E-04 **b**	2.15E-05 **a**	1.68E-05 **a**	7.73E-05 **a**	1.10E-04 **a**
	S (m $s^{-1/2}$)	HT	8.23E-07 **a**	3.24E-06 **b**	9.02E-06 **a**	1.96E-07 **a**	3.09E-06 **a**	1.80E-05 **a**
		LT	6.34E-06 **b**	1.20E-05 **b**	2.37E-06 **a**	6.50E-04 **a**	4.87E-07 **a**	2.39E-06 **a**
	I (m)	HT	6.39E-02 **a**	2.62E-01 **b**	1.75E-02 **a**	2.39E-02 **a**	2.40E-01**ab**	2.12E-01**ab**
		LT	4.10E-01 **b**	3.41E-01 **b**	2.10E-02 **a**	1.53E-01 **b**	7.17E-02 **a**	2.02E-01 **b**
2006 Corn	i_{rate} (m s^{-1})	HT	4.50E-05 **a**	3.00E-05 **a**	1.90E-04 **a**	3.07E-04 **a**	+	+
		LT	7.78E-04 **b**	2.95E-04 **b**	4.72E-04 **a**	3.05E-04 **a**	+	+
	k_w (m s^{-1})	HT	1.27E-06 **a**	7.45E-07 **a**	5.07E-06 **a**	3.48E-06 **a**	+	+
		LT	3.54E-05 **b**	1.36E-05 **b**	1.39E-05 **a**	5.58E-06 **a**	+	+
	S (m $s^{-1/2}$)	HT	4.90E-05 **a**	3.80E-05 **a**	2.91E-04 **a**	6.53E-04 **ab**	+	+
		LT	1.16E-04 **b**	3.20E-05 **a**	5.64E-04 **ab**	1.34E-03 **b**	+	+
	I (m)	HT	9.75E-03 **a**	6.00E-03 **a**	2.41E-02 **a**	4.08E-02 **a**	+	+
		LT	8.51E-02 **b**	5.90E-02 **b**	6.83E-02 **a**	6.98E-02 **a**	+	+
2006 Rye	i_{rate} (m s^{-1})	HT	7.50E-05 **a**	1.43E-03 **b**	1.50E-05 **a**	3.50E-05 **a**	1.24E-03 **a**	4.07E-03 **ab**
		LT	1.33E-03 **b**	2.21E-03 **b**	3.67E-05 **a**	2.03E-04 **b**	4.30E-04 **b**	4.59E-04 **b**
	k_w (m s^{-1})	HT	5.36E-06 **a**	5.85E-05 **b**	1.91E-07 **a**	7.75E-07 **a**	6.48E-05 **a**	1.28E-04 **ab**
		LT	5.77E-05 **b**	9.94E-05 **b**	7.44E-07 **a**	7.27E-06 **b**	1.82E-04 **b**	1.11E-04 **ab**
	S (m $s^{-1/2}$)	HT	5.50E-05 **a**	4.75E-04 **b**	1.60E-05 **ab**	2.10E-05 **a**	3.80E-05 **a**	1.37E-03 **a**
		LT	4.15E-04 **b**	5.50E-04 **b**	6.00E-05 **ab**	6.70E-05 **b**	2.29E-03 **a**	9.90E-04 **a**
	I (m)	HT	9.75E-03 **a**	1.54E-01 **b**	1.33E-03 **a**	4.25E-03 **a**	2.39E-01 **a**	2.20E-01 **ab**
		LT	1.98E-01 **b**	2.22E-01 **b**	3.34E-03 **a**	3.54E-02 **b**	3.02E-01 **b**	3.26E-01 **b**

Table 3.3 – Water infiltration rate (i_{rate}), hydraulic conductivity(k_w), sorptivity(S), and cumulative infiltration (I) of fallow and cover crop treatments and high traffic (HT) and low traffic (LT) rows at three locations, Poplar Hill, Wye, and Clarksville for rye 2005, corn 2006, and rye 2006. Letters compare fallow and cover crop treatments and traffic condition for each parameter, within a season and site. Means are significantly different at $p< 0.10$. See Appendix F for standard errors.

+ Data was not collected for corn 2006 at the Clarksville location.

Table 3.4: Comparison of soil moisture retention of high traffic (HT) and low traffic (LT) areas of cover crop and winter fallow rotations at three locations Poplar Hill, Wye, and Clarksville for rye and corn sampling seasons of 2006. Letters compare rotation treatment and traffic condition within a water potential, site, and sampling season. Means are significantly different at $p<0.10$.

		Crop	Traffic	Water Potential (kPa)				
Site	Season	Rotation	level	0	-0.1	-0.2	-0.3	-10
Poplar Hill	Corn	Fallow	HT	0.388 **a**	0.372 **a**	0.365 **a**	0.357**ab**	0.329**ac**
			LT	0.412 **bc**	0.392 **b**	0.376 **a**	0.367**ab**	0.309 **b**
		Cover	HT	0.395 **ab**	0.384 **b**	0.374 **a**	0.369 **a**	0.341 **a**
			LT	0.432 **c**	0.383**ab**	0.365 **a**	0.355 **b**	0.316**cb**
	Rye	Fallow	HT	0.390 **a**	0.365**bc**	0.352 **a**	0.352 **a**	0.298**ab**
			LT	0.393 **a**	0.382 **a**	0.356 **a**	0.351 **a**	0.287 **a**
		Cover	HT	0.410 **a**	0.377**ab**	0.356 **a**	0.353 **a**	0.307 **b**
			LT	0.441 **b**	0.353 **c**	0.335 **b**	0.329 **b**	0.292 **a**
Wye	Corn	Fallow	HT	0.424 **a**	0.406 **a**	0.400 **a**	0.392**ab**	0.362**ab**
			LT	0.450 **b**	0.403 **a**	0.392 **a**	0.384**ab**	0.349 **c**
		Cover	HT	0.422 **a**	0.412 **a**	0.407 **a**	0.399 **a**	0.376 **b**
			LT	0.447 **b**	0.405 **a**	0.394 **a**	0.381 **b**	0.344 **c**
	Rye	Fallow	HT	0.393 **a**	0.383 **a**	0.371 **a**	0.368 **a**	0.319 **a**
			LT	0.413 **ab**	0.394 **a**	0.380 **a**	0.374 **a**	0.318 **a**
		Cover	HT	0.411 **ab**	0.398 **a**	0.380 **a**	0.376 **a**	0.324 **a**
			LT	0.426 **b**	0.401 **a**	0.373 **a**	0.369 **a**	0.311 **a**
Clarksville	Rye	Fallow	HT	0.461 **a**	0.448 **a**	0.425 **a**	0.428 **a**	0.355 **a**
			LT	0.463 **a**	0.436 **a**	0.395 **b**	0.394 **b**	0.301 **b**
		Cover	HT	0.464 **a**	0.450 **a**	0.426 **a**	0.422 **a**	0.344 **a**
			LT	0.467 **a**	0.451 **a**	0.420 **a**	0.421 **a**	0.342 **a**

		Crop	Traffic	Water Potential (kPa)				
Site	Season	Rotation	level	-30	-60	-500	-1000	-1500
Poplar Hill	Corn	Fallow	HT	0.288 **a**	0.274 **a**			
			LT	0.258 **b**	0.238 **b**	0.100 **a**	0.084**a**	0.081 **a**
		Cover	HT	0.309 **c**	0.299 **c**			
			LT	0.279 **a**	0.265 **a**	0.081**a**	0.079**a**	0.079 **a**
	Rye	Fallow	HT	0.279 **ab**	0.261 **a**			
			LT	0.255 **c**	0.234 **b**	0.104 **a**	0.081**a**	0.078 **a**
		Cover	HT	0.280 **a**	0.246**ab**			
			LT	0.267 **bc**	0.238 **b**	0.096 **a**	0.081**a**	0.075 **a**
Wye	Corn	Fallow	HT	0.323 **a**	0.306 **a**			
			LT	0.309 **b**	0.295 **a**	0.106**a**	0.089**a**	0.081 **a**
		Cover	HT	0.331 **a**	0.309 **a**			
			LT	0.306 **b**	0.291 **a**	0.101**a**	0.084**a**	0.080 **a**
	Rye	Fallow	HT	0.293 **ab**	0.262 **a**			
			LT	0.289 **ab**	0.263 **a**	0.115**a**	0.095**a**	0.075 **a**
		Cover	HT	0.300 **a**	0.269 **a**			
			LT	0.283 **b**	0.248 **a**	0.097**b**	0.085**a**	0.079 **a**
Clarksville	Rye	Fallow	HT	0.322 **a**	0.317 **a**			
			LT	0.268 **b**	0.259 **b**	0.125 **a**	0.113 **a**	0.112 **a**
		Cover	HT	0.315 **a**	0.298 **a**			
			LT	0.305 **a**	0.289 **a**	0.129 **a**	0.116 **a**	0.114 **a**

Appendices

Appendix A: Sampling dates for each procedure during the corn and rye sampling periods of 2005 and 2006.

Sampling date	Bulk density	Air permeability	Water Infiltration	Aggregate Stability, Organic matter, & Labile C	Residue cover
Corn 2005					
Clarksville	June 10th	July 30th Aug. 24th	+	Aug. 24th	+
Wye	June 16th	Aug. 2nd Aug. 6th	+	Sept. 17th	+
Poplar Hill	June 17th	Aug. 14th Aug. 18th Sept. 3rd	+	Sept. 3rd	+
Rye 2005					
Clarksville	Feb. 2nd	Dec. 28th Jan. 5th Jan. 12th	Nov. 27th	Jan. 12th	+
Wye	Feb. 7th	Dec 30th Jan. 9th Jan.13th	Oct. 28th	Jan. 13th	April 26th
Poplar Hill	Feb. 10th	Jan. 4th Jan. 9th Jan19th	Nov. 14th	Jan. 19th	April 26th
Corn 2006					
Clarksville	+	+	+	+	+
Wye	Oct. 23rd	June 13th July10th July 25th	April 19th	July 25th	Oct. 24th
Poplar Hill	Nov. 3rd	Oct. 20th Oct. 28th	Oct. 26th	Oct. 28th	Oct. 31st
Rye 2006					
Clarksville	Nov. 21st	Nov. 7th	Nov. 7th	Nov. 21st	Nov. 7th
Wye	Jan. 20th	Nov. 9th	Nov. 9th	Jan. 20th	Nov. 9th
Poplar Hill	Jan. 12th	Nov. 19th	Nov. 19th	Jan. 12th	March 2nd

+ Data was not collected these sampling periods.

Appendix B: Additional soil properties (texture and pH) for Clarksville, Poplar Hill and Wye locations. Sampled 1997, analyzed by Cooperative Extension Service, University of Maryland, College park.

Site	Replicate	pH	%Sand	%Silt	%Clay	Soil texture
Clarksville	1	5.9	53	28	19	Sandy loam
	2	6.3	50	28	22	Loam
	3	6.5	46	35	19	Loam
	4	6.4	57	31	17	Loam
Poplar Hill	1	6.1	34	48	18	Loam
	2	6.0	34	46	20	Loam
	3	6.0	33	47	20	Loam
	4	5.9	34	45	21	Loam
Wye	1	6.3	26	53	21	Silt Loam
	2	6.5	26	56	18	Silt Loam
	3	6.3	27	53	20	Silt Loam
	4	6.5	25	54	21	Silt Loam

Appendix C: Sample SAS program code.

The following is an example of SAS mixed program code used to analyze the majority of datasets.

```
proc mixed data=wpbulkdensity;
by year;
class site season subject rep rotation row ;
model bulkdensity = season|rotation|row;
random site site*rep site*rotation*rep site*rotation*row*rep;
repeated season / subject = site*season*rep*rotation*row type=cs;
lsmeans season|rotation|row /  pdiff;
quit;
```

The analysis contains the following changes to the basic RCB split-plot ANOVA:

1. "`site`" is included separately in the "`random`" statement, allowing for Wye and Poplar Hill to be combined as two blocks.
2. "`season`" is designated as the repeated unit by the "`repeated`" statement. The subject being repeated is designated as the subplot unit by the statement "`subject = site*season*rep*rotation*row`"

The following is an example of SAS mixed program code used when the sites could not be combined.

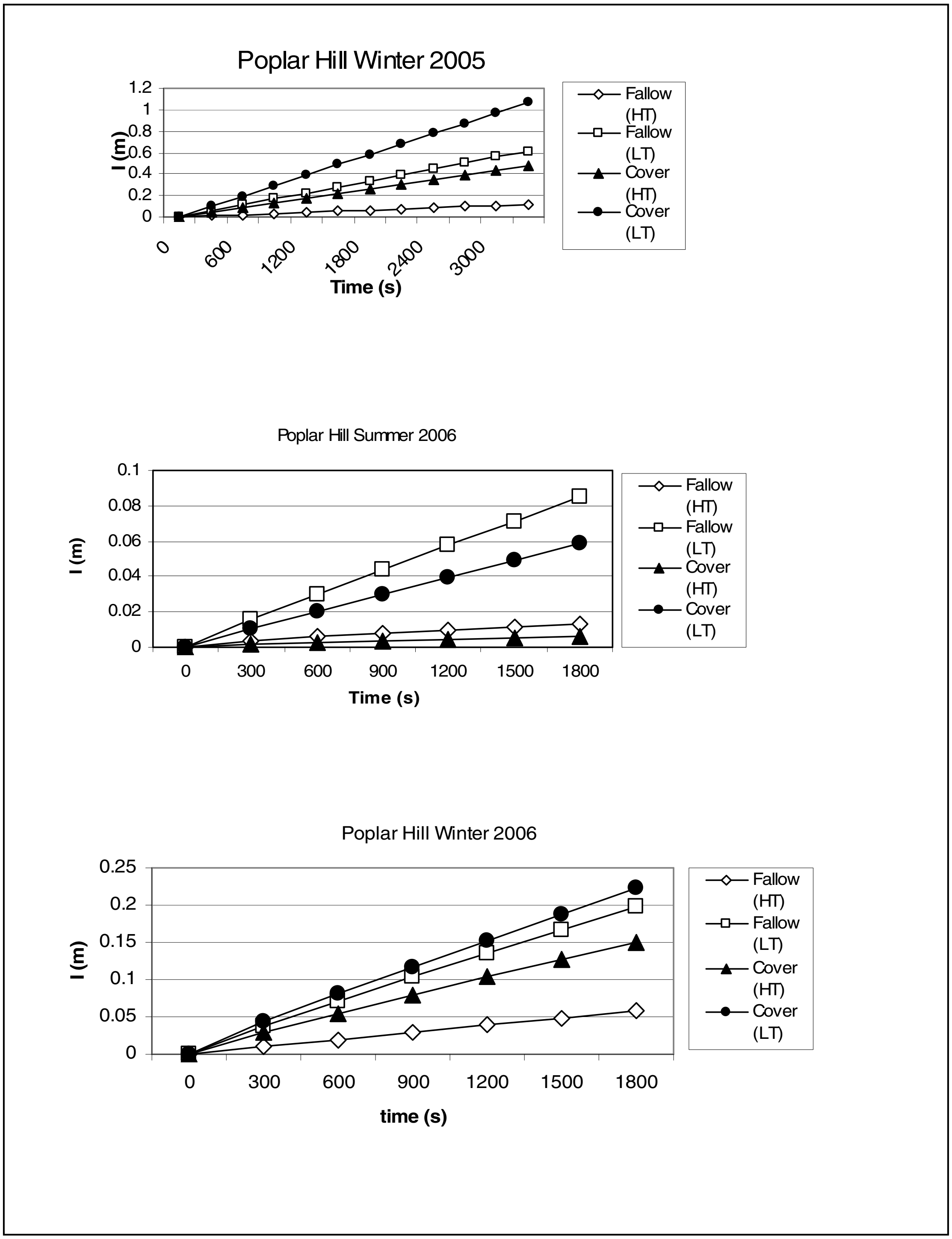
```
proc mixed data=wpbulkdensity;
by year site;
class season subject rep rotation row ;
model bulkdensity = season|rotation|row;
random rep rotation*rep rotation*row*rep;
repeated season / subject = season*rep*rotation*row type=cs;
lsmeans season|rotation|row /  pdiff;
quit;
```

The following is an example of SAS mixed program code used when the sites could not be combined and the repeated measure procedure could not be utilized.

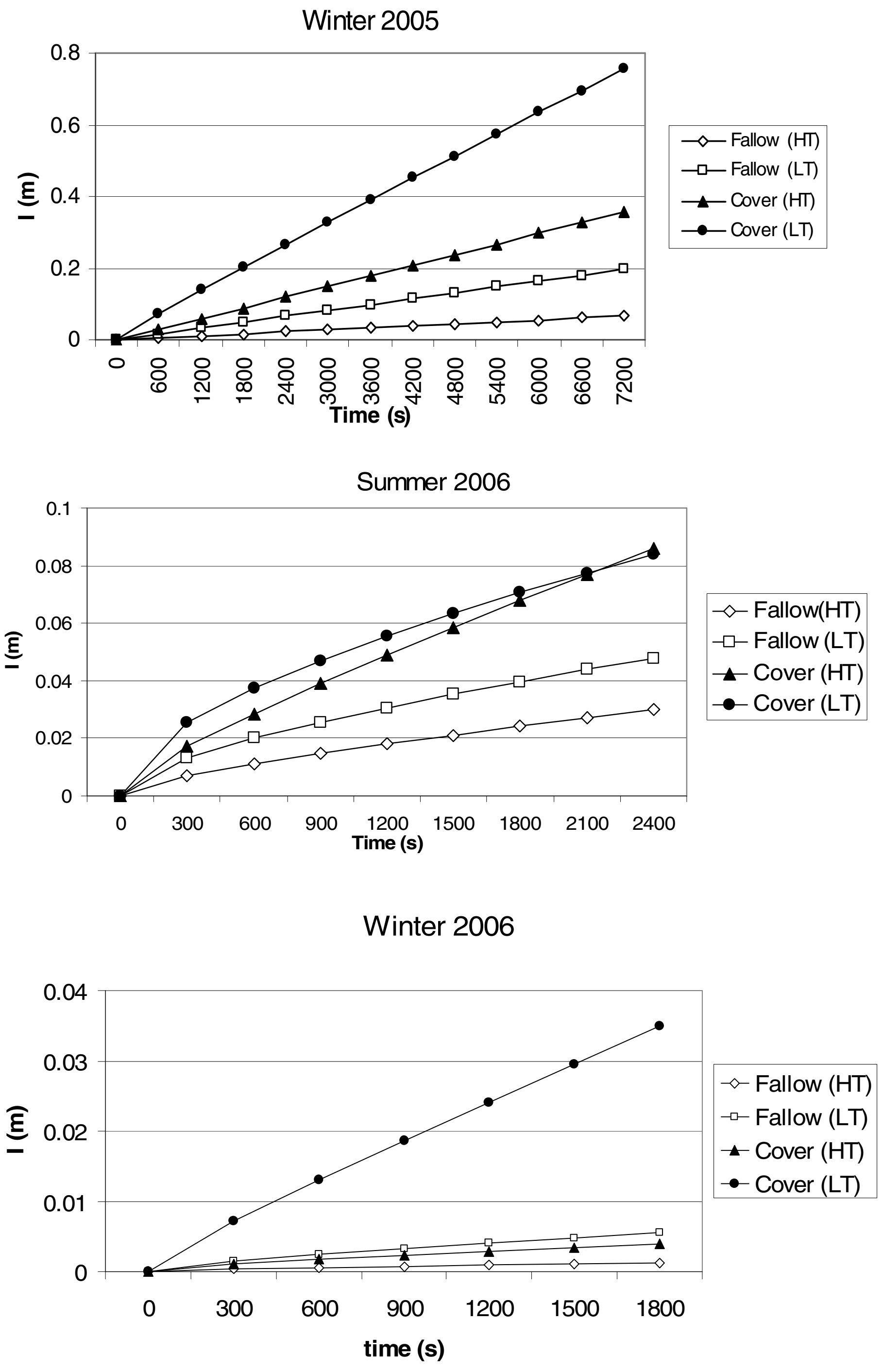
```
proc mixed data=wpbulkdensity;
by year site season;
class rep rotation row ;
model bulkdensity = season|rotation|row;
random rep rotation*rep rotation*row*rep;
lsmeans season|rotation|row /  pdiff;
quit;
```

Appendix D: Water infiltration curves of Clarksville, Poplar Hill, and Wye for cover crop and fallow treatments and wheel traffic condition.

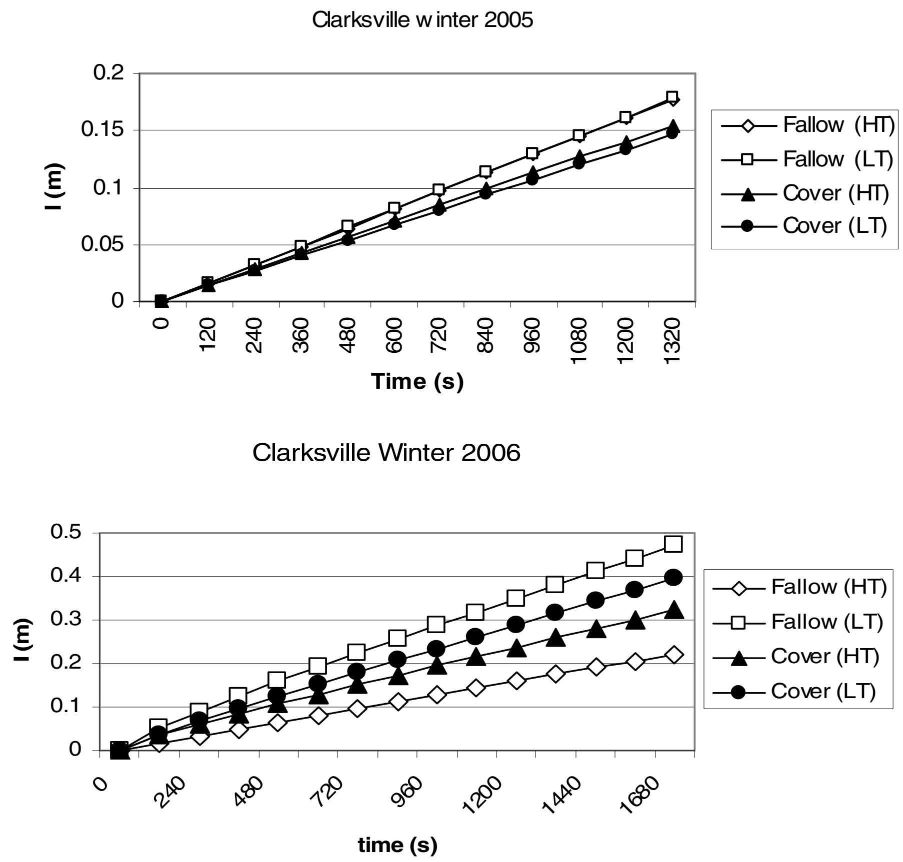
Appendix D,a: Water infiltration (I) of Poplar Hill for fallow (WF), cover crop (CC) and high traffic (HT) and low traffic (LT)



Appendix D,b: Water infiltration (I) of Wye for fallow, cover crop, high traffic (HT), and low traffic (LT)



Appendix D,c: Water infiltration (I) of Clarksville for fallow, cover crop, high traffic (HT), and low traffic (LT)



Clarksville w inter 2005

Clarksville Winter 2006

Appendix E: Standard error for water movement parameters for winter fallow and cover crop comparisons for all locations and sampling seasons.

Year	Season	Water movement parameter	Poplar Hill (Coastal Plain)		Wye (Coastal Plain)		Clarksville (Piedmont)
			Std. Error		Std. Error		Std. Error
2005	Rye	i_{rate} (m s^{-1})	$2.42*10^{-4}$		$3.31*10^{-4}$		$1.92*10^{-4}$
		k_w (m s^{-1})	$2.25*10^{-4}$		$3.31*10^{-4}$		$2.46*10^{-4}$
		S (m s$^{-1/2}$)	$2.47*10^{-4}$		$5.44*10^{-4}$		$2.89*10^{-4}$
		I (m)	$2.07*10^{-4}$		$2.41*10^{-4}$		$2.19*10^{-4}$
2006	Corn	i_{rate} (m s^{-1})	$2.56*10^{-4}$		$2.24*10^{-4}$		+
		k_w (m s^{-1})	$3.03*10^{-4}$		$2.67*10^{-4}$		+
		S (m s$^{-1/2}$)	$2.30*10^{-4}$		$2.25*10^{-4}$		+
		I (m)	$2.58*10^{-4}$		$2.33*10^{-4}$		+
2006	Rye	i_{rate} (m s^{-1})	$2.56*10^{-4}$		$2.24*10^{-4}$		$2.48*10^{-4}$
		k_w (m s^{-1})	$3.03*10^{-4}$		$2.67*10^{-4}$		$2.84*10^{-4}$
		S (m s$^{-1/2}$)	$2.30*10^{-4}$		$2.25*10^{-4}$		$3.49*10^{-4}$
		I (m)	$2.58*10^{-4}$		$2.33*10^{-4}$		$2.37*10^{-4}$

Appendix F: Standard error for water movement parameters for winter fallow and cover crop comparisons for all locations and sampling seasons.

Year	Season	Water movement parameter	Poplar Hill (Coastal Plain)		Wye (Coastal Plain)		Clarksville (Piedmont)
			Std. Error		Std. Error		Std. Error
2005	Rye	i_{rate} (m s^{-1})	$2.54*10^{-4}$		$3.65*10^{-4}$		$2.03*10^{-4}$
		k_w (m s^{-1})	$2.42*10^{-4}$		$4.14*10^{-4}$		$2.68*10^{-4}$
		S (m s$^{-1/2}$)	$2.64*10^{-4}$		$8.53*10^{-4}$		$3.64*10^{-4}$
		I (m)	$2.17*10^{-4}$		$2.46*10^{-4}$		$2.46*10^{-4}$
2006	Corn	i_{rate} (m s^{-1})	$2.86*10^{-4}$		$2.49*10^{-4}$		+
		k_w (m s^{-1})	$3.67*10^{-4}$		$3.21*10^{-4}$		+
		S (m s$^{-1/2}$)	$2.60*10^{-4}$		$2.55*10^{-4}$		+
		I (m)	$2.94*10^{-4}$		$2.58*10^{-4}$		+
2006	Rye	i_{rate} (m s^{-1})	$2.86*10^{-4}$		$2.49*10^{-4}$		$2.58*10^{-4}$
		k_w (m s^{-1})	$3.67*10^{-4}$		$3.21*10^{-4}$		$2.98*10^{-4}$
		S (m s$^{-1/2}$)	$2.60*10^{-4}$		$2.55*10^{-4}$		$3.21*10^{-4}$
		I (m)	$2.94*10^{-4}$		$2.58*10^{-4}$		$2.50*10^{-4}$

Appendix G: Data for all parameters for Clarksville, Wye, and Poplar Hill.

									WSA	
year	season	Site	rep	rotation	row	k_a	VWC	D_b	2.0 mm	0.5 mm
2005	Corn	Clarksville	1	1	t	2.64	31.75	1.192	0.395	0.546
2005	Corn	Clarksville	1	1	u	6.22	31.25	1.185	0.343	0.569
2005	Corn	Clarksville	1	2	t	2.33	32	1.148	0.708	0.828
2005	Corn	Clarksville	1	2	u	6.11	36.25	1.171	0.566	0.775
2005	Corn	Clarksville	2	1	t	3.24	32.75	1.199	0.706	0.824
2005	Corn	Clarksville	2	1	u	4.34	37.25	1.164	0.647	0.823
2005	Corn	Clarksville	2	2	t	4.46	30.25	1.274	0.675	0.827
2005	Corn	Clarksville	2	2	u	5.55	28.5	1.254	0.568	0.721
2005	Corn	Clarksville	3	1	t	7.61	24.25	1.262	0.473	0.707
2005	Corn	Clarksville	3	1	u	20.23	24.75	1.240	0.593	0.793
2005	Corn	Clarksville	3	2	t	3.71	30.75	1.214	0.646	0.791
2005	Corn	Clarksville	3	2	u	4.79	27.5	1.148	0.719	0.857
2005	Corn	Clarksville	4	1	t	6.1	26	1.298	0.523	0.782
2005	Corn	Clarksville	4	1	u	27.91	21.5	1.144	0.737	0.845
2005	Corn	Clarksville	4	2	t	1.41	29.75	1.293	0.631	0.802
2005	Corn	Clarksville	4	2	u	8.85	24.75	1.225	0.741	0.839
2005	Corn	Poplar Hill	1	1	t	3.83	22.66	1.534	0.359	0.521
2005	Corn	Poplar Hill	1	1	u	11.84	24	1.413	0.211	0.400
2005	Corn	Poplar Hill	1	2	t	2.95	24.33	1.536	0.645	0.779
2005	Corn	Poplar Hill	1	2	u	10.93	25.33	1.468	0.619	0.764
2005	Corn	Poplar Hill	2	1	t	6.03	22.33	1.515	0.318	0.562
2005	Corn	Poplar Hill	2	1	u	18.44	24	1.373	0.456	0.637
2005	Corn	Poplar Hill	2	2	t	11.58	22.33	1.497	0.375	0.651
2005	Corn	Poplar Hill	2	2	u	11.14	22.5	1.287	0.687	0.797
2005	Corn	Poplar Hill	3	1	t	3.78	20	1.525	0.334	0.530
2005	Corn	Poplar Hill	3	1	u	32.88	18.16	1.395	0.280	0.433
2005	Corn	Poplar Hill	3	2	t	5.99	23.33	1.507	0.512	0.658
2005	Corn	Poplar Hill	3	2	u	11.64	22.66	1.359	0.326	0.539
2005	Corn	Poplar Hill	4	1	t	6.07	21.83	1.383	0.324	0.514
2005	Corn	Poplar Hill	4	1	u	26.23	22.16	1.271	0.353	0.596
2005	Corn	Poplar Hill	4	2	t	6.78	22.83	1.561	0.522	0.763
2005	Corn	Poplar Hill	4	2	u	26.88	22	1.388	0.677	0.830
2005	Corn	Wye	1	1	t	4.58	31.16	1.437	0.506	0.705
2005	Corn	Wye	1	1	u	1.11	31.83	1.331	0.698	0.885
2005	Corn	Wye	1	2	t	0.667	31.5	1.471	0.326	0.588
2005	Corn	Wye	1	2	u	0.393	34.7	1.414	0.750	0.857
2005	Corn	Wye	2	1	t	1.7	29.83	1.458	0.331	0.592
2005	Corn	Wye	2	1	u	5.18	30	1.375	0.238	0.480
2005	Corn	Wye	2	2	t	2.71	30	1.362	0.799	0.917
2005	Corn	Wye	2	2	u	13.13	25	1.379	0.389	0.757
2005	Corn	Wye	3	1	t	1.85	31.33	1.434	0.395	0.641
2005	Corn	Wye	3	1	u	6.88	30.83	1.321	0.517	0.775
2005	Corn	Wye	3	2	t	2.37	29.66	1.450	0.576	0.769
2005	Corn	Wye	3	2	u	1.77	25.2	1.367	0.559	0.771
2005	Corn	Wye	4	1	t	1.89	29.16	1.422	0.409	0.587
2005	Corn	Wye	4	1	u	22.77	22	1.319	0.379	0.563
2005	Corn	Wye	4	2	t	3.69	28	1.434	0.561	0.796
2005	Corn	Wye	4	2	u	5.75	27.3	1.356	0.559	0.769
2005	Rye	Clarksville	1	1	t	19.7	35.33	1.130	0.189	0.431
2005	Rye	Clarksville	1	1	u	0.242	35.33	1.217	0.258	0.514

									WSA	
year	season	Site	rep	rotation	row	k_a	VWC	D_b	2.0 mm	0.5 mm
2005	Rye	Clarksville	1	2	t	2.26	35.83	1.172	0.354	0.672
2005	Rye	Clarksville	1	2	u	25.73	37.33	1.149	0.318	0.534
2005	Rye	Clarksville	2	1	t	4.34	37.16	1.198	0.177	0.451
2005	Rye	Clarksville	2	1	u	0.31	37.5	1.156	0.231	0.573
2005	Rye	Clarksville	2	2	t	5.42	35.5	1.180	0.446	0.669
2005	Rye	Clarksville	2	2	u	2.69	39	1.137	0.206	0.446
2005	Rye	Clarksville	3	1	t	2.4	36.83	1.280	0.403	0.621
2005	Rye	Clarksville	3	1	u	0.89	37	1.193	0.140	0.509
2005	Rye	Clarksville	3	2	t	47.15	36	1.170	0.342	0.624
2005	Rye	Clarksville	3	2	u	37.66	37	1.116	0.382	0.675
2005	Rye	Clarksville	4	1	t	9.31	31.33	1.249	0.292	0.485
2005	Rye	Clarksville	4	1	u	16.29	31.66	1.204	0.241	0.468
2005	Rye	Clarksville	4	2	t	6.2	35.83	1.171	0.357	0.580
2005	Rye	Clarksville	4	2	u	7.54	35	1.171	0.305	0.589
2005	Rye	Poplar Hill	1	1	t	0.24	34	1.540	0.155	0.350
2005	Rye	Poplar Hill	1	1	u	26.41	32.66	1.389	0.221	0.378
2005	Rye	Poplar Hill	1	2	t	50.29	29.33	1.229	0.352	0.618
2005	Rye	Poplar Hill	1	2	u	40.15	33.33	1.222	0.316	0.652
2005	Rye	Poplar Hill	2	1	t	3.53	31.33	1.474	0.369	0.616
2005	Rye	Poplar Hill	2	1	u	37.66	31	1.332	0.276	0.537
2005	Rye	Poplar Hill	2	2	t	4.9	30.83	1.327	0.359	0.633
2005	Rye	Poplar Hill	2	2	u	15.98	32.83	1.296	0.185	0.488
2005	Rye	Poplar Hill	3	1	t	7.4	31.16	1.503	0.212	0.460
2005	Rye	Poplar Hill	3	1	u	5.27	30.83	1.329	0.193	0.418
2005	Rye	Poplar Hill	3	2	t	47.01	28.83	1.248	0.297	0.524
2005	Rye	Poplar Hill	3	2	u	50.14	31.5	1.227	0.132	0.380
2005	Rye	Poplar Hill	4	1	t	0.34	32	1.558	0.147	0.369
2005	Rye	Poplar Hill	4	1	u	13.99	30.66	1.338	0.309	0.507
2005	Rye	Poplar Hill	4	2	t	27.21	26.66	1.235	0.294	0.625
2005	Rye	Poplar Hill	4	2	u	12.36	28	1.089	0.316	0.634
2005	Rye	Wye	1	1	t	0.688	35.66	1.445	0.387	0.593
2005	Rye	Wye	1	1	u	1.29	40.16	1.221	0.303	0.616
2005	Rye	Wye	1	2	t	0.768	39.66	1.295	0.229	0.574
2005	Rye	Wye	1	2	u	7.01	39.3	1.329	0.416	0.700
2005	Rye	Wye	2	1	t	0.33	39.33	1.359	0.318	0.554
2005	Rye	Wye	2	1	u	0.29	39.66	1.408	0.245	0.470
2005	Rye	Wye	2	2	t	3.017	40.5	1.265	0.581	0.805
2005	Rye	Wye	2	2	u	5.7	36	1.226	0.474	0.719
2005	Rye	Wye	3	1	t	0.38	37.33	1.418	0.205	0.480
2005	Rye	Wye	3	1	u	0.51	37.5	1.307	0.306	0.594
2005	Rye	Wye	3	2	t	3.77	34.46	1.295	0.328	0.654
2005	Rye	Wye	3	2	u	1.39	38	1.214	0.354	0.585
2005	Rye	Wye	4	1	t	0.16	36.5	1.439	0.225	0.510
2005	Rye	Wye	4	1	u	10.4	37	1.330	0.304	0.518
2005	Rye	Wye	4	2	t	18.83	38	1.354	0.492	0.743
2005	Rye	Wye	4	2	u	26.43	38.3	1.257	0.426	0.628
2006	Corn	Poplar Hill	1	1	t	1.22	29	1.559		
2006	Corn	Poplar Hill	1	1	u	7.59	25.33	1.405		
2006	Corn	Poplar Hill	1	2	t	1.49	30.83	1.464		
2006	Corn	Poplar Hill	1	2	u	16.5	26.16	1.335		

									WSA	
year	season	Site	rep	rotation	row	k_a	VWC	D_b	2.0 mm	0.5 mm
2006	Corn	Poplar Hill	2	1	t	1.11	29	1.526		
2006	Corn	Poplar Hill	2	1	u	7.84	26.33	1.426		
2006	Corn	Poplar Hill	2	2	t	1.69	32.166	1.484		
2006	Corn	Poplar Hill	2	2	u	18.34	27.33	1.291		
2006	Corn	Poplar Hill	3	1	t	0.83	29.58	1.566		
2006	Corn	Poplar Hill	3	1	u	22.88	23.08	1.356		
2006	Corn	Poplar Hill	3	2	t	1.277	30.58	1.552		
2006	Corn	Poplar Hill	3	2	u	7.71	25.83	1.387		
2006	Corn	Poplar Hill	4	1	t	0.54	27	1.479		
2006	Corn	Poplar Hill	4	1	u	12.404	26.66	1.334		
2006	Corn	Poplar Hill	4	2	t	0.304	31.166	1.381		
2006	Corn	Poplar Hill	4	2	u	5.94	25.08	1.275		
2006	Corn	Wye	1	1	t	3.72	31.91	1.470		
2006	Corn	Wye	1	1	u	5.12	30.75	1.232		
2006	Corn	Wye	1	2	t	2.06	30.25	1.407		
2006	Corn	Wye	1	2	u	7.41	31.33	1.323		
2006	Corn	Wye	2	1	t	5.24	32.66	1.416		
2006	Corn	Wye	2	1	u	2.18	30.33	1.317		
2006	Corn	Wye	2	2	t	7.58	32.1	1.399		
2006	Corn	Wye	2	2	u	2.9	31.5	1.304		
2006	Corn	Wye	3	1	t	0.56	34.41	1.411		
2006	Corn	Wye	3	1	u	1.11	34.83	1.259		
2006	Corn	Wye	3	2	t	8.89	33.16	1.451		
2006	Corn	Wye	3	2	u	3.78	35.41	1.276		
2006	Corn	Wye	4	1	t	3.79	32.16	1.451		
2006	Corn	Wye	4	1	u	3.11	32	1.334		
2006	Corn	Wye	4	2	t	3.41	29.166	1.428		
2006	Corn	Wye	4	2	u	8.9	21.66	1.280		
2006	Rye	Clarksville	1	1	t	3.1	31.33	1.229		
2006	Rye	Clarksville	1	1	u	10.72	32.66	1.180		
2006	Rye	Clarksville	1	2	t	8.6	37.5	1.243		
2006	Rye	Clarksville	1	2	u	1.13	34	1.243		
2006	Rye	Clarksville	2	1	t	4.93	36.66	1.249		
2006	Rye	Clarksville	2	1	u	18.54	31.83	1.197		
2006	Rye	Clarksville	2	2	t	1.87	32.83	1.202		
2006	Rye	Clarksville	2	2	u	6.13	33.33	1.148		
2006	Rye	Clarksville	3	1	t	9.51	43.66	1.342		
2006	Rye	Clarksville	3	1	u	10.11	37	1.169		
2006	Rye	Clarksville	3	2	t	8.34	34.66	1.254		
2006	Rye	Clarksville	3	2	u	3.55	35.33	1.211		
2006	Rye	Clarksville	4	1	t	2.05	29.5	1.320		
2006	Rye	Clarksville	4	1	u	9.8	28.5	1.236		
2006	Rye	Clarksville	4	2	t	0.96	32.83	1.241		
2006	Rye	Clarksville	4	2	u	5.14	30.66	1.231		
2006	Rye	Poplar Hill	1	1	t	0.509	32	1.492		
2006	Rye	Poplar Hill	1	1	u	2.36	31	1.404		
2006	Rye	Poplar Hill	1	2	t	1.35	30.16	1.353		
2006	Rye	Poplar Hill	1	2	u	44.99	28	1.296		
2006	Rye	Poplar Hill	2	1	t	1.94	31.83	1.533		
2006	Rye	Poplar Hill	2	1	u	10.03	32.16	1.346		

year	season	Site	rep	rotation	row	k_a	VWC	D_b
2006	Rye	Poplar Hill	2	2	t	0.344	33.83	1.337
2006	Rye	Poplar Hill	2	2	u	26.56	30.5	1.259
2006	Rye	Poplar Hill	3	1	t	5.47	31.66	1.439
2006	Rye	Poplar Hill	3	1	u	5.9	28.5	1.381
2006	Rye	Poplar Hill	3	2	t	38.92	29	1.292
2006	Rye	Poplar Hill	3	2	u	45.41	27.66	1.259
2006	Rye	Poplar Hill	4	1	t	1.76	33.5	1.528
2006	Rye	Poplar Hill	4	1	u	3.5	30.33	1.369
2006	Rye	Poplar Hill	4	2	t	26.46	31.5	1.241
2006	Rye	Poplar Hill	4	2	u	9.12	32.83	1.130
2006	Rye	Wye	1	1	t	0.339	46.66	1.396
2006	Rye	Wye	1	1	u	0.781	42.33	1.298
2006	Rye	Wye	1	2	t	0.352	34.16	1.313
2006	Rye	Wye	1	2	u	15.52	32.83	1.222
2006	Rye	Wye	2	1	t	0.1902	40.66	1.332
2006	Rye	Wye	2	1	u	0.352	38.83	1.382
2006	Rye	Wye	2	2	t	1.68	39.83	1.259
2006	Rye	Wye	2	2	u	8.08	35.83	1.169
2006	Rye	Wye	3	1	t	0.184	37.5	1.435
2006	Rye	Wye	3	1	u	3.35	38.17	1.332
2006	Rye	Wye	3	2	t	0.255	37	1.333
2006	Rye	Wye	3	2	u	4.14	35.66	1.211
2006	Rye	Wye	4	1	t	0.27	36.33	1.445
2006	Rye	Wye	4	1	u	2.12	33.67	1.327
2006	Rye	Wye	4	2	t	0.21	37.16	1.290
2006	Rye	Wye	4	2	u	13.56	33.5	1.227

year	season	Site	rep	rotation	row	irate	k_w	sorptivity	I
2005	Rye	Clarksville	1	1	t	8.63	5.94E-05	1.77E-07	1.64E-01
2005	Rye	Clarksville	1	1	u	4.81	3.98E-05	2.60E-07	9.15E-02
2005	Rye	Clarksville	1	2	t	14.6	1.18E-04	6.97E-05	2.81E-01
2005	Rye	Clarksville	1	2	u	13.89	1.07E-04	1.03E-06	2.64E-01
2005	Rye	Clarksville	2	1	t	7.51	1.95E-04	4.84E-06	4.45E-01
2005	Rye	Clarksville	2	1	u	4.5	3.80E-05	9.51E-07	8.55E-02
2005	Rye	Clarksville	2	2	t	8.63	1.92E-05	4.83E-07	4.10E-02
2005	Rye	Clarksville	2	2	u	12.81	1.18E-04	3.39E-06	2.60E-01
2005	Rye	Clarksville	3	1	t	2.72	2.21E-05	5.47E-07	5.30E-02
2005	Rye	Clarksville	3	1	u	6.89	5.86E-05	1.46E-07	1.31E-01
2005	Rye	Clarksville	3	2	t	25.61	2.17E-04	5.48E-07	4.80E-01
2005	Rye	Clarksville	3	2	u	15.1	1.21E-04	2.77E-06	2.87E-01
2005	Rye	Clarksville	4	1	t	7.51	2.61E-04	6.80E-06	5.39E-01
2005	Rye	Clarksville	4	1	u	2.78	4.03E-04	5.91E-07	5.30E-02
2005	Rye	Clarksville	4	2	t	13.6	1.13E-04	8.06E-07	2.59E-01
2005	Rye	Clarksville	4	2	u	11.44	9.61E-05	2.39E-06	2.18E-01
2005	Rye	Poplar Hill	1	1	t	1.05	9.53E-06	2.00E-07	2.90E-02
2005	Rye	Poplar Hill	1	1	u	29.84	2.59E-04	7.31E-06	4.24E-01
2005	Rye	Poplar Hill	1	2	t	7.42	6.47E-05	1.33E-06	2.08E-01
2005	Rye	Poplar Hill	1	2	u	15.54	1.37E-04	2.84E-06	4.37E-01
2005	Rye	Poplar Hill	2	1	t	1.17	1.04E-05	2.16E-07	3.40E-02
2005	Rye	Poplar Hill	2	1	u	21.08	1.87E-04	3.90E-06	2.49E-01
2005	Rye	Poplar Hill	2	2	t	16.57	1.43E-04	2.95E-06	4.56E-01
2005	Rye	Poplar Hill	2	2	u	25.71	2.18E-04	4.77E-06	6.27E-01
2005	Rye	Poplar Hill	3	1	t	4.08	3.73E-05	7.79E-07	1.17E-01
2005	Rye	Poplar Hill	3	1	u	43.13	1.05E-04	4.40E-06	6.43E-01
2005	Rye	Poplar Hill	3	2	t	22.06	1.94E-04	4.22E-06	4.40E-01
2005	Rye	Poplar Hill	3	2	u	13.52	1.16E-04	2.38E-06	3.77E-01
2005	Rye	Poplar Hill	4	1	t	9.05	8.19E-05	2.12E-06	1.66E-01
2005	Rye	Poplar Hill	4	1	u	21.06	1.93E-04	9.76E-06	3.89E-01
2005	Rye	Poplar Hill	4	2	t	77.8	1.73E-04	4.46E-06	4.00E-01
2005	Rye	Poplar Hill	4	2	u	98.4	8.21E-04	3.76E-05	4.92E-01
2005	Rye	Wye	1	1	t	0.856	6.44E-06	3.56E-05	5.20E-02
2005	Rye	Wye	1	1	u	0.853	7.26E-06	1.22E-06	5.05E-02
2005	Rye	Wye	1	2	t	0.025	6.36E-06	0.00E+00	1.23E-02
2005	Rye	Wye	1	2	u	0.6	1.64E-07	0.00E+00	4.80E-02
2005	Rye	Wye	2	1	t	0.963	7.77E-06	1.13E-07	5.30E-02
2005	Rye	Wye	2	1	u	1.535	1.37E-05	2.01E-07	8.75E-02
2005	Rye	Wye	2	2	t	1.577	1.38E-05	2.52E-07	5.35E-02
2005	Rye	Wye	2	2	u	45.322	3.05E-04	2.60E-03	4.96E-01
2005	Rye	Wye	3	1	t	0.553	4.74E-06	7.93E-08	2.35E-02
2005	Rye	Wye	3	1	u	17.438	1.64E-04	7.85E-06	3.30E-02
2005	Rye	Wye	3	2	t	0.6823	5.66E-06	9.53E-08	2.90E-02
2005	Rye	Wye	3	2	u	3.224	2.84E-05	4.74E-07	1.40E-01
2005	Rye	Wye	4	1	t	1.989	1.73E-05	2.90E-07	8.65E-02
2005	Rye	Wye	4	1	u	1.47	1.32E-05	2.22E-07	6.25E-02
2005	Rye	Wye	4	2	t	3.035	2.62E-05	4.38E-07	1.29E-01
2005	Rye	Wye	4	2	u	6.23	5.61E-05	9.39E-07	2.72E-01
2006	Corn	Poplar Hill	1	1	t	0.028	6.54E-08	0.00E+00	5.00E-04
2006	Corn	Poplar Hill	1	1	u	11.625	9.56E-05	0.00E+00	2.33E-01

year	season	Site	rep	rotation	row	irate	k_w	sorptivity	I
2006	Corn	Poplar Hill	1	2	t	0.233	1.24E-06	4.97E-05	5.00E-03
2006	Corn	Poplar Hill	1	2	u	2.35	1.79E-05	1.01E-04	4.70E-02
2006	Corn	Poplar Hill	2	1	t	1.475	1.19E-05	3.64E-05	2.95E-02
2006	Corn	Poplar Hill	2	1	u	2.066	1.54E-05	0.00E+00	3.85E-02
2006	Corn	Poplar Hill	2	2	t	0.0785	1.22E-07	2.96E-05	1.50E-03
2006	Corn	Poplar Hill	2	2	u	0.3	1.67E-06	0.00E+00	4.00E-03
2006	Corn	Poplar Hill	3	1	t	0.6	2.89E-06	1.40E-04	1.30E-02
2006	Corn	Poplar Hill	3	1	u	5.625	4.26E-05	2.14E-04	1.13E-01
2006	Corn	Poplar Hill	3	2	t	0.057	2.45E-07	0.00E+00	1.00E-03
2006	Corn	Poplar Hill	3	2	u	1.614	1.17E-05	0.00E+00	3.00E-02
2006	Corn	Poplar Hill	4	1	t	0.2	1.17E-06	2.07E-05	3.50E-03
2006	Corn	Poplar Hill	4	1	u	3.525	2.49E-05	2.51E-04	7.20E-02
2006	Corn	Poplar Hill	4	2	t	0.907	8.31E-06	7.32E-05	1.80E-02
2006	Corn	Poplar Hill	4	2	u	8.71	9.69E-05	2.69E-05	1.76E-01
2006	Corn	Wye	1	1	t	2.219	1.40E-05	4.07E-04	5.25E-02
2006	Corn	Wye	1	1	u	1.64	9.35E-06	2.72E-04	3.55E-02
2006	Corn	Wye	1	2	t	1.633	9.53E-06	3.40E-04	3.85E-02
2006	Corn	Wye	1	2	u	0.958	1.36E-06	3.95E-04	2.30E-02
2006	Corn	Wye	2	1	t	1.25	4.28E-06	3.27E-04	2.50E-02
2006	Corn	Wye	2	1	u	5.9	4.07E-05	7.68E-04	1.34E-01
2006	Corn	Wye	2	2	t	2.389	7.18E-06	7.90E-04	5.35E-02
2006	Corn	Wye	2	2	u	4.4	1.52E-05	4.04E-03	2.38E-01
2006	Corn	Wye	3	1	t	0.674	6.16E-06	6.22E-05	1.35E-02
2006	Corn	Wye	3	1	u	6.485	4.54E-05	6.98E-04	1.12E-01
2006	Corn	Wye	3	2	t	3.507	9.41E-06	1.06E-03	7.30E-02
2006	Corn	Wye	3	2	u	1.27	5.48E-06	3.79E-04	3.10E-02
2006	Corn	Wye	4	1	t	0.914	1.79E-06	3.66E-04	2.25E-02
2006	Corn	Wye	4	1	u	1.025	2.19E-06	5.19E-04	3.00E-02
2006	Corn	Wye	4	2	t	0.832	2.28E-07	4.20E-04	2.00E-02
2006	Corn	Wye	4	2	u	2.117	8.59E-06	5.43E-04	4.65E-02
2006	Rye	Clarksville	1	1	t	42.73	3.75E-04	0.00E+00	6.41E-01
2006	Rye	Clarksville	1	1	u	52.37	3.76E-04	3.14E-03	5.01E-01
2006	Rye	Clarksville	1	2	t	37.2	2.49E-04	3.98E-03	5.34E-01
2006	Rye	Clarksville	1	2	u	41.23	3.37E-04	7.95E-04	4.94E-01
2006	Rye	Clarksville	2	1	t	10.98	1.01E-04	1.52E-04	1.68E-01
2006	Rye	Clarksville	2	1	u	41.23	3.37E-04	7.95E-04	4.94E-01
2006	Rye	Clarksville	2	2	t	31.79	2.56E-04	1.18E-03	3.42E-01
2006	Rye	Clarksville	2	2	u	38.27	2.07E-04	1.25E-04	4.35E-01
2006	Rye	Clarksville	3	1	t	3.85	3.43E-05	0.00E+00	5.40E-02
2006	Rye	Clarksville	3	1	u	14.35	9.29E-05	2.61E-03	2.54E-01
2006	Rye	Clarksville	3	2	t	34.28	5.81E-05	2.49E-04	3.18E-01
2006	Rye	Clarksville	3	2	u	17.79	1.28E-05	2.81E-03	3.20E-01
2006	Rye	Clarksville	4	1	t	1.69	1.36E-05	0.00E+00	2.37E-02
2006	Rye	Clarksville	4	1	u	14.35	9.29E-05	2.61E-03	2.54E-01
2006	Rye	Clarksville	4	2	t	8.75	7.14E-05	8.69E-05	1.23E-01
2006	Rye	Clarksville	4	2	u	20.45	1.73E-04	2.30E-04	3.08E-01
2006	Rye	Poplar Hill	1	1	t	0.133	1.83E-07	4.96E-05	2.00E-03
2006	Rye	Poplar Hill	1	1	u	5.533	4.16E-05	1.90E-04	2.35E-01
2006	Rye	Poplar Hill	1	2	t	15.366	1.13E-04	5.89E-04	2.31E-01
2006	Rye	Poplar Hill	1	2	u	12.311	9.16E-05	4.89E-04	1.85E-01

year	season	Site	rep	rotation	row	irate	k_w	sorptivity	I
2006	Rye	Poplar Hill	2	1	u	9.44	7.00E-05	3.80E-04	1.42E-01
2006	Rye	Poplar Hill	2	2	t	2.711	1.61E-05	3.08E-04	4.07E-02
2006	Rye	Poplar Hill	2	2	u	8.8	6.62E-05	3.16E-04	1.32E-01
2006	Rye	Poplar Hill	3	1	t	0.777	5.18E-06	0.00E+00	1.17E-02
2006	Rye	Poplar Hill	3	1	u	17.066	1.28E-04	7.66E-04	3.48E-01
2006	Rye	Poplar Hill	3	2	t	9.8	7.68E-05	2.20E-04	1.47E-01
2006	Rye	Poplar Hill	3	2	u	10.22	7.60E-05	3.69E-04	1.53E-01
2006	Rye	Poplar Hill	4	1	t	1.4	8.08E-06	1.70E-04	2.10E-02
2006	Rye	Poplar Hill	4	1	u	4.5	2.98E-05	3.23E-04	6.75E-02
2006	Rye	Poplar Hill	4	2	t	13.377	8.40E-05	7.83E-04	2.01E-01
2006	Rye	Poplar Hill	4	2	u	28.066	2.12E-04	1.03E-03	4.21E-01
2006	Rye	Wye	1	1	t	0.088	7.05E-08	3.16E-05	1.33E-03
2006	Rye	Wye	1	1	u	0.066	4.03E-07	9.01E-06	1.00E-03
2006	Rye	Wye	1	2	t	0.066	1.34E-07	1.99E-05	1.00E-03
2006	Rye	Wye	1	2	u	0.422	1.81E-06	9.58E-05	6.33E-03
2006	Rye	Wye	2	1	t	0.1	5.86E-07	0.00E+00	1.33E-03
2006	Rye	Wye	2	1	u	0.377	9.92E-07	8.01E-05	5.67E-03
2006	Rye	Wye	2	2	t	0.155	8.14E-07	5.88E-06	2.33E-03
2006	Rye	Wye	2	2	u	2.17	1.72E-05	1.51E-05	3.27E-02
2006	Rye	Wye	3	1	t	0.1	4.40E-07	1.35E-05	1.50E-03
2006	Rye	Wye	3	1	u	0.1	1.49E-07	2.96E-05	1.50E-03
2006	Rye	Wye	3	2	t	0.6	2.27E-06	1.03E-05	9.00E-03
2006	Rye	Wye	3	2	u	0.777	3.86E-06	8.68E-05	1.17E-02
2006	Rye	Wye	4	1	t	0.066	7.33E-08	1.80E-05	1.00E-03
2006	Rye	Wye	4	1	u	0.977	5.14E-06	1.20E-04	1.47E-02
2006	Rye	Wye	4	2	t	0.311	1.46E-06	4.68E-05	4.67E-03
2006	Rye	Wye	4	2	u	3.1	2.33E-05	7.09E-05	9.10E-02

Soil Moisture retention Data

year	season	Site	rep	rotation	row	0	10	20	30
2006	Corn	Poplar Hill	1	1	t	0.373467	0.359768	0.341544	0.341291
2006	Corn	Poplar Hill	1	1	u	0.446982	0.387446	0.380919	0.365242
2006	Corn	Poplar Hill	1	2	t	0.389382	0.377158	0.374716	0.368133
2006	Corn	Poplar Hill	1	2	u	0.415972	0.379944	0.36426	0.354302
2006	Corn	Poplar Hill	2	1	t	0.407446	0.372358	0.366618	0.358575
2006	Corn	Poplar Hill	2	1	u	0.398898	0.384028	0.360568	0.354477
2006	Corn	Poplar Hill	2	2	t	0.383888	0.379909	0.369067	0.36553
2006	Corn	Poplar Hill	2	2	u	0.431404	0.387116	0.363046	0.3536
2006	Corn	Poplar Hill	3	1	t	0.392828	0.377607	0.375544	0.364098
2006	Corn	Poplar Hill	3	1	u	0.409565	0.393804	0.375951	0.367284
2006	Corn	Poplar Hill	3	2	t	0.404653	0.378604	0.37146	0.366428
2006	Corn	Poplar Hill	3	2	u	0.418344	0.380982	0.366021	0.35386
2006	Corn	Poplar Hill	4	1	t	0.37873	0.376961	0.375137	0.363846
2006	Corn	Poplar Hill	4	1	u	0.392498	0.403109	0.38654	0.381011
2006	Corn	Poplar Hill	4	2	t	0.402449	0.400175	0.382274	0.376232
2006	Corn	Poplar Hill	4	2	u	0.460105	0.384246	0.367186	0.35993
2006	Corn	Wye	1	1	t	0.431354	0.399418	0.393958	0.387698
2006	Corn	Wye	1	1	u	0.468182	0.396449	0.384035	0.374989
2006	Corn	Wye	1	2	t	0.445775	0.424561	0.418232	0.407937
2006	Corn	Wye	1	2	u	0.452372	0.413102	0.401116	0.385509
2006	Corn	Wye	2	1	t	0.442323	0.41694	0.414246	0.401502
2006	Corn	Wye	2	1	u	0.431649	0.396975	0.392323	0.382653
2006	Corn	Wye	2	2	t	0.40273	0.404084	0.399684	0.389607
2006	Corn	Wye	2	2	u	0.459846	0.422751	0.408793	0.394049
2006	Corn	Wye	3	1	t	0.417095	0.40986	0.401298	0.396625
2006	Corn	Wye	3	1	u	0.444358	0.416274	0.399818	0.396632
2006	Corn	Wye	3	2	t	0.40313	0.412049	0.403249	0.400218
2006	Corn	Wye	3	2	u	0.448281	0.420218	0.411761	0.402646
2006	Corn	Wye	4	1	t	0.405825	0.396014	0.39033	0.383011
2006	Corn	Wye	4	1	u	0.454765	0.400182	0.391347	0.380035
2006	Corn	Wye	4	2	t	0.435123	0.408147	0.407298	0.398323
2006	Corn	Wye	4	2	u	0.429221	0.365249	0.352779	0.342646
2006	rye	Clarksville	1	1	t	0.494828	0.467207	0.438596	0.443081
2006	rye	Clarksville	1	1	u	0.487256	0.456484	0.401551	0.399095
2006	rye	Clarksville	1	2	t	0.462821	0.452772	0.427179	0.4264
2006	rye	Clarksville	1	2	u	0.477214	0.439411	0.406386	0.405782
2006	rye	Clarksville	2	1	t	0.447221	0.443874	0.429025	0.437628
2006	rye	Clarksville	2	1	u	0.427425	0.420175	0.390758	0.382505
2006	rye	Clarksville	2	2	t	0.480842	0.47393	0.442519	0.444463
2006	rye	Clarksville	2	2	u	0.460547	0.455081	0.421242	0.425396
2006	rye	Clarksville	3	1	t	0.43666	0.437986	0.422189	0.42407
2006	rye	Clarksville	3	1	u	0.465712	0.426849	0.391396	0.393368
2006	rye	Clarksville	3	2	t	0.456674	0.435284	0.414954	0.411404
2006	rye	Clarksville	3	2	u	0.432239	0.425432	0.397895	0.402105
2006	rye	Clarksville	4	1	t	0.446449	0.441775	0.410239	0.408954
2006	rye	Clarksville	4	1	u	0.451684	0.440337	0.396274	0.39974
2006	rye	Clarksville	4	2	t	0.452084	0.438414	0.417186	0.405102
2006	rye	Clarksville	4	2	u	0.494533	0.484358	0.455937	0.451909
2006	rye	Poplar Hill	1	1	t	0.394351	0.358211	0.348028	0.34454
2006	rye	Poplar Hill	1	1	u	0.401088	0.373895	0.345137	0.342625

year	season	Site	rep	rotation	row	0	10	20	30
2006	rye	Poplar Hill	1	2	t	0.397446	0.384786	0.37313	0.370351
2006	rye	Poplar Hill	1	2	u	0.413923	0.3576	0.336204	0.332575
2006	rye	Poplar Hill	2	1	t	0.381319	0.373207	0.36407	0.357375
2006	rye	Poplar Hill	2	1	u	0.384512	0.375698	0.355298	0.348695
2006	rye	Poplar Hill	2	2	t	0.408435	0.387228	0.367537	0.363214
2006	rye	Poplar Hill	2	2	u	0.439284	0.364126	0.343326	0.339965
2006	rye	Poplar Hill	3	1	t	0.362098	0.360175	0.346681	0.347586
2006	rye	Poplar Hill	3	1	u	0.389677	0.387326	0.367705	0.362568
2006	rye	Poplar Hill	3	2	t	0.417565	0.3672	0.344	0.337916
2006	rye	Poplar Hill	3	2	u	0.474028	0.330877	0.305796	0.30386
2006	rye	Poplar Hill	4	1	t	0.42174	0.369663	0.3504	0.357235
2006	rye	Poplar Hill	4	1	u	0.395881	0.391481	0.355032	0.351691
2006	rye	Poplar Hill	4	2	t	0.414975	0.36946	0.339796	0.339396
2006	rye	Poplar Hill	4	2	u	0.438477	0.362421	0.353446	0.341579
2006	rye	Wye	1	1	t	0.377916	0.373593	0.365979	0.360526
2006	rye	Wye	1	1	u	0.397726	0.396709	0.386667	0.371151
2006	rye	Wye	1	2	t	0.399607	0.395396	0.382196	0.379411
2006	rye	Wye	1	2	u	0.420239	0.409916	0.384365	0.380168
2006	rye	Wye	2	1	t	0.428309	0.406933	0.387832	0.387642
2006	rye	Wye	2	1	u	0.411579	0.388498	0.372814	0.369186
2006	rye	Wye	2	2	t	0.422898	0.414295	0.384849	0.381151
2006	rye	Wye	2	2	u	0.397705	0.392674	0.364961	0.361347
2006	rye	Wye	3	1	t	0.375123	0.367474	0.357158	0.353312
2006	rye	Wye	3	1	u	0.41934	0.41106	0.397902	0.394196
2006	rye	Wye	3	2	t	0.411509	0.389333	0.372253	0.371621
2006	rye	Wye	3	2	u	0.440393	0.392561	0.368309	0.363698
2006	rye	Wye	4	1	t	0.389993	0.384786	0.372526	0.371691
2006	rye	Wye	4	1	u	0.422835	0.378632	0.364154	0.362056
2006	rye	Wye	4	2	t	0.408681	0.392189	0.379635	0.37546
2006	rye	Wye	4	2	u	0.446793	0.410274	0.375439	0.371965

year	season	Site	rep	rotation	row	100	300	600
2006	Corn	Poplar Hill	1	1	t	0.317165	0.279916	0.271944
2006	Corn	Poplar Hill	1	1	u	0.304505	0.240996	0.213446
2006	Corn	Poplar Hill	1	2	t	0.343881	0.32127	0.296435
2006	Corn	Poplar Hill	1	2	u	0.319846	0.289025	0.265263
2006	Corn	Poplar Hill	2	1	t	0.328646	0.279053	0.262877
2006	Corn	Poplar Hill	2	1	u	0.30094	0.258175	0.243888
2006	Corn	Poplar Hill	2	2	t	0.338737	0.305214	0.297404
2006	Corn	Poplar Hill	2	2	u	0.299782	0.255867	0.246105
2006	Corn	Poplar Hill	3	1	t	0.336267	0.299804	0.278463
2006	Corn	Poplar Hill	3	1	u	0.308477	0.254618	0.237951
2006	Corn	Poplar Hill	3	2	t	0.342386	0.303768	0.304611
2006	Corn	Poplar Hill	3	2	u	0.319474	0.282568	0.266112
2006	Corn	Poplar Hill	4	1	t	0.332414	0.293347	0.280772
2006	Corn	Poplar Hill	4	1	u	0.321635	0.277951	0.255228
2006	Corn	Poplar Hill	4	2	t	0.339523	0.303937	0.298498
2006	Corn	Poplar Hill	4	2	u	0.326175	0.29134	0.2816
2006	Corn	Wye	1	1	t	0.356758	0.323895	0.311151
2006	Corn	Wye	1	1	u	0.33946	0.294175	0.278779
2006	Corn	Wye	1	2	t	0.406849	0.338716	0.319368
2006	Corn	Wye	1	2	u	0.343649	0.296112	0.283818
2006	Corn	Wye	2	1	t	0.369291	0.323565	0.303439
2006	Corn	Wye	2	1	u	0.35574	0.321944	0.312056
2006	Corn	Wye	2	2	t	0.360358	0.322919	0.295263
2006	Corn	Wye	2	2	u	0.347179	0.299389	0.281319
2006	Corn	Wye	3	1	t	0.368442	0.331144	0.321361
2006	Corn	Wye	3	1	u	0.35433	0.307944	0.296295
2006	Corn	Wye	3	2	t	0.36866	0.336926	0.3168
2006	Corn	Wye	3	2	u	0.374604	0.339319	0.32473
2006	Corn	Wye	4	1	t	0.352091	0.312961	0.287453
2006	Corn	Wye	4	1	u	0.349074	0.310463	0.292281
2006	Corn	Wye	4	2	t	0.367389	0.325067	0.307789
2006	Corn	Wye	4	2	u	0.310056	0.289509	0.273207
2006	rye	Clarksville	1	1	t	0.362239	0.316751	0.30694
2006	rye	Clarksville	1	1	u	0.296098	0.251067	0.231551
2006	rye	Clarksville	1	2	t	0.361186	0.317916	0.304639
2006	rye	Clarksville	1	2	u	0.331923	0.29214	0.266316
2006	rye	Clarksville	2	1	t	0.360505	0.347333	0.361811
2006	rye	Clarksville	2	1	u	0.288961	0.273586	0.284372
2006	rye	Clarksville	2	2	t	0.340919	0.322554	0.292204
2006	rye	Clarksville	2	2	u	0.329158	0.292484	0.283109
2006	rye	Clarksville	3	1	t	0.356042	0.326119	0.304407
2006	rye	Clarksville	3	1	u	0.316007	0.277768	0.25727
2006	rye	Clarksville	3	2	t	0.344842	0.317453	0.296379
2006	rye	Clarksville	3	2	u	0.346709	0.322519	0.322695
2006	rye	Clarksville	4	1	t	0.342007	0.2964	0.294456
2006	rye	Clarksville	4	1	u	0.304344	0.268021	0.264147
2006	rye	Clarksville	4	2	t	0.330035	0.300568	0.295839
2006	rye	Clarksville	4	2	u	0.358021	0.311375	0.28506
2006	rye	Poplar Hill	1	1	t	0.288365	0.259382	0.238737
2006	rye	Poplar Hill	1	1	u	0.27833	0.246919	0.232281

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