REDUCTION OF SOIL COMPACTION IN A COTTON AND PEANUT ROTATION USING CONSERVATION SYSTEMS

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REDUCTION OF SOIL COMPACTION IN A COTTON AND PEANUT ROTATION USING CONSERVATION SYSTEMS

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THESIS ABSTRACT

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Southern Coastal plain soils have a long history of intensive continuous monoculture cropping, and are highly weathered due to geoclimatic conditions. These soils pose a challenge to the adoption of conservation agriculture due to subsoil compaction (densification of subsurface layers). This problem is usually addressed with adoption of non-inversion deep tillage. However, with ever-increasing prices of fuel this operation is often questioned by farm managers as too costly. Another problem facing farmers in this region is the lack of a good rotation system. In recent years, rotations of cotton (*Gossypium hirsutum L.)* and peanuts (*Arachis hypogaea L.*) have increased substantially in Southern Coastal plain due to reduced disease pressure and increased economic benefits provided by this rotation. Nevertheless many farmers are skeptical about adopting conservation tillage practices for peanut production due to fear of depressed yields caused by pests and diseases.

We attempted to develop a conservation tillage system that included several methods of subsoil disruption. Three subsoiling implements were evaluated against a non-subsoiled treatment with and without a rye *(Secale cereale L.)* cover crop on a 4-yr cotton/peanut rotation at the Wiregrass Research Station in Headland, AL on a Dothan loamy sand (fine loamy, kaolinitic, thermic Plinthic Kandiudult). Plant, soil, and machinery parameters were evaluated: crop yield, cover crop biomass, cotton leaf temperature, soil moisture, bulk density, cone index, total soil carbon and nitrogen, saturated hydraulic conductivity, and tillage energy. Results showed consistently lower yields for non-subsoiled (11 and 51% lower, for peanuts and cotton, respectively) treatments. In one year of the study which was dramatically affected by drought, a cover crop provided a 26% increase in seed cotton yield. No differences between implements were found. Soil strength was greatly reduced by in-row subsoiling. During the 2006 cotton season, the no-till treatment had cone index of 3.6 MPa at the 10 cm depth which was significantly greater than any of the other in-row subsoiling treatments; Strip-till (0.9MPa), Paratill (1.4 MPa), and Worksaver (1.2 MPa). Our yield and economic results demonstrate that it is highly recommendable to in-row subsoil and plant a winter cover crop as they significantly boost productivity to competitive levels, increase net economic return, and improve system sustainability.

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Computer software used: Microsoft Word 2003, Microsoft Excel 2003, Microsoft PowerPoint 2003, Statistical Analysis System (SAS) software Package for Windows v.9.1, Grapher Version 5.0, Surfer Version 8.06.

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LITERATURE REVIEW

The effect of tillage systems on soil properties and crop productivity has been abundantly investigated in scientific literature. Several studies describe the many physical, chemical and biological changes in soil properties as well as different plant responses under a great variety of geographic conditions. The following review is a brief collection of studies deemed relevant to our study matter, which is: the effect of soil tillage practices and the use of a winter cover crop on selected soil properties. The answer to this question will allow the development of a tillage system for a cotton-peanut rotation that will be profitable and sustainable while considering soil and climate specificities of the southern Coastal Plain.

This review sections are separated by: soil properties (bulk density; soil strength; soil moisture; hydraulic conductivity; soil organic matter); plant response (yield and leaf temperature); and tillage energy requirements.

Bulk Density

Soil bulk density (Bd) is directly related to pore-space, and it is influenced by texture. While texture is an inherent and relatively stable soil physical property, near surface pore-space can be rapidly modified by growing plants and tillage procedures hence altering original Bd. A myriad of studies can be found on harmful effects of increased bulk density, several of these describe how compaction affects soil structure

(Hamza and Anderson, 2005; Batey and McKenzie, 2006; Raper and Kirby, 2006). Soil compaction has been found to reduce soil water, air flow, and alter patterns of root growth, which translate into reduced productivity causing environmental and economic losses (Raper and Kirby, 2006; Batey and McKenzie, 2006).

The adoption of conservation tillage or no-till systems coupled with a winter cover crop can impact soil Bd in diverse ways. Some papers discuss the effect of cover crop alone on effectively reducing soil compaction while others are focused on the tillage component, or a combination of the two factors (Ess et al., 1998; Mahboubi et al., 1993; Fabrizzi et al., 2005).

Cover crops can mitigate soil compaction as demonstrated in a study by Ess et al. (1998), in which a rye winter cover crop growing on a Typic Hapludult soil in Virginia reduced the effects of multiple machine passes on soil structure by lowering bulk density and increasing non-capillary porosity. Furthermore, Cresswell and Kirkegaard (1995), suggested that “biopores” created by cover crop roots can be later used by roots of subsequent crop as a low resistance path in a process called “biodrilling”, which was later confirmed in a study by Williams and Weil (2004) when the root channels created by forage radish (*Raphanus sativus* L.) and rye (*Secale cereale L.*), combined as cover crop, were effectively used by the following soybean [*Glycine max* (L.) Merr.] crop roots resulting in a significant yield increase compared to the no-cover treatment.

The effect of tillage on bulk density is abundant documented in the literature. While the great majority of the studies agree that tillage will significantly reduce bulk density, such effects may be temporary, due to natural wetting and drying cycles or traffic-induced conditions that cause the soil to once again densify (Mapa et al., 1986).

Therefore, the transition from conventional to no-till may establish favorable conditions for a bulk density increase, especially in soils with poor structure (low aggregate stability) due to low organic matter content. (Reynolds et al., 2002; Leij et al., 2002; Six et al., 2002).

The long term effects of no-till and crops on bulk density are known to vary and research suggests they are often soil specific. Due to the relatively slow accumulation of organic matter and development of soil structure under conservation systems, time has a substantial effect on Bd (Franzluebbers and Arshad, 1996; Potter et al., 1998). Some studies report a Bd increase on no-till compared to conventional or conservation tillage methods (Potter and Chichester, 1993; Yoo and Wander, 2006; Lopez-Fando et al., 2007; Franzluebbers et al., 2007), while others state the opposite, which is a Bd decrease for no-till in the long term (Edwards et al., 1992; Lal et al., 1994). There are also reports that Bd was not different between no-till and conventional or conservation tillage systems (Blanco-Canqui et al., 2004; Reynolds et al., 2007).

Several comparisons involving conservation tillage practices and the use of cover crops can be found in the literature. Typically their results converge on the effectiveness of in-row subsoiling (deep tillage, strip-tillage, or paraplowing) on lowering Bd (Lopez-Fando et al, 2007; Varsa et al., 1997; Franzluebbers et al., 2007). However, they diverge concerning the duration of these lower Bd values, recognizing that specific climate, soil and traffic conditions will control the maintenance of a non-compacted soil profile. Franzluebbers et al. (1999), working on a Typic Kanhapludult in Georgia, estimated reconsolidation occurred between one and two years. These findings are similar to the findings of Raper et al. (2005b) on a Typic Paleudult in Alabama, who concluded that reconsolidation started immediately after subsoiling and took almost three years to reach the same Bd values of the no-till treatment. Baumhardt and Jones (2005) found lower Bd and penetration resistance values measured 30 years after the deep tillage treatment was applied on a Pullman clay loam (Torrertic Paleustoll) in Texas.

Soil Strength

Soil strength measurement is an effective way to simulate the resistance plant roots encounter to penetrate the soil while growing. Penetration resistance values are influenced by several soil factors including water content, bulk density, soil texture and structure, as reported by numerous studies (Taylor and Gardner, 1963; Reinert et al., 2001). Soil strength is inversely correlated with water content, and directly correlated to bulk density and sand content (Byrd and Cassel, 1980; Reinert et al., 2001). Plant root penetration is restricted as soil strength increases and for many plant species ceases at 2.5 MPa (Taylor, 1971). Specific limiting cone index (CI) values for cotton and peanuts have been established by Taylor and Gardner (1963) and Taylor and Ratliff (1969). They concluded that CI values increasing from 1.0 MPa to 2.0 MPa reduced cotton root penetration by 50%, additionally there was no root penetration beyond 2.9MPa. Peanuts roots showed similar behavior as root elongation rate dropped 50% at 1.9 MPa. However, some root elongation was observed at 3.5MPa.

Rather than investigate how increased soil strength affects root development, which has been done by several authors (Hamza and Anderson, 2005), we are focused on the effects of tillage and cover crop on reducing CI values and retarding reconsolidation effects, consequently producing higher yields.

It has been demonstrated that cover crops can alleviate compaction through increased in pore space, consequently reducing soil strength (Ess et al., 1998; Raper et al., 2000).Also, the use of a cover crop can increase water content due to the insulating effects of surface residue which diminish evapotranspiration, increase organic matter, contributing to lower CI values (Fabrizzi et al., 2005).

Soil strength is usually lowest immediately after tillage and increases as reconsolidation takes place (Raper et al., 2005b; Mapa et al., 1986), however, the long term management effects can vary, according to specific interactions between tillage, crop, and soil characteristics. Several studies have found an increase in soil strength under no-till, especially during initial years after transition from conventional tillage was made (Raper et al., 2005b; Raper et al., 2005a; Lopez-Fando et al, 2007; Varsa et al., 1997; Potter and Chichester, 1993). The increased CI values may recede after several years of continuous no-till. Wilkins et al. (2002) found CI values increased 2 to 3 fold during the first year of no-till compared to conventional tillage, but after 17 years, values were not statistically significant between no-till and conventional, suggesting an improvement of soil structure of this silt loam soil in the long term.

Conservation tillage systems have proven to efficiently reduce CI values and increase water content when compared to no-till (Lopez-Fando et al., 2007). Several different implement models have been used for non- inversion deep tillage (in-row subsoiling; deep ripping; strip-tillage, paraplowing). In general, they were able to significantly reduce soil strength and increase yields (Schwab et al., 2002; Wells et al., 2005; Sojka et al., 1997).

Soil Water Content and Hydraulic Conductivity of Saturated Soil

Water controls or greatly influences most all physical, chemical and biological processes occurring in the soil. Crop productivity is highly dependent on water availability, which in turn depends on soil properties and the supply from natural precipitation or irrigation. In agricultural soils, specific crops and tillage strategies are known to modify water movement, storage and availability.

Many studies reported above mentioned changes by investigating changes in soil physical properties as porosity, saturated hydraulic, water retention, and plant available water among others. Strict no-till and conservation tillage effects on these properties are known to vary greatly according to weather conditions, history and intensity of management (Mahboubi et al., 1993). Some studies reported an increase in water storage under conservation tillage due to reduced evaporation, greater infiltration, and protection from rainfall impact (Fabrizzi et al., 2005; Triplett et al., 1968; Jones et al., 1968). This increase of course depends on soil texture, an inherent soil property that controls porosity and aggregation (Xu and Mermoud, 2001; Buczko et al., 2006). Additionally, comparisons between no-till, conventional tillage and conservation tillage have been made. Busscher and Sojka (1987) found deep tillage increased gravimetric water content 12.1 to 15.1 % (0-55cm depth) compared to conventional tillage. Sojka et al. (1997) concluded that paraplowing increased water content (mass basis) especially on the upper profile (0-20cm depth) compared to surface tillage. Lopez-Fando et al. (2007) also measured greater volumetric water content from 0-20cm depth for paraplowed treatments against conventional and no-till. On the other hand, Erbach et al. (1992) found no difference in volumetric water content when comparing no-till to Paratill. Xu and

Mermoud (2001) observed an increase in saturated water content created by subsoiling compared to no-till and conventional, but a decrease in total available water due to a reduction in volume of smaller pores (<10μm). Hulugalle and Entwistle (1997) found that even though minimum tillage resulted in slightly higher penetration resistance than conventional tillage, plants could absorb more water (84 mm vs. 78mm) due to the "by-pass" channels created by preceding crops or associated with greater macrofauna activity.

Cover crops also have great effects on soil temperature and consequently water content. This is explained by three processes: (1) residue act as an insulating layer; (2) residue reflects more light than bare soil; and (3) residue reduces (blocks) evaporation (Shinners et al., 1994). Shinners et al. (1994) found that soil temperature and moisture were inversely related to width of residue-free band on the soil surface.

Saturated hydraulic conductivity (K_s) is critically important for agronomic production as it relates to the capacity of a soil to transmit plant-available water and nutrients to the root zone, drain excess water (water-logging), and reduce runoff. It is also used as parameter in the assessment of soil physical quality and design and performance of irrigation and drainage systems (Reynolds et al., 2000; Reynolds et al., 2007).

Similarly to water content, K_s is regulated to a large extent by soil macroporosity, which can be defined by macropore volume fraction, diameter distribution, and connectivity of the macropore network (Buczko et al., 2006). Tillage and crop management practices, therefore, have great impact on macropore network.

The impact of no-till or conservation tillage system on K_s is somewhat inconsistent; some results point to an increase in K_s when compared to conventional tillage (Mahboubi et al., 1993; Reynolds et al., 2007).The greater K_s of this soil was attributed to a larger number and connectivity of macropores, which in turn, were explained by earthworm activity and reduced surface disturbance (Reynolds et al., 1995). On the other hand, some investigations found decreased K_s with no-till systems (Heard et al., 1988; Zachmann et al., 1987).

Similar comparisons can be found including deep tillage (in-row subsoiling, paraplowing) against conventional or no-till systems. Sojka et al. (1997) found that Paratill more than doubled K_s compared to no-till ($14x10^{-4}$ m s^{-1} vs. 5.8 $x10^{-4}$ m s^{-1}, respectively). Xu and Mermoud (2001) also found increased K_s caused by subsoiling compared to conventional and no-till, even at late stages (100 days after emergence) of the growing season.

Crops can also affect K_s. Blanco-Canqui et al. (2004) concluded that chisel and moldboard plows were not significantly different from no-till, regarding K_s. But K_s was severely reduced when excessive tillage (spring moldboard + disking + cultivations after rain to break crusts and kill weeds) and fallow was applied. Most importantly was the effect of crop on K_s and other soil properties. Under corn, the soils had decreased $K_{s,}$ increased bulk density and organic matter than under soybean. Means for corn were, respectively: 7.3, 12.0, and 11.1 mm h^{-1} for moldboard plow, chisel plow and no-till, while soybean K_s means were, respectively: 19.9; 25.1 and 11.4 mm h^{-1}.

Soil organic carbon and total nitrogen content

Soil organic carbon (SOC) is widely considered to be an indicator of soil health as it correlates or influences all physical, chemical and biological parameters of soil quality. According to Shukla et al. (2006), SOC is the single most important attribute of soil quality where it acts as the dominant factor behind soil aeration and aggregation. Despite the importance of SOC increase in the soil, ideal levels have not yet been established for field crops. Greenland (1981) suggested a critical SOC limit (2.3 % wt.) under which tillage may induce a structural loss.

Numerous studies presented the effect of tillage practices and cover crop management effects on soil C storage. According to their results, long term no-till and conservation tillage systems increased SOC near the surface (< 20cm) (Potter et al., 1998; Kern and Johnson, 1993; Motta et al., 2002). This increased retention of SOC under conservation or no-till system has been reported to vary widely from 0 to 1300 kg $ha^{-1}year^{-1}$ (Reicosky et al., 1995). Under southeastern conditions which were similar to our study in a warm and humid climate of Alabama, no-till has increased organic matter in the surface (0-15 cm) from 10 to 15.5 g kg^{-1}, a 56% increase over conventional tillage along a 10 year period (Edwards et al., 1992). Tillage and plowing are usually perceived as the culprits of SOC loss as they promote decomposition through soil aeration, physical breakdown of aggregates and residue, and incorporation of residues into the soil profile (Paustian et al., 2000; Six et al., 2002). Mann (1986) indicated losses of 20 % or up to 1500g m^{-2} of the initial SOC after cultivation of soils under forests and grasslands within 30 cm depth. Similarly, Davidson and Ackerman (1993) measured a 30% loss of SOC after 20 years of cultivation with the major losses occurring in the first 5 years.

However the adoption of no-till or conservation systems may not guarantee a boost in SOC sequestration throughout the soil profile (Dick et al., 1991; Angers et al., 1997; Needleman et al., 1999). Instead a redistribution of SOC may take place where the organic matter is concentrated at shallow depths near the surface, as demonstrated by Kay and VandenBygaart (2002) and Torbert et al. (1999).

Consequently the ability of no-till and conservation tillage systems to sequester C has been questioned. For example, in a comprehensive review, Baker et al. (2007) concluded that most of the soil sampling studies have biased methodology because sampling is not done below 30cm. Also, they stated when deeper sampling is included, conventionally tilled soil had greater C storage.

Total nitrogen concentration tends to follow the same pattern as total carbon, because 95 % of total N is organic (Tisdale et al., 1993). C/N ratios should be reduced with increasing depth because of lower C amounts (Tisdale et al., 1993). Nitrogen as well as C is reported to decline along several years of continuous soil tilling (Haas and Evans, 1957; Reeder et al., 1998). Additionally no-till or conservation systems residue with high C/N ratio (>30 to 1) may create a layer capable of immobilizing surface applied N (Tisdale et al., 1993).

Cash Crop Yields

Of all parameters usually measured in tillage studies, perhaps yield has been the most readily measured and debated.

There are several benefits of conservation systems explained in the scientific literature: decreased consumption of fossil fuel; reduced labor; reduced soil erosion; improved physical structure, increased soil water and organic matter (Franzluebbers and Arshad, 1996; Wright and Hons, 2004). However, the yield reduction during early years of the transition from conventional to conservation may outweigh stated benefits from a farmer’s point of view. Therefore the necessity to maximize the yield performance of conservation systems has been addressed by several authors (Raper et al., 2000; Schomberg et al., 2006).

The effects of cover crop on crop yields has been variable, some studies have observed a cash crop yield increase due to cover crop utilization (Busscher and Bauer, 1993; Raper et al., 2000; Williams and Weil, 2004). However, the same authors have occasionally found distinctly different results. Bauer and Busscher (1996) found a positive effect of rye on cotton yields compared to legumes or fallow with conservation tillage but observed no difference in cotton yields among cover crop treatments with conventional tillage. Raper et al. (2007) found no overall yield effect of rye (*Secale Cereale L.)* and crimson clover (*Trifolium incarnatum L.*) covers in a 4-year cotton-corn rotation period.

The effect of tillage system on crop yields varies according to soil type and climatic conditions. As soil physical, chemical, and biological properties are affected by tillage, a wide range of results was found in the literature. No-till and conservation systems are often compared to conventional tillage through selected soil properties but it is crop yield and ultimately, economic benefits that usually dictate land management strategies.

Some studies showed increased crop productivity in no-till or conservation systems compared to conventional. Smith (1995) found in-row subsoiling increased seed cotton yield by 14.7% compared to conventional tillage in Mississippi. Schwab et al. (2002) found that subsoil and Paratill treatments increased seed cotton yield by 15 % compared to conventional tillage over a 5-year period. Other results show a yield reduction for no-till treatments. Hajabbasi and Hemmat (2000) found that no-till had the lowest wheat (*Triticum aestivum L.*) yield compared to six other conventional tillage methods. A peanut study in North Carolina by Jordan et al. (2001) found no-till yielded significant lower than either conventional or strip till: 3310, 3650, and 3690 kg ha^{-1}, respectively.

Schwab et al. (2002) also found that subsoiled and Paratill treatments had 7% higher yields than no-till. Abu-Hamdeh (2003) found a 20% reduction in corn yield caused by compaction which was removed through subsoiling, effectively restoring production levels. Lopez-Fando et al. (2007), Schomberg et al. (2006), and Raper et al. (2007) have found increased cash crop yields from deep tillage (in-row subsoiling) compared to no-till. These increases may be attributed to lower soil strength and increased water permeability created by in-row subsoiling.

Cotton leaf temperature

Cotton leaf temperature is determined by energy exchange among convection, radiation and transpiration. Transpiration cools down the leaf due to the large amount of latent heat removed with vaporization of water. Hence, temperature depression should be proportional to the transpiration (Wiegand and Namken, 1966). Transpiration may lead to soil moisture depletion causing decreased transpiration and elevated leaf temperature (Wiegand and Namken, 1966).

Normal ranges for healthy cotton leaf temperature will sure vary with air temperature and vapor pressure conditions. In a study with healthy and diseased cotton plants, Pinter Jr. et al., (1979) established healthy plant mean temperature to be 29.2°C at

12:00 pm in Arizona while mean air temperature was around 32.4°C. Other studies reported leaf temperatures 4 to 5°C degrees above air temperature (Wiegand and Namken, 1966). These variations are attributed to light intensity, relative humidity and wind speed conditions (Pallas Jr. et al., 1967). Some studies have shown that drought conditions cause cotton stomata to close, reducing evaporative losses of heat, and causing leaf temperature to increase (Ehrler, 1973; Sharpe, 1973).

Tillage energy

As numerous studies have established, in-row subsoiling is an effective way to diminish harmful effects of compaction (Raper and Kirby, 2006; Hamza and Anderson, 2005). However, there are also drawbacks to this tillage practice that should be taken into account: cost of operation (fuel, labor) and equipment, high draft forces required (tractor capability), and recurring traffic. These factors have to be carefully weighed against the improvement of productivity provided by in-row subsoiling, otherwise, energy and money can be wasted.

It was estimated that one single pass of tractor wheel on loose soil was responsible for 85% of the total compaction, and in conventional tillage system 70% of the area of the field may be trafficked (Cooper et al., 1969). In subsoiled areas, research indicates that 2 wheel passes can recompact the soil to levels found before subsoiling (Raper, 2005a; Reeder et al., 1993). Therefore in order to obtain maximum benefits from in-row susbsoiling, controlled traffic is recommended, or else tillage energy is wasted.

Reducing soil surface disturbance and high draft forces and soil required for subsoiling has been a motivation for several studies involving: shank design, tillage timing, tillage depth, and speed of operation (Raper et al., 2000; Reeder et al. 1993; Garner et al., 1984).

Soil moisture content can have a significant effect on soil compaction and the benefits offered by in-row subsoiling. Traffic in excessively moist soil condition (60% of field capacity) can lead to excessive compaction (Raper, 2005b). Also there is a risk of a shank causing smearing of soil “walls” creating a plow pan (Dexter, 1988). Subsoiling at very dry conditions, however, increases draft requirements and spoil area (surface disturbance) thereby wasting energy (Raper and Sharma, 2004). Depending on soil and climate, subsoiling operations are usually scheduled for the fall season when there is more time available. However, as confirmed by the results of Franzluebbers et al. (1999) and Raper et al. (2005b), some Coastal Plain soils reconsolidate so quickly that subsoiling should be applied in spring or closer to anticipated planting date (Raper and Sharma 2004).

Shank design also has an impact on energy requirements of subsoiling. Khalilian et al. (1988) found no difference in draft force and drawbar power between straight (KMC) and bentleg (Paraplow) shank designs, however, most studies usually show significant differences in power requirements e.g.: Raper et al. (2005b) found the straight leg KMC (27.1 kN) to have the lower draft requirements when compared to the bentleg shanks of Paratill (38.3 kN) and Terratill (45 kN).

Raper (2005c) tested a curved versus an angled shank and concluded that the angled shank had significantly reduced draft requirements, however, this finding was only significant on coarser texture sandy loam soil and not so pronounced in a clay loam soil. This calls attention to an inherent soil property that greatly affects draft requirements. Coarser soils tend to require less energy than finer texture ones, that is, energy demands increased with increasing clay content (Raper, 2005c; ASABE Standards, 2006)

In a study including 8 different shank designs, Raper (2005d) determined that the bentleg shanks of Paratill and Worksaver shanks had lowest draft requirements compared to 5 straight leg subsoilers. The same Paratill and Worksaver bentleg shanks had the smallest spoil resistance index (SRI), which was defined by draft force multiplied by the area of surface disturbance. Thus, lower SRI represents more efficient design. These bentleg shanks were selected as the best available shanks for conservation tillage.

Drawbar power, is defined by force (draft) multiplied by speed of operation. Therefore, an increase in speed means a direct proportional increase in power. A straight leg subsoiler operating at depth of 52cm ranged from 24 to 36 kW when speed changed from 3.6 to 5.0 km h^{-1} (Smith and Williford, 1988). Many studies have shown how tillage depth increased demand in draft and consequently power. Shinners (1989) found that a Paraplow operating at 4 km h^{-1} and 22 cm depth required 28kW which increased to 32 kW when depth was increased to 30 cm at the same speed. Additionally, as presented by Raper et al. (2000; 2007), shallower (site-specific) subsoiling might be adequate to reduce compaction, fuel consumption, and draft forces thus increasing profitability.

The assessment of soil quality indicators is fundamental to determine sound farm management strategies. The present study addresses relevant production issues faced by southeastern U.S Coastal Plain farmers and proposes solutions that are currently available. Moreover, continued research on tillage equipment that will reduce energy requirements, and facilitate the detection of soil compaction is of great importance to increase efficacy of tillage practices.

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I. REDUCTION OF SOIL COMPACTION IN COTTON AND PEANUT ROTATION USING CONSERVATION SYSTEMS

ABSTRACT

Southern Coastal Plain soils benefit from the adoption of conservation tillage systems as water retention and organic matter increase thus improving soil structure. However, some Coastal Plain soils are prone to compaction and tend to form hardpans which restrict root growth and reduce yields. The adoption of non-inversion deep tillage has been recommended to disrupt compacted soil layers and create an adequate medium for crop development. In spite of its efficacy, increased fuel prices could reduce in-row subsoiling adoption due to increased cost. We evaluated three subsoiling implements against a non-subsoiled treatment with and without a rye *(Secale cereale L.)* cover crop on a 4-yr cotton (*Gossypium hirsutum L.)*- peanut (*Arachis hypogaea L.*) rotation at the Wiregrass Research Station in Headland, AL on a Dothan loamy sand (fine loamy, kaolinitic, thermic Plinthic Kandiudult). Plant, soil, and machinery parameters evaluated were: crop yield, cover crop biomass, cone index, and tillage energy. Results showed consistently lower yields for non-subsoiled treatments (11 and 51% lower yields for peanuts and cotton, respectively). Soil strength values had a 2 fold increase or greater (1.5 to 4.0 MPa) in less than a year. On average in-row subsoiling returned 698 $/ha/year for cotton and 612 $/ha/year more than non subsoiled treatments. No differences between implements were found. Annual paratilling combined with winter cover crop proved to be the most productive and profitable system.

INTRODUCTION

Any tillage or seeding system that maintains a minimum of 30% residue cover on the soil surface after planting is classified as conservation tillage (ASAE Standards, 2005). Conservation tillage has been used to reduce soil erosion and decrease production costs worldwide. In the southeastern USA, conservation systems were used on approximately 50% of the 2.9 million hectares of cotton (*Gossypium hirsutum L.)* planted in 2004 (CTIC, 2005). Another important southeastern US crop, peanut (*Arachis hypogaea L.*), has shown an increased acreage of 33,000 hectares under conservation systems from 2002 to 2004 (CTIC, 2005). In 2005, peanut was planted on 525,000 thousand hectares in the Southeast with 55% of the total area being in rotation with cotton (CTIC, 2005).

Southern Coastal Plain soils are usually highly weathered, erodible, carbon depleted and have low water holding capacity. Therefore, they should benefit from the adoption of conservation systems due to increased water retention, increased organic matter, and improved soil structure (Reeves, 1994; Ess et al., 1998; Raper et al., 2000).

However, the successful implementation of a conservation system for a cotton-peanut rotation faces some obstacles that have been addressed by several scientists. A cotton-peanut rotation is desirable from an economic standpoint, but until mid 1980's was not recommended in southeastern U.S. due to difficult peanut disease (stem and limb rot) control and cotton stalk interference with peanut mechanization (Johnson et al., 2001). Current advances in fungicide technology and tillage practices have reduced these problems. However, excessive use of chemical control may not be economically and environmentally recommended (Johnson et al., 2001).

Another major problem facing peanut production in southeastern U.S. is the incidence of spotted wilt virus that is vectored by thrips (*Frakliniella fusca* Hinds). The use of insecticide to control thrips is ineffective in suppressing spotted wilt, e.g.: the application of phorate has not been recommended due its cost (\$18 ha^{-1}) and low effectiveness (Marois and Wright, 2003). Spotted wilt virus is managed by controlling production strategies such as: choice of resistant cultivars, planting dates, increasing seed rates, and decreasing tillage intensity (Brown et al., 2000). Conservation tillage has been recommended to lower incidence of spotted wilt in peanuts. Johnson et al. (2001) found reduced tillage had 42% lower incidence of spotted wilt than conventional tillage. Marois and Wright (2003) found greater yields and lower spotted wilt incidence in strip-till treatment when a drought occurred.

However, controversy exists regarding peanut yields under conservation tillage systems. While some studies report conservation or no-till to have lower productivity compared to conventional tillage (Jordan et al., 2001; Tubbs and Gallaher, 2005), others state there is no difference and competitive yields can be obtained under conservation systems (Johnson et al., 2001; Marois and Wright, 2003). Much of the controversy is caused by stand establishment in conservation systems due to seed misplacement over mulch or compacted seedbeds (Jordan et al., 2001; Marois and Wright, 2003).The latter is especially problematic in southern Coastal Plain soils which are susceptible to compaction due to their sandy topsoil which increases in clay content with depth. These soils also tend to form hardpans extending from the surface Ap to the transitional E horizon, thus restricting root growth and reducing yields (Busscher et al., 1996; Raper et al., 2005a). These hardpans are a product of soil reconsolidation which may occur through multiple cycles of wetting and drying causing the soil bulk density to increase (Mapa et al., 1986; Assouline, 2006).

Deep tillage has been recommended to disrupt compacted soil layers and create an adequate medium for crop development (Reeder et al., 1993; Khalilian et al., 1988; Raper, 2005a). Even though in-row subsoiling has been shown to ameliorate effects of compaction, it is still considered to be an expensive operation, especially with increased fuel prices. Raper and Bergtold (2007) estimated that if producers used proper shank design, correct tillage depth, controlled traffic and correct tillage timing, the cost of subsoiling can be substantially reduced to approximately \$32 ha^{-1}, which represents approximately 2.5% of cotton production costs for the Southeastern U.S.

While there is a vast literature and farming knowledge about advantages of conservation tillage systems for cotton production (Raper et al., 2007; Schwab et al., 2002), peanut farmers still need to be convinced about the environmental and economic advantages of these systems. There is a need for research relating tillage system and its effect on soil parameters that can explain peanut yield improvements and/or economic benefits, which usually dictate land management strategies.

The objective of this study was to develop a conservation tillage system for a cotton-peanut rotation on Coastal Plain soil. This system should produce competitive yields, remediate compaction problems and increase economic return. Additionally, due to the extensive soil disruption that takes place with peanut harvesting, this study will also determine if additional in-row subsoiling is beneficial after this harvesting process.

MATERIAL AND METHODS

Study site

This study was conducted at Wiregrass Research and Extension Center (WGS) (31°21'N, 85°19'W) located in Headland, AL in Henry County which is the southeastern part of the state. The 0.4 ha site consists of a Dothan soil series on a 0 to 1% slope and has been cropped for many years under conventional tillage. The soil is classified as Dothan sandy loam (fine loamy, kaolinitic, thermic Plinthic Kandiudult), which are deep and well drained. This soil series is extensive and is distributed throughout the Coastal Plain of Alabama, Florida, Georgia, North Carolina, South Carolina, and Virginia. These soils are low in organic matter and natural fertility, but they can be easily tilled, respond to improved management, and are well suited to row cropping (NRCS, 2008). The climate for this area is humid subtropical, with a mean annual air temperature of 18° C and 1400-mm annual precipitation.

The experimental design was a split-plot with four replications. Main plots were represented by the rye *(Secale cereale L.)* winter cover crop (cover or no cover), and subplots were the four in-row subsoiling treatments (no-till and three in-row subsoilers). Each plot had 4 (8m long) rows spaced at 0.92 m. In-row subsoiling was implemented at 38 cm depth using the following implements: Ripper-Stripper[1] strip-till (Unverferth Manufacturing Co, Inc., Kalida, OH); Paratill (Bigham Brothers, Inc., Lubbock, TX); and Terramax Worksaver (Worksaver Inc., Litchfield, IL).

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[1] The use of company names or trade names does not indicate endorsement by Auburn University or USDA-ARS.

Rye cover crop was sprayed with 2.3 l/ha of glyphosate and mechanically terminated using a spiral blade roller-crimper (Raper et al., 2004) two weeks prior to spring planting. To ensure correct row position, a Trimble AgGPS Autopilot (Trimble, Sunnyvale, CA) steering system was used for subsoiling and planting. The variety of peanut planted was Georgia Green in 2003 and 2005, while the variety of cotton planted was the transgenic Delta Pine 555 BG/RR stacked for 2004 and 2006. Peanuts and cotton were planted with a John Deere 1700 (Deere & Company, Moline, IL) 4-row vacuum planter. Cotton was planted with a seeding rate of 11.5 seeds/meter (116,000 plants/hectare) and received 100 kg/ha of nitrogen, 100 kg/ha of potassium and 22 kg/ha of sulfur while the peanut seeding rate was 20 seeds/meter (197,000 plants/hectare) and received no fertilization.

Data collection

Cone Index

A tractor-mounted, hydraulically-driven, soil cone penetrometer was used for determination of soil strength (Raper et al., 1999): before harvesting in the fall of 2003 and 2004; after subsoiling and planting in 2005; before and after subsoiling in 2006. The tractor-mounted penetrometer determined soil strength in five positions simultaneously: (i) in-row, (ii) 23 cm from the row in the trafficked middle, (iii) 46 cm (midway) from the row in the trafficked middle, (iv) 23 cm from the row in the no trafficked middle, and (v) 46 cm (midway) from the row in the no trafficked middle. A cone with a base area of 130 mm^2 was used on each of the penetrometers (ASAE Standards, 2004a; ASAE Standards, 2004b). Three readings per plot were taken continuously (25 points per second) throughout the soil profile to a depth of 50 cm. The cone index data were then averaged every 5cm for statistical analysis (SAS Institute, 2000) and for contour graphs using Surfer for Windows (Golden Software Inc., Golden, CO). These contour graphs were generated by Kriging point interpolation (linear variogram). Soil samples were taken from 0-15cm and 15-30cm and oven dried at 105°C until constant weight to determine soil moisture at the time of penetrometer readings.

Crop Yield

Harvesting of seed cotton consisted of picking the two center rows with a John Deere 9910 (Deere & Company; Moline, IL) two row cotton harvester spindle harvester with a bagging attachment. Peanut was harvested with a Hustler 5000 (Gregory Manufacturing, Lewiston Woodville, NC) in the two middle rows.

Tillage Energy

The in-row subsoiling implements were mounted on a three-dimensional dynamometer, which has an overall draft load capacity of 44 kN. Draft, vertical force, side force, and speed of operation were recorded at a sampling rate of 50 Hz during each implement test. Speed was held constant at 1.12 m/s and depth of operation was 40 cm for all tests.

Cover crop biomass total nitrogen and carbon

Rye (S*ecale cereale L.)* was sampled using 2 (0.25 meter square) frames, the above ground biomass was then oven-dried at 55° C to remove moisture and weighed to determine dry matter. Samples were ground to pass a 1mm sieve and sub-samples were taken to determine N and C content using the dry combustion method, TruSpec analyzer (Leco Corporation , St. Joseph, MI).

Data Analysis

Data was subjected to ANOVA (GLM procedure) using Statistical Analysis System (SAS Institute, 1988), where it was analyzed by year due to the crop rotation. Multiple means comparisons were separated by Fisher's protected LSD and Least Square Means at significance level of $P< 0.1$.

RESULTS AND DISCUSSION

Cover Crop Biomass

The use of winter cover can have a positive impact on soil quality that is accomplished by increasing soil organic matter, aggregate stability, water retention, and consequently reducing soil bulk density and soil strength (Reeves, 1994). Our results showed that cover crop production was substantially lower in the no-till treatment from 2004 through 2006 compared to subsoiled treatments (fig.1). However, in 2005, this difference was not statistically significant which could be explained by a shorter growing period for the 2005 year of 161 days. The shorter growing period was caused by a delay on the planting date due to farm operation logistics. In 2004, the growing season was 176 days and in 2006 it was 171 days. We also analyzed the rainfall, average temperature and growing degree day (GDD) (table 1) during the rye growing periods and found no differences that could justify lower biomass production in 2005. The rye requirement of GDD given by Abraha and Savage (2008) is 1000 GDD for flowering and 1800 GDD for physiological maturity in grain production. Our GDD totals (1576; 1536; and 1680 for 2003/2004; 2004/2005; and 2005/2006 respectively) for each rye growing season are above the suggested flowering requirements of 1000 GDD.

In 2006, in-row subsoiling increased cover crop production from 76 % (Paratill) up to 99 % (Strip-till) compared to strict no-till. Another important point is that in-row subsoiled plots were able to produce more than 4500 kg ha^{-1} of biomass during 2004 and 2006, which was recommended by Reiter et al. (2003) for a high residue cereal crop in Alabama. There were no significant differences among the subsoiling implements for any year of the study. We also noticed rye production increased after peanuts which may suggest some beneficial effect due to residual nutrients left by the legume to the subsequent rye crop. However, this effect cannot be ascertained because no plant or soil samples were taken along all the experiment years. Previous studies tried to establish the contribution of peanut residue as a source of nitrogen, however, Balkcom et al. (2004) found no significant increase in nitrogen mineralization from the peanut residue. Additionally Meso et al. (2006) and Balkcom et al. (2007) found no significant increase in nitrogen concentration and N uptake in the plant samples of cotton and rye, respectively, when peanut residue was removed or retained.

The rye biomass C and N concentration was determined only during 2006 crop, where no-till treatment had the lowest C concentration and the highest N concentration resulting in the lowest C/N ratio (table 2). Even though this difference was statistically significant, all the results were under 2% of N concentration which is defined by Palm and Sanchez (1991) as boundary concentration for N mineralization to take place. According to Tisdale et al. (1993), C/N ratios of residues are usually indicators of N mineralization. Low ratios (<20 to1) indicate N mineralization as high ratios (>30 to 1) result in N immobilization. Our results fell within the range of 20-30 to 1 indicating a balance or equilibrium between N mineralization and immobilization. Overall results confirmed the expected outcome that in-row subsoiling would increase cover crop production by offsetting the effects of compaction.

Soil Strength

Our cone index results are presented by year since they were taken during different crop stages in a cotton-peanut rotation. During our CI analysis, position and depth factors were, as expected, found to be significant ($P\leq 0.01$), therefore the analysis of variance was conducted by row position and by depth levels. Statistical significance was found mostly for in-row subsoiling treatments at the in-row position, which can impact root growth, therefore in-row CI values were investigated further (tables 3 to 6). High significance levels for the subsoiling factor ($P<0.01$) occurred at most depth levels for all years at the in-row position (tables 3 to 6). The cover crop factor or the interaction between susbsoiling and cover crop showed little significance depending on the year.

The CI means were plotted on contour graphs establishing penetration isolines or lines of equal resistance (fig. 2 to 6). Moisture at time of CI measurement showed little variation range among treatments; the differences were attributed to treatment effects itself. Moisture at time of CI sampling is presented by depth (table 7). These values differ among years but no difference was found among treatments.

In southern Coastal Plain soils, a mixture of coarse particles from the topsoil and fine particles at the argillic horizon tends to fill most of the void spaces at this horizon interface. This is accelerated by the high precipitation regime, creating a root restrictive layer. During all years of the experiment, no-till CI index values are significantly higher than in-row subsoiling treatments, particularly at in-row position (fig. 2 to 6). It is important to notice that we have two sets of readings for 2006 (fig. 5 and 6). The first one shows CI values after terminating the rye cover on 2006, 11 months after the 2005 readings (fig. 4). During this time peanuts were harvested, rye was planted, rolled, and terminated. Rainfall during this period totaled 1190 mm. Note that CI index values were elevated (3 to 4 fold) after this period, with much of the area above 2MPa. Even for the no-till treatment an enlargement of the compacted layer occurred, also there were no significant differences among treatments (table 6). Another set of CI data for 2006 (fig.6) taken 1 day after the first set of readings (fig. 5) illustrates how in-row subsoiling breaks most of the compacted profile significantly reducing CI values (table 6). These results show the necessity of in-row susbsoiling and how reconsolidation happens in warm, humid conditions combined with highly weathered C depleted soils.

Annual CI sampling is recommended after cash crop harvesting to assess necessity of in-row subsoiling. Efforts have been made to establish methods for specific hardpan depth detection and developing on-the-go soil strength systems that would make this sampling quicker and more representative, resulting in tillage energy savings (Alihamsyah and Humphries, 1991; Hall and Raper, 2005).

Tillage energy

Drawbar power results were not significantly different by year or cover crop. Therefore, 2005 and 2006 were averaged to produce drawbar power means by implement (fig. 7). The results showed statistical significance with the Paratill having lower power requirements compared to Worksaver and Strip-till which did not differ from each other. Our results for the Paratill (7.75 kW/shank) are somewhat lower than the ones found by

Khalilian et al. (1988) and Reeder et al. (1993), 11.6 and 10.1kW/shank, respectively. These differences can be explained manly by different speeds of operation since soil type and moisture conditions were similar to our experiment. Our speed was maintained at 4 km h^{-1} while the other two experiments had speed targeted to 7 km h^{-1}.

All other energy parameters were analyzed by year, as this factor was significant, (table 8). Draft force for Paratill was significantly lower than that for the other two implements in 2005 and no differences were found in 2006. All the draft force values were in accordance to the ones found by Raper et al. (2005a; 2005b).

Strip-till with its straight shank design created greater vertical downward force that was statistically significant during both years. In 2006, Paratill had a negative value for vertical force which means an upward force exerted by the soil. This may seem contrary to popular belief but has also been reported for other subsoilers by previous research (Garner et al., 1987).

Side force values were also within range of previous studies (Raper, 2005b) with strip-till having the lowest values for two years which was not surprising due the bentleg design of the Paratill and Worksaver.

Cash Crop Yields

Yield results were significantly impacted by cover crop and tillage with no interactions. Rye cover crop significantly increased yield during the latter 2 years of the experiment, peanuts in 2005 and cotton in 2006. Overall increase for the 4-year period totaled 7% for peanuts and 14% for cotton compared to treatments without cover (fig. 8).

These findings are attributed to the greater volumetric water content found with the cover treatment (21%) compared (17.7%) to fallow treatments.

Our CI results accurately reflect our yield results with the no-till treatment having the lowest production in three out of four experimental years. These findings agree with Busscher et al. (2000) when yields of soybean and wheat increased at least 1 Mg ha^{-1} for each 0.1 MPa reduction from 2.0 to 0.9 MPa due to subsoiling in loamy sand. However they contrast with results from Raper et al. (2005b) and Wells et al., (2005) where increases in yields of cotton, soybeans, corn and wheat were not enough to justify additional operational costs of in-row subsoiling in silt loam soils.

During 2006, a severe drought hit the Southeastern states and Alabama farmers suffered great losses. In the period of April to October (fig. 9) 2006, the cumulative precipitation was 505 mm which was 28% below the minimum requirement for cotton (700 mm; Brouwer, 1986). Also, greater soil water content provided by the cover crop could have reduced soil strength and improved root growth, emphasizing the effect of cover, which in 2006 yielded 26% more than no-cover.

Subsoiling greatly increased peanut and cotton yields in all years but 2003 (fig. 10). Crop yields for no-till were lowest in every year except 2003 when no-till had the highest peanut production (although not significant). We hypothesize that a residual effect of conventional tillage existed in 2003. Additionally, the peanut crop had abundant rain from April to October in 2003 at 950mm (fig. 9). Optimal peanut production water requirements are normally approximately 500 to 750 mm (Baker et al., 2000).

Paratilling produced the highest yields from 2004 to 2006 although they were not statistically different from the other in-row subsoiling treatments (fig.10). Yield increases can be attributed to reduced soil strength. However, as seen in the soil strength results, the effects of subsoiling typically don't persist longer than a year in our climatic and edaphic conditions.

An interesting comparison can also be established between our yield results and Alabama average cotton and peanut yields (NASS, 2008). Peanut average yields for both years (2003 and 2005) in Alabama were 3080 kg ha^{-1}.Our 2003 yields were at least 1000 kg ha^{-1} greater for all treatments. In 2005, only the in-row subsoiled treatments produced yields above 3080 kg ha^{-1}, while no-till yielded 1145 kg ha^{-1} less than state average. Average cotton yield for all in-row subsoiled treatments (3220 and 2110 kg ha^{-1}) were above the state average of 2300 and 1850 kg ha^{-1} for 2004 and 2006, while no-till yielded 2190 and 1500 kg ha^{-1} respectively. It is important to note that the state averages cover a diverse set of soil and climate conditions.

Economic Return

Subsoiling costs are estimated to be approximately 32 to 43 \$ ha^{-1} (Raper and Bergtold, 2007; Alabama Cooperative Extension System (ACES) 2008). Our yield increase for each in-row subsoiling treatment versus no-till are shown in tables 9 and 10. Using ACES (2008) current production costs of peanuts (1611 \$ ha^{-1}) no-till treatment would result in net loss of 546 \$ ha^{-1}, while in-row subsoiling minimized losses, and resulted in positive return. It is important to notice that budget information for peanut production under conservation tillage is not available. Therefore, modifications were made on the conventional tillage budget (ACES, 2008) in order to lower the variable and fixed costs of the machinery parameter.

The increase of productivity provided by in-row subsoiling may represent the difference between profit and loss. Our net revenue increase results differ from the ones of Raper et al. (2005b) and Wells et al. (2005) which found increases in yield were not enough to justify the subsoiling cost. However, under our study conditions of high soil strength, acceptable productivity levels may not be obtained without in-row subsoiling. It is also important to note that under current prices (to our specific conditions) peanuts should produce 2930 kg ha^{-1} at \$ 550 Mg^{-1} just to break even.

For cotton, the scenario was more advantageous once we included the seed yield revenue, which is usually excluded in crop budgets. All treatments had a positive net return for the two cotton seasons except for no-till (table 10). Among in-row subsoilers there was substantial variation and Paratill once again proved to be most profitable implement.

The effect of cover crop was also substantial for both crops. At a cost of \$74ha^{-1} (ACES, 2008), cover crops were a worthy investment, especially when cotton was hit by drought resulting in approximately \$370 ha^{-1} increase in net return.

CONCLUSIONS

In-row subsoiling was particularly effective in reducing soil compaction as measured by cone index values. Consequently, cash and cover productivity were also increased by in-row subsoiling regardless of the implement model.

Implement energy requirements differ slightly with the Paratill having the lower demands for draft and power. Paratill also produced highest cash crop yields in the rotation. No statistical yield differences were found among subsoiler implements. Rye cover crop was also found to increase net returns and had greater impact when yields were depressed by drought.

Soil strength results showed reconsolidation occurred very fast in these soils and after 11 months soil was recompacted to root restrictive levels. Even after soil disruption by peanut harvesting, in–row subsoiling was needed to alleviate compaction.

In-row subsoiling is an indispensable practice for obtaining satisfactory productivity and should be coupled with a winter cover crop to reduce risk and increase yield, especially during a growing season that might experience a short-term drought.

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Table 1. Monthly growing Celsius degree days (GDD ° C) and rainfall during rye growing seasons.

	2003/2004*		2004/2005**		2005/2006***	
Month	**Rain(mm)**	**GDD ° C**	**Rain(mm)**	**GDD ° C**	**Rain(mm)**	**GDD ° C**
November	52	284	0	8	72	247
December	50	167	65	199	115	177
January	38	201	74	254	96	282
February	166	157	77	230	113	190
March	10	391	126	300	14	334
April	84	376	202	388	41	450
May	0	0	47	157	0	0
Total	401	1576	592	1536	452	1680

* Planted on 11/5/2003 and terminated on 4/29/2004 (176 days)

** Planted on 11/30/2004 and terminated on 5/10/2005 (161 days)

*** Planted on 11/9/2005 and terminated on 4/29/2006 (171 days)

Table 2. Rye cover crop carbon and nitrogen concentrations and C/N ratio in 2006 as affected by tillage treatment. Different letters indicate statistical significance.

Tillage treatment	Carbon	Nitrogen	C/N ratio
	g kg^{-1}		
No-till	411.2 b	19.3 a	21.7 c
Paratill	423.4 a	15.1 b	28.6 a
Strip-till	419.9 a	17.0 b	24.9 bc
Worksaver	419.4 a	15.8 b	27.1 ab
$\text{LSD}_{(0.1)}$	7.3	2.1	3.2

Table 3. Significance level of factors in soil strength analysis of variance (Fall 2003). Letters indicate cover (C), subsoiling (S) and interaction cover x subsoiling (C x S). Numbers in bold are significant at the 0.10 significance level.

2003	**No-traffic**			**In-row**			**Traffic**		
Depth (cm)	P-value								
	C	**S**	**C x S**	**C**	**S**	**C x S**	**C**	**S**	**C x S**
0	0.32	0.36	0.98	0.17	**0.01**	0.71	0.64	0.13	0.55
5	0.12	**0.05**	**0.01**	0.55	**0.01**	0.95	0.63	0.10	0.45
10	0.47	0.29	0.29	0.26	**0.01**	0.35	0.38	0.55	0.83
15	0.36	0.86	0.87	0.14	**0.01**	0.18	0.14	**0.06**	0.54
20	0.06	0.63	0.27	0.12	**0.01**	0.30	0.34	0.29	0.50
25	**0.07**	0.17	0.10	0.52	**0.01**	0.85	0.58	0.02	0.79
30	0.36	0.23	0.79	0.66	**0.57**	0.42	0.58	0.24	0.51
35	0.39	0.22	0.36	0.33	0.98	0.11	0.57	0.25	0.27

Table 4. Significance level of factors in soil strength analysis of variance (Fall 2004). Letters indicate cover (C), subsoiling (S) and interaction cover x subsoiling (C x S). Numbers in bold are significant at the 0.10 significance level.

2004	**No-traffic**			**In-row**			**Traffic**		
Depth (cm)	P-value								
	C	**S**	**C x S**	**C**	**S**	**C x S**	**C**	**S**	**C x S**
0	0.40	0.40	0.40	0.39	0.41	0.41	0.65	0.47	0.15
5	0.52	0.52	0.52	0.38	0.44	0.39	0.50	**0.05**	0.17
10	0.21	0.66	0.45	0.32	**0.07**	0.17	**0.02**	**0.01**	0.54
15	0.24	0.84	0.34	0.47	**0.01**	**0.05**	**0.05**	0.12	0.74
20	0.16	0.87	0.30	0.73	**0.01**	0.74	0.11	0.31	0.94
25	0.67	0.67	0.67	0.96	**0.01**	0.98	0.37	0.27	0.70
30	0.75	0.75	0.75	0.78	**0.01**	0.99	0.45	0.95	0.50
35	0.47	0.47	0.47	0.15	**0.01**	0.88	0.80	0.22	0.58
40	0.41	0.41	0.41	0.35	**0.01**	0.94	0.54	**0.03**	0.68
45	0.37	0.37	0.37	0.31	**0.01**	0.99	0.90	0.56	0.68
50	0.33	0.33	0.33	0.77	**0.01**	0.31	0.22	0.35	0.22

Table 5. Significance level of factors in soil strength analysis of variance (Spring 2005). Letters indicate cover (C), subsoiling (S) and interaction cover x subsoiling (C x S). Numbers in bold are significant at the 0.10 significance level.

2005	**No-traffic**			**In-row**			**Traffic**		
Depth (cm)	P-value								
	C	**S**	**C x S**	**C**	**S**	**C x S**	**C**	**S**	**C x S**
0	0.16	0.16	0.16	0.13	**0.01**	**0.01**	0.23	**0.02**	0.83
5	0.14	0.14	0.14	**0.08**	**0.01**	**0.01**	0.58	0.58	0.58
10	0.33	0.22	0.20	0.65	**0.01**	0.49	0.34	0.34	0.34
15	0.51	0.51	0.51	0.75	**0.01**	0.74	0.84	0.11	0.55
20	0.26	0.26	0.26	0.40	**0.01**	0.32	0.53	**0.04**	0.66
25	0.47	0.59	0.13	0.71	**0.01**	0.25	0.60	**0.01**	0.48
30	0.35	0.67	**0.05**	0.79	**0.01**	0.41	0.87	0.10	0.76
35	0.73	0.68	0.23	0.87	**0.01**	0.65	0.39	0.77	0.46
40	0.43	0.92	0.61	0.15	0.15	0.15	0.38	0.60	0.36
45	0.23	0.28	0.31	0.60	**0.01**	0.69	0.78	0.78	0.78
50	0.14	0.14	0.14	0.84	**0.01**	0.62	0.94	0.94	0.94

Table 6. Significance level of factors in soil strength analysis of variance (Spring 2006), before and after tillage. Letters indicate cover (C), subsoiling (S) and interaction cover x subsoiling (C x S). Numbers in bold are significant at the 0.10 significance level.

2006 Before Till	**No-traffic**			**In-row**			**Traffic**		
Depth (cm)	P-value								
	C	**S**	**C x S**	**C**	**S**	**C x S**	**C**	**S**	**C x S**
0	0.81	**0.01**	0.17	0.22	0.22	0.22	**0.05**	NS	0.10
5	0.72	0.13	0.33	0.66	0.66	0.66	**0.01**	NS	0.25
10	0.19	0.11	0.83	0.71	0.71	0.71	**0.01**	**0.05**	0.20
15	**0.09**	**0.01**	0.11	0.11	0.11	0.11	0.43	**0.01**	**0.05**
20	**0.06**	**0.01**	**0.04**	0.36	0.51	**0.07**	0.11	**0.01**	**0.01**
25	**0.04**	**0.01**	**0.05**	0.15	0.15	0.15	**0.09**	**0.01**	**0.02**
30	**0.06**	**0.06**	**0.08**	0.12	0.12	0.12	**0.07**	**0.01**	0.15
35	0.11	0.11	0.11	**0.02**	0.46	0.48	0.18	0.10	0.68
40	0.35	0.35	0.35	0.11	0.34	0.24	0.49	0.93	0.64
45	0.33	0.33	0.33	0.30	0.31	0.31	0.32	0.32	0.32
50	**0.06**	**0.04**	0.21	0.33	0.33	0.33	0.48	0.48	0.48

2006-After Till	**No-traffic**			**In-row**			**Traffic**		
Depth (cm)	P-value								
	C	**S**	**C x S**	**C**	**S**	**C x S**	**C**	**S**	**C x S**
0	0.28	0.28	0.28	0.51	**0.01**	0.76	0.36	**0.02**	0.53
5	0.37	0.37	0.37	0.17	**0.01**	0.77	0.14	0.34	0.44
10	0.18	**0.02**	0.36	0.61	**0.01**	0.98	0.11	0.11	0.11
15	0.12	0.12	0.12	0.57	**0.01**	0.93	0.26	0.26	0.26
20	0.34	0.34	0.34	0.90	**0.01**	0.97	0.36	**0.07**	0.35
25	0.35	0.35	0.35	0.52	**0.01**	0.85	0.13	0.13	0.13
30	0.15	0.15	0.15	0.78	**0.01**	0.69	0.28	0.28	0.28
35	0.15	0.15	0.15	0.90	**0.01**	0.78	0.16	0.59	0.21
40	0.43	**0.01**	0.50	0.49	**0.01**	0.91	0.13	0.13	0.13
45	0.67	**0.04**	0.18	0.31	**0.05**	0.95	0.31	0.31	0.31
50	0.86	**0.05**	0.17	0.37	0.35	0.56	0.54	0.54	0.54

Table 7. Mean gravimetric water content (GWC) of the soil (Dothan sandy loam) at the time of penetrometer readings by depth.

	Year			
	2003	2004	2005	2006
	Fall	Fall	Spring	Spring
Depth(cm)	GWC (kg kg^{-1})			
0-15	0.091	0.077	0.117	0.069
15-30	0.098	0.079	0.102	0.077
LSD$_{(0.1)}$	ns	0.001	0.004	0.002

Table 8. Draft, vertical and side forces means by subsoiler for 2005 and 2006. Means are averaged across cover crop treatment. Letters indicate statistical significance.

	Draft (kN)		Vertical (kN)		Side (kN)		Speed (km/h)	
	Year							
Implement	2005	2006	2005	2006	2005	2006	2005	2006
Paratill	26 a	37	2.9 b	-1.08 c	0.74	0.56	4.03	3.2 a
Strip-till	31.4 b	40	14.1 a	11.6 a	0.61	0.39	3.97	3.09 b
Worksaver	30.5 b	40.1	3.8 b	1.38 b	0.67	0.88	4.25	3.18 a
$LSD_{(0.1)}$	2.74	ns	0.98	0.8	ns	ns	ns	0.04

Table 9. Estimated costs and economic return for peanut crop in 2005.

	Peanut Yield 2005	Yield Increase	Revenue Increase*	Cost Increase**	Net Increase	Net Return***
	kg ha^{-1}		US \$ ha^{-1}			
No-till[†]	1935	0	0	0	0	-546
Paratill	3561	1626	894	43	851	305
Strip-till	3130	1195	657	43	614	68
Worksaver	3179	1244	684	43	641	95
No-cover [†]	2826	0	0	0	0	-57
Cover	3078	252	139	74	64	7

[†] no-till and no-cover are the base comparison

Source (ACES, 2008)

* Peanut price at \$ 550 Mg^{-1}

** (Fuel 0.8 \$/Liter; 0.66 hour/ha; 135hp tractor 47\$/hour; Ripper-Bedder 17\$/hour; cover crop 74\$/ha)

*** Net return over total production costs 2008 (1611 \$ ha^{-1})

Table 10. Estimated costs and economic return for cotton crops 2004 and 2006.

	Seed Cotton Yield						
	2004	2006	Average Increase	Revenue Increase*	Cost Increase**	Net Increase	Net Return***
	kg ha^{-1}			US $ ha^{-1}			
No-till	2191	1497	0	0	0	0	-431
Paratill	3293	2612	2217	1729	86	1643	1212
Strip-till	3232	2425	1969	1536	86	1450	1019
Worksaver	3147	2059	1517	1183	86	1097	666
No-cover	2895	1899	0	0	0	0	430
Cover	3035	2395	636	496	148	348	778

[†] no-till and no-cover are the base comparison

Source (ACES, 2008)

* Based on 40% lint yield. Lint $ 1.65/kg ; seed cotton $ 0.2/kg

** (Fuel 0.8 $/Liter; 0.66 hour/ha; 135hp tractor 47$/hour; Ripper-Bedder 17$/hour; cover crop 74$/ha)

*** Net return over total production costs 2008 (1654 $ ha^{-1})

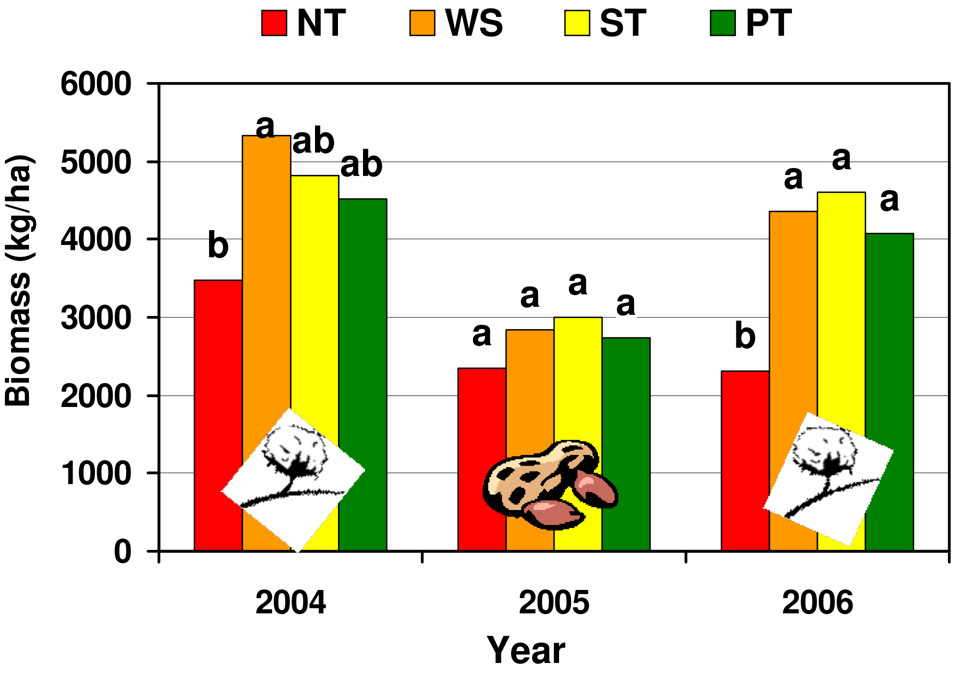

Fig. 1. Annual winter rye cover crop biomass production as affected by in-row susbsoiling. Letters indicate NT-no-till; WS- worksaver; ST- strip-till; PT- paratill. Different lower case letters indicate statistical significance $\mathrm{LSD}_{(0.1)}$.

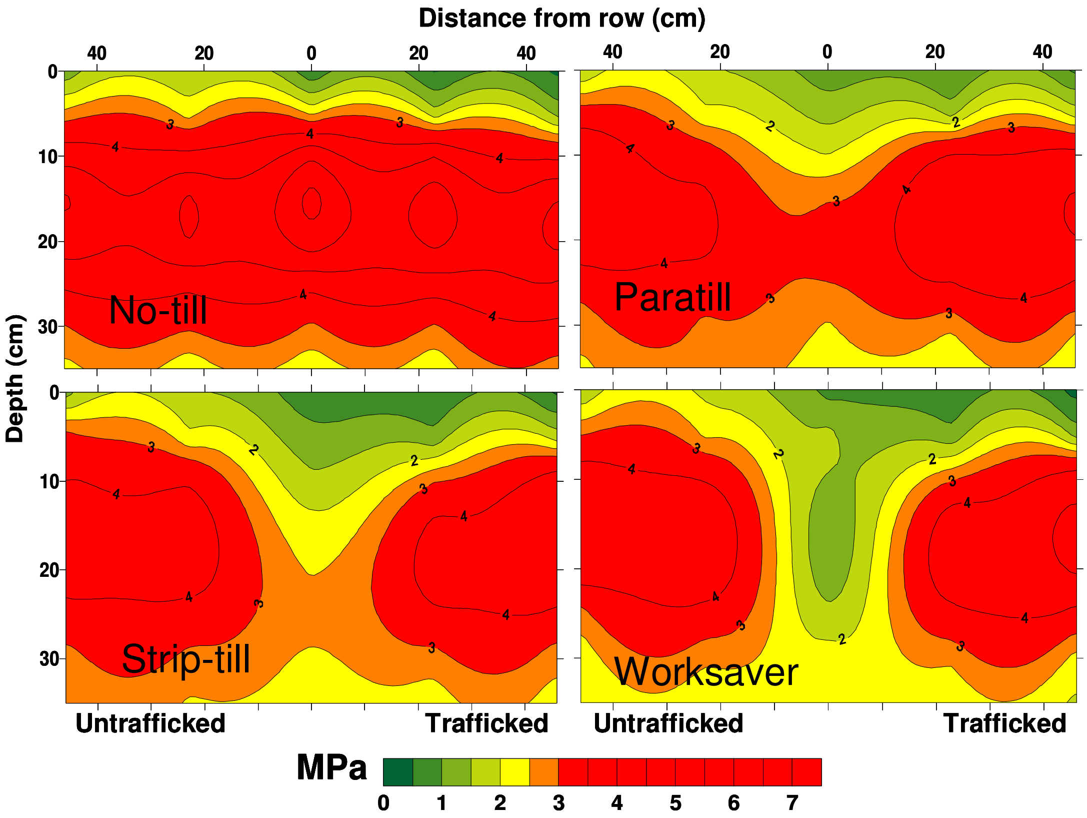

Fig. 2. Fall 2003 soil strength of a Dothan sandy loam in southeastern AL before peanut harvest. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

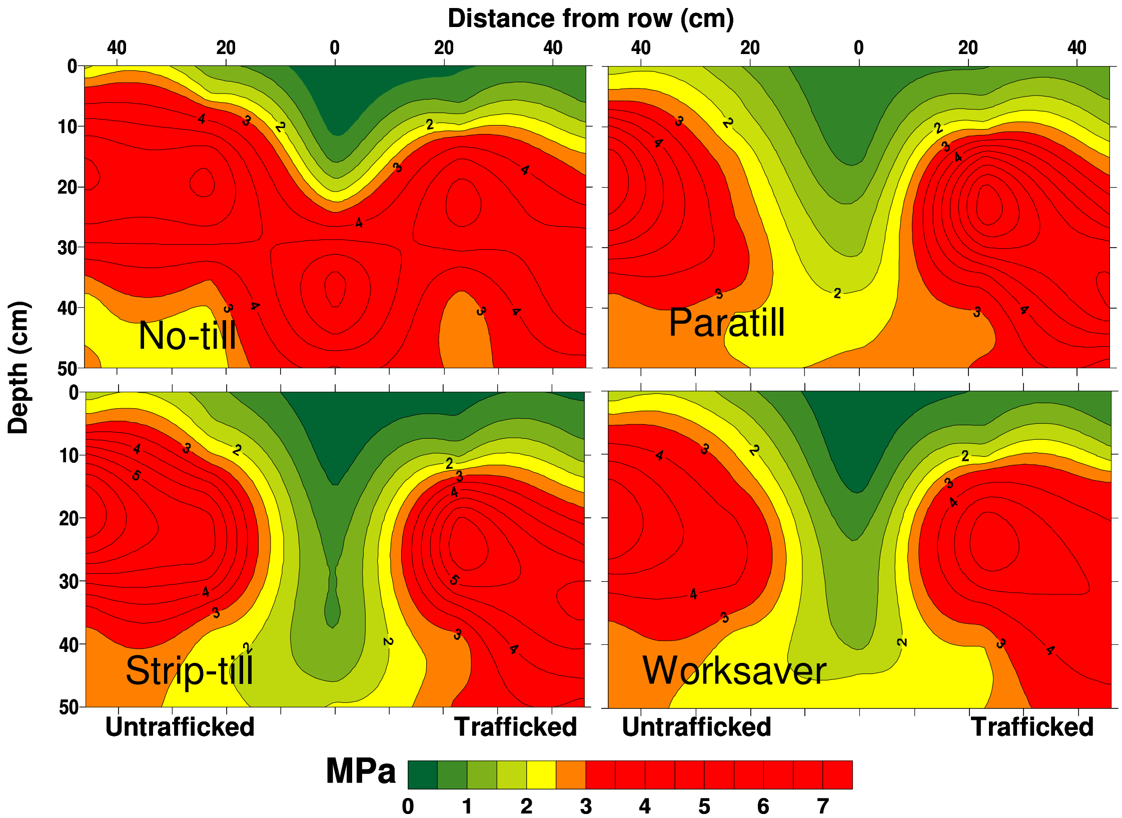

Fig. 3. Fall 2004 soil strength of a Dothan sandy loam in southeastern AL before cotton harvest. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

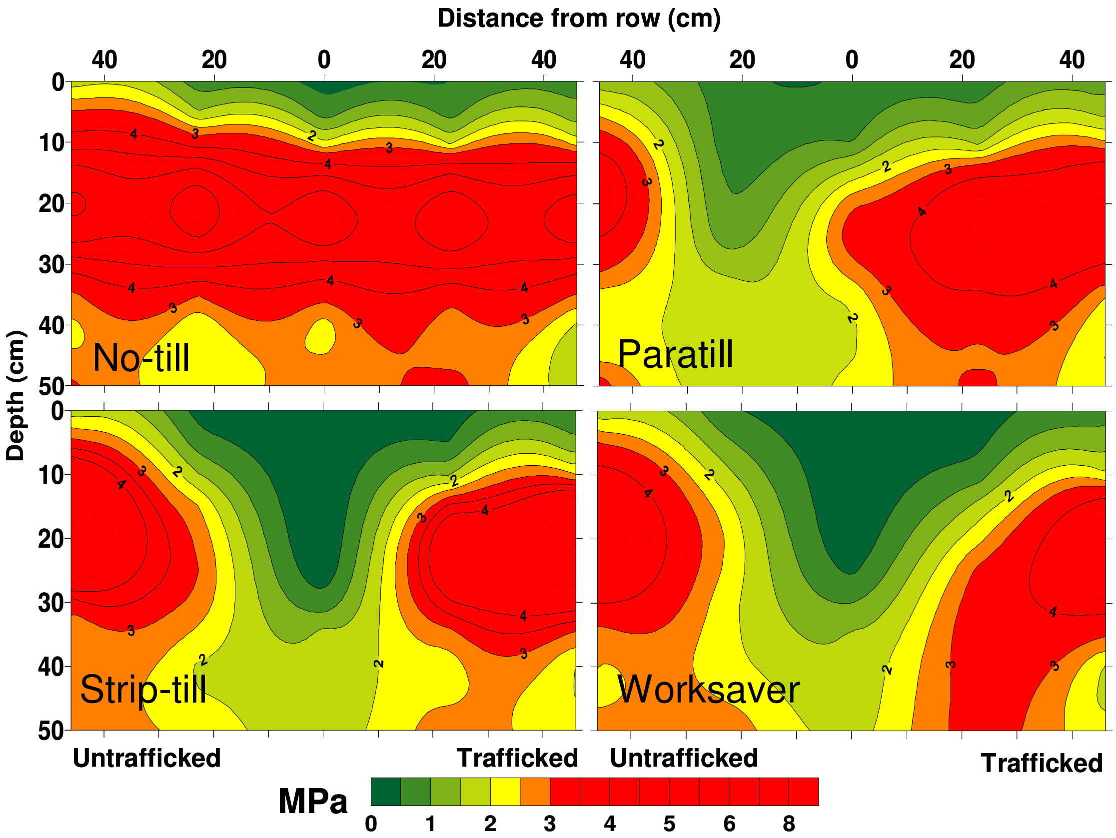

Fig. 4. Spring 2005 soil strength of a Dothan sandy loam in southeastern AL after planting the peanut crop. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

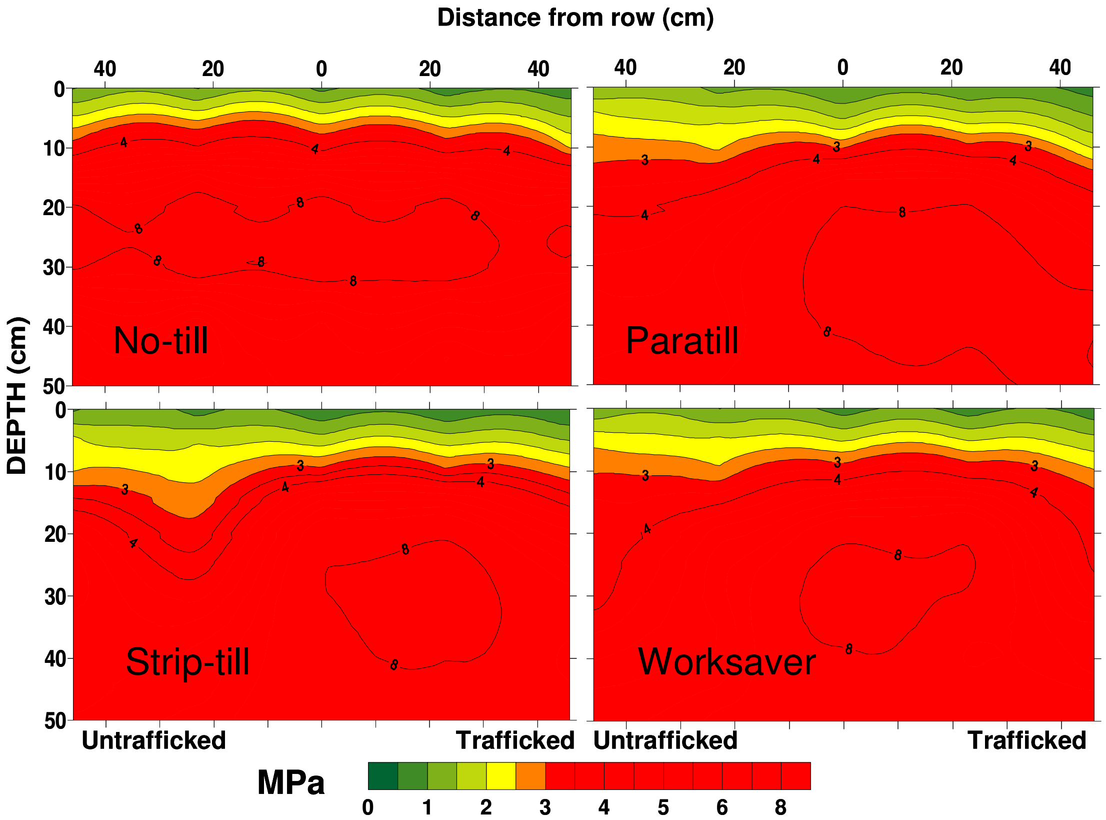

Fig. 5. Spring 2006 soil strength of a Dothan sandy loam in southeastern AL before tillage for cotton planting. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

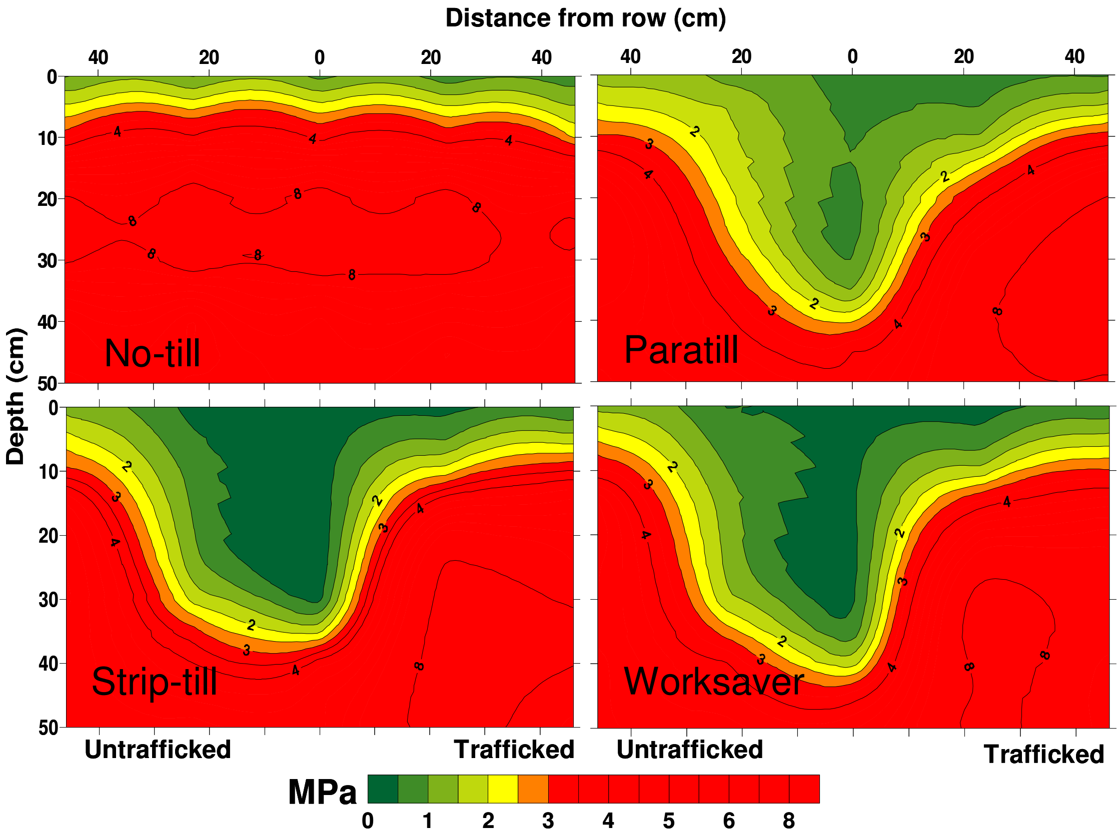

Fig. 6. Spring 2006 soil strength of a Dothan sandy loam in southeastern AL after tillage for cotton planting. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

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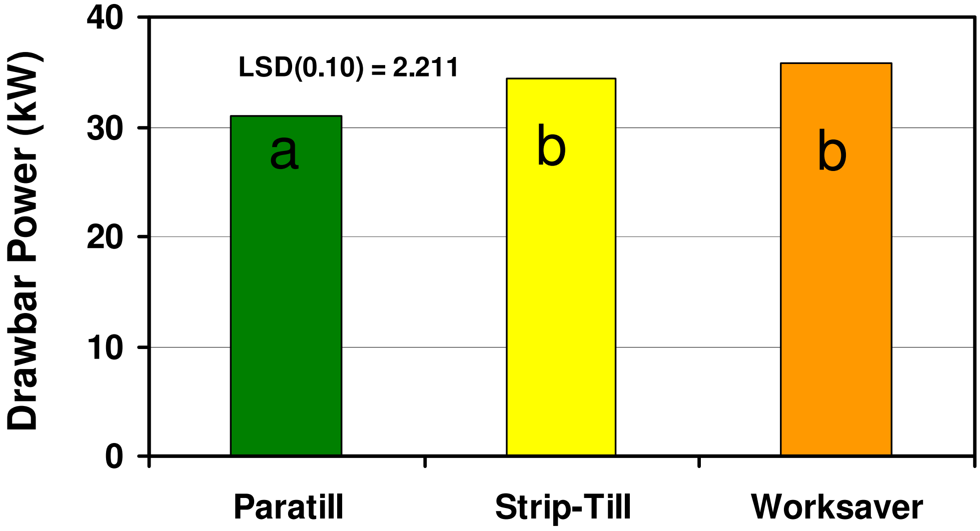

Fig. 7. Drawbar power means by subsoiler for Dothan sandy loam in southeastern AL. Implements averaged across year and cover crop treatments. Speed set to 4 km h^{-1} at 38 cm depth. Different letters indicate $LSD_{(0.1)}$.

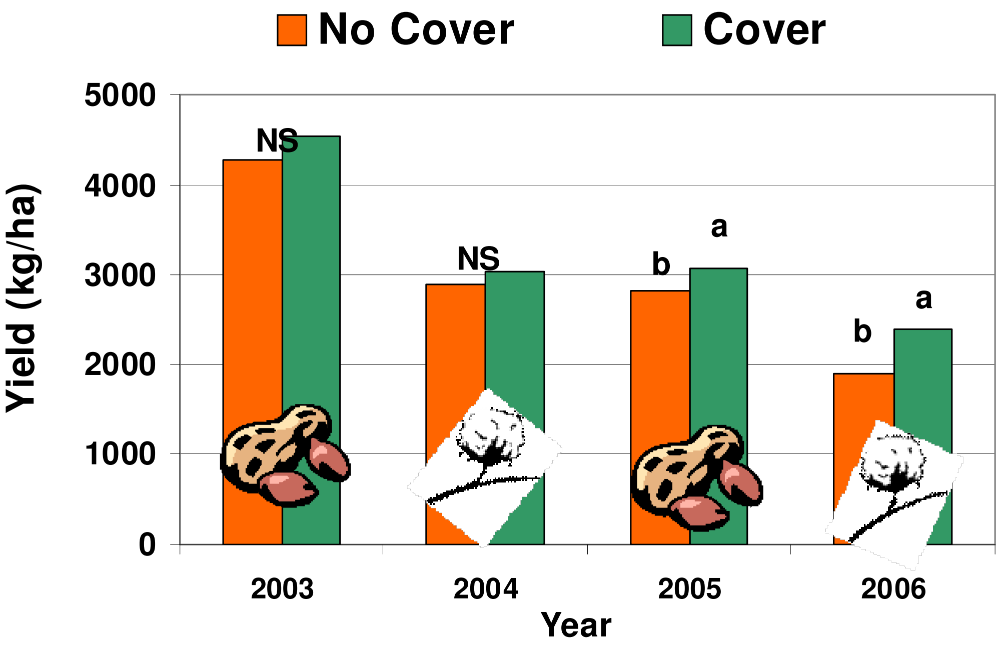

Fig. 8. Peanuts and cotton yields by year as affected by cover crop on a Dothan sandy loam in southeastern Alabama. Different letters indicate $LSD_{(0.1)}$.

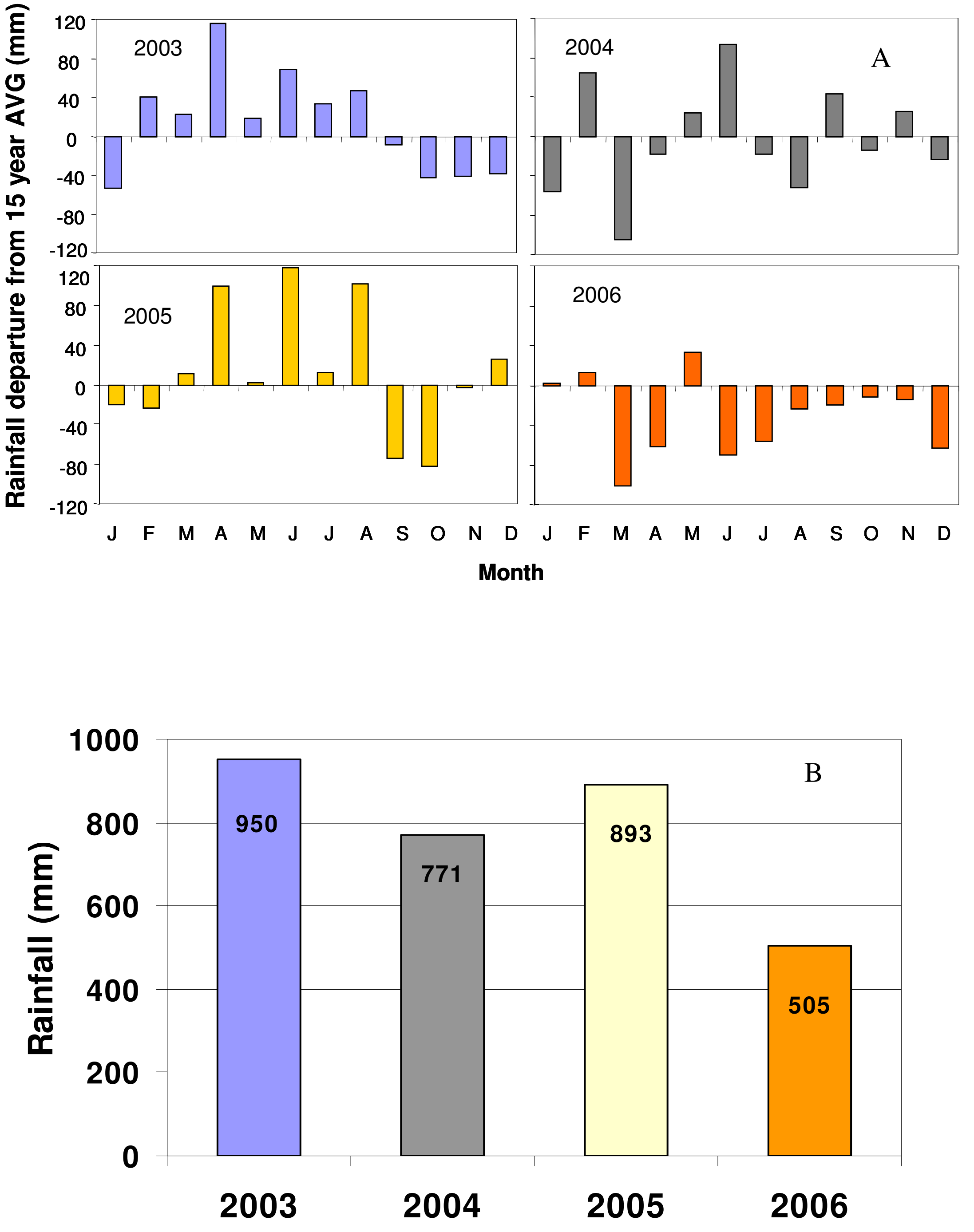

Fig. 9. Rainfall departure from 15 year average (AVG) (A) and cumulative rainfall from April to October (B) for each experiment year at Wiregrass Research Station, Headland Alabama.

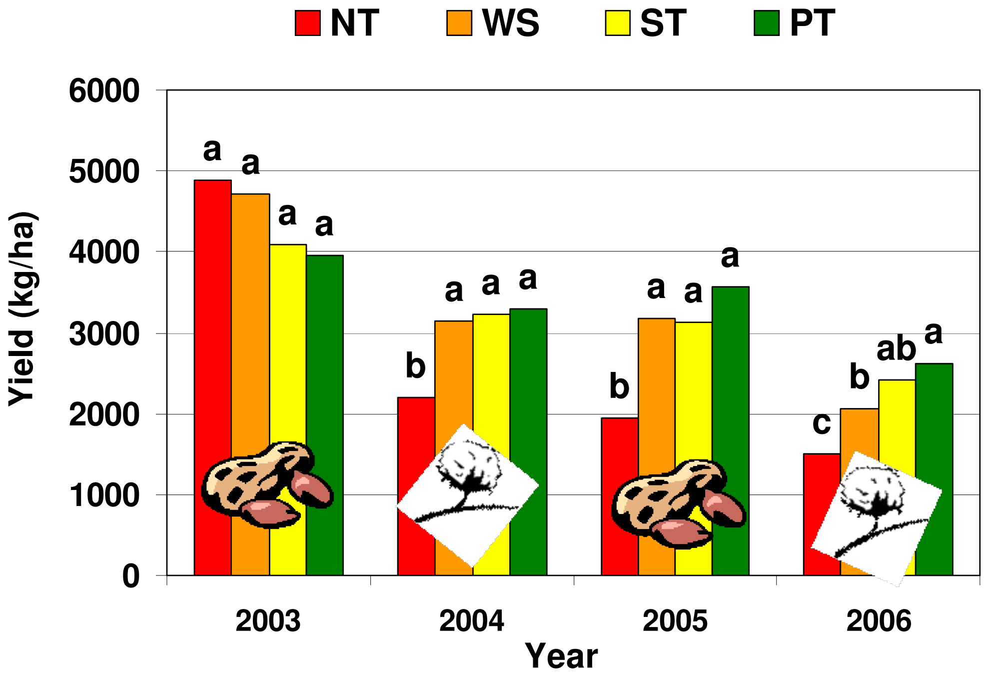

Fig. 10. Peanuts and cotton yields as affected by in-row subsoiling. Letters indicate NT-no-till; WS- Worksaver; ST- strip-till; PT- Paratill. Different lower case letters indicate statistical significance $LSD_{(0.1)}$.

II. COTTON DROUGHT TOLERANCE AS INFLUENCED BY TILLAGE AND COVER CROP

ABSTRACT

Conservation tillage practices have proven advantageous over conventional tilled systems, however, some soils have limitations to the adoption of strict no-till. In the Southern Coastal Plain, subsoil compaction presents a major restriction to root system development thereby depressing yields and requiring mechanical disruption of hardpans. We evaluated 4 different tillage treatments combined with rye *(Secale cereale L.)* cover crop or winter fallow. Soil quality indicators (soil carbon, bulk density, hydraulic conductivity, soil water content) and plant productivity were compared to determine the best management alternative. Additionally, a severe drought during the 2006 cotton (*Gossypium hirsutum L.)* growing season allowed the conservation systems to be evaluated for their ability to increase drought tolerance. In-row subsoiling and rye cover crop increased cotton productivity. The cover crop effectively increased soil water content up to 29% during the growing season compared to fallow treatments. In-row subsoiled treatments averaged bulk density was 1.53 and 1.55 Mg m^{-3} at 15 and 25 cm depth while no-till plots averaged 1.65 and 1.77 Mg m^{-3}, respectively. In-row subsoiled increased more than 100% the hydraulic conductivity of saturated soil compared to no-till plots. These results showed the necessity off in-row subsoiling and cover crops to reduce risk and increase drought resistance on compacted and weathered southern Ultisols.

INTRODUCTION

Soil quality is basically defined as soil's ability to execute specific functions (agricultural, environmental, and social). For agricultural purposes, this is the capacity to sustain or enhance productivity while maintaining soil resources for the future (Shukla et al., 2006). It is becoming evident through numerous studies that comprehensive indicators of soil quality have to include: organic matter, hydraulic characteristics, density, permeability (porosity) and soil stability to erosion (Reynolds et al., 2007).

Increased soil quality and satisfactory productivity can be obtained with conservation tillage systems which are based on the maintenance of surface residue (>30%) and minimal soil profile disruption, which improves structural development (ASAE Standards, 2005).

Winter cover crops can alleviate compaction, increase surface organic matter, reduce erosion, improve weed control, break synchronism of plant diseases and pests, and change water soil water dynamics (infiltration, conductivity, and storage) (Fabrizzi et al., 2005; Raper et al., 2000; Marois and Wright, 2003; Lampurlanes and Cantero-Martinez, 2006). However soil, climate and plant specific conditions will require customization of each system.

The majority (85 %) of crop production is done under dryland conditions (EPA, 2008), so a successful strategy of crop rotation has to carefully consider water management issues. In the southeastern Coastal Plain, the high mean annual temperature coupled with low water holding capacity of most soils (Busscher et al., 2006) can cause moisture stress to crops when rainfall is absent for more than 2 weeks (Sadler and Camp, 1986). Crop productivity was decimated across the Southeast U.S. in 2006 and 2007 when drought reached exceptional levels expected only once every 50 years (U.S Drought Monitor, 2007). This caused devastating economic losses in 2007 when the government of Alabama classified 88% of the corn, 85% of soybeans and 74% of the cotton crops to be rated as poor or very poor (WSWS, 2007). Even though such a severe drought is not likely to happen frequently, water stress is not a new issue on cotton production and different scientific approaches have been used to address the problem. For example: genetic improvement of varieties and seedling treatment with mepiquat chloride to accelerate root growth and increase water absorption (Xu and Taylor, 1992; Quinsberry et al., 1981; Basal et al., 2005).

Despite the well documented benefits of cover crops in conservation tillage systems, few studies have established the impact of winter cover on improving drought resistance. We believe that with proper management of tillage and winter cover crops, drought impacts can be lessened.

Our study objective was to evaluate different conservation tillage systems (no-till versus annual subsoiled) with and without a cover crop and determine its efficacy on alleviating drought stresses in cotton production. Results are presented by selected soil properties (bulk density, soil water content, hydraulic conductivity, and soil carbon content) and cotton productivity under the dry growing season of 2006.

MATERIAL AND METHODS

Study site

This study was conducted at Wiregrass Research and Extension Center (WGS) (31°21'N, 85°19'W) located in Headland, AL in Henry County which is the southeastern part of the state. The 0.4 ha site consists of a Dothan soil series on a 0 to 1% slope and has been cropped for many years under conventional tillage. The soil is classified as Dothan sandy loam (fine loamy, kaolinitic, thermic Plinthic Kandiudult), which are deep and well drained. This soil series is extensive and is distributed throughout the Coastal Plain of Alabama, Florida, Georgia, North Carolina, South Carolina, and Virginia. These soils are low in organic matter and natural fertility, but they can be easily tilled, respond to improved management, and are well suited to row cropping (NRCS, 2008). The climate for this area is humid subtropical, with a mean annual air temperature of 18° C and 1400-mm annual precipitation.

The experimental design was a split-plot with four replications. Main plots were represented by the rye *(Secale cereale L.)* winter cover crop (cover or no cover), and subplots were the four in-row subsoiling treatments (no-till and three in-row subsoilers). Each plot had 4 (8m long) rows spaced at 0.92 m. In-row subsoiling was implemented at 38 cm depth using the following implements: Ripper-Stripper[2] strip-till (Unverferth Manufacturing Co, Inc., Kalida, OH); Paratill (Bigham Brothers, Inc., Lubbock, TX); and Terramax Worksaver (Worksaver Inc., Litchfield, IL).

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[2] The use of company names or trade names does not indicate endorsement by Auburn University or USDA-ARS.

Rye cover crop was sprayed with 2.3 l/ha of glyphosate and mechanically terminated using a spiral blade roller-crimper (Raper et al., 2004) two weeks prior to spring planting. To ensure correct row position a Trimble AgGPS Autopilot (Trimble, Sunnyvale, CA) steering system was used for subsoiling and planting. The variety of cotton planted was the transgenic Delta Pine 555 BG/RR stacked. Cotton was planted with a seeding rate of 11.5 seeds/meter (116,000 plants/hectare) and received 100 kg/ha of nitrogen, 100 kg/ha of potassium and 22 kg/ha of sulfur. It is relevant to add that samples collected in 2006 reflect tillage and cover treatment effects over a 4 year period of experiment.

Data collection

Soil Moisture

Volumetric water content (Wv) was measured using the dielectric soil moisture sensors (Decagon Devices Inc, Pullman WA). These probes were connected to an EM5 data logger (Decagon Devices Inc, Pullman WA) recording hourly moisture values for the 2006 growing season. Probe readings collected for the 2006 cotton crop from June to August were converted to Wv using a calibration equation obtained for our study soil ($Wv = 0.000401 * \text{reading} - 0.234$) (Decagon Devices Inc, Pullman WA). These probes were 20cm long and were placed below the planting row at a 45 degree angle to a depth of 35cm from soil surface, so reading depth was from 28 to 42 cm.

Bulk Density

The in-row subsoiling was applied on spring and samples were taken after the autumn harvest in 2006. A tractor-mounted, hydraulically-driven (Raper et al., 1999) soil sampling unit was used to obtain measurements of bulk density at 5cm depth increments following harvest of the 2006 crop. A total of 45 cores per plot were taken at three positions: (i) in-row, (ii) trafficked middle and (iii) nontrafficked. Within each position, soil bulk density values were taken at the following depths: (i) 0-5 cm; (ii) 5-10 cm; (iii) 10-15 cm; (iv) 20-25 cm and (v) 30-35 cm. These soil cores were then oven dried at 105°C until constant weight.

Cotton Leaf Temperature

The temperature of the uppermost fully extended leaf was recorded weekly at cotton blooming (July to August 2006).A Raynger MX (Raytek Corporation, Santa Cruz, CA) hand-held infrared thermometer was used. Leaf temperature can be correlated to plant moisture stress and consequently performance and productivity (Pettigrew, 2004).

Crop Yield

Harvesting of cotton consisted of picking the two center rows of each plot with a John Deere 9910 (Deere & Company; Moline, IL) two row spindle harvester with a bagging attachment. The bags content were then weighed and seed cotton yield was calculated.

Hydraulic Conductivity of Saturated Soil

A constant head well permeameter was used to read hydraulic conductivity of saturated soil (K_{sat}) (Amoozegar, 1992). In each plot three 7.6cm diameter in-row holes were dug to a 40 cm depth using a bucket auger. Inside each hole, water level was kept at 20 cm below the soil surface, so the depth of reading was from 20 to 40 cm. These readings were used to calculate K_{sat} with the Glover equation (Amoozegar, 1992). Averages were then taken establishing a single K_{sat} value per plot.

Soil organic carbon and total nitrogen content

Sampling was conducted after harvest in fall 2006 with a total of 45 cores per plot taken at three positions: (i) in-row, (ii) trafficked middle and (iii) nontrafficked. Within each position, soil cores were taken at the following depths: (i) 0-5 cm; (ii) 5-10 cm; (iii) 10-15 cm; (iv) 20-25 cm and (v) 30-35 cm. Samples were oven-dried at 55° C , ground in a roller grinder to a 150µm particle size, and then subjected to dry combustion analysis (Yeomans and Bremner, 1991) using LECO TruSpec analyzer (Leco Corporation , St. Joseph, MI).

Data Analysis

Data were subjected to ANOVA (GLM procedure) using Statistical Analysis System (SAS Institute, 1988), where it was analyzed by year due to the crop rotation. Multiple means comparisons were conducted with Fisher's protected LSD and Least Square Means at significance level of $P < 0.1$.

RESULTS AND DISCUSSION

Soil organic carbon and total nitrogen content

Depth and position had a significant effect on soil organic carbon (SOC) and total nitrogen (TN). Soil organic carbon was not different at the traffic middle position for any depth. In-row SOC was affected by cover at 25 cm depth (fig.1), with the cover treatments averaging 0.45 g kg^{-1} versus 0.41 g kg^{-1} without rye cover crop. The no-traffic middle position was the most interesting, where interactions between cover and subsoiling were observed at 5cm ($P<0.076$) and 35cm ($P<0.054$) depths (fig.2). Total nitrogen and C/N results had no statistical difference, at any row position or depth (table 1). Total N distribution was as expected with higher concentration at the surface decreasing with depth; likewise C/N ratios were smaller with increasing depth. We could reason that similar to previous studies (Shinners et al., 1994; Villamil et al., 2006), the cover crop created more favorable environment for the cotton root growth by retaining more water, as confirmed by our data. Additionally the decaying cover crop roots could have favored SOC accumulation (fig.3). In-row subsoiling was responsible for breaking the hardpan, decreasing bulk density, and creating pore space that could be utilized by growing roots and for water storage. According to the analysis, it was not clear to state which of the factors had the greatest impact on the SOC and TN but our concentration levels were very low, < 0.5% (Rodriguez and Self, 1999). These low levels can be explained by humid subtropical conditions and land use history of highly weathered soils under long-term conventional cropping (Edwards et al., 1992; Torbert et al., 1999).

Our TN and C/N results were similar to the ones of Torbert et al. (1999), where no differences were found for TN and C/N concentrations between conventional and conservation tillage. It can be argued that our results were somewhat premature (4 years of no-till), since it has been reported that, little to no detectable increase in SOC would occur in the first 2–5 years after switching to conservation tillage (Franzluebbers and Arshad, 1996). On the other hand, these findings concur with the results of Eghball et al. (1994) when less intensive tillage with residue management practiced for extended periods of time has been shown to increase SOC concentrations near the surface. Also, we found no difference between in-row subsoiled and strict no-till treatments, conflicting with the results of Kern and Johnson (1993) where no response on SOC was found for reduced tillage compared to conventional tillage.

Bulk Density

Soil bulk density (Bd) was significantly different according to row position ($P \leq 0.01$) and depth ($P \leq 0.01$). Significant differences were found for subsoiling at in-row traffic position for depths >10cm (fig. 4). No-till resulted in highest Bd values (1.64; 1.76; and 1.66 Mg m^{-3} at 15; 25; and 35cm depths respectively).These values werre above 1.6 Mg m^{-3} threshold of growth limiting Bd suggested by Daddow and Warrington (1983) for a sandy loam in most row crops. They also indicate that this limiting Bd decreases with increased amount of clay, was is the case in our plots which had 14% clay at 0-20cm depth and increased to 26% at 20-40cm depth (NRCS Soil Survey, 2008). The Ripper-Stripper strip-till had the minimum values of bulk density above 15 cm that could be attributed to its design of being a straight-leg subsoiler. The bent-leg subsoilers like the Paratill and the Worksaver were designed to cause minimal surface disturbance and may not disrupt the soil in the in-row position quite as effectively as the Ripper-Stripper strip-till.

Cover crop significantly increased bulk density below 20cm (fig.4), which was similar to results of Villamil et al. (2006), where the bulk density increase with depth was greater with winter cover crop treatments compared to fallow winter. We also considered that alternating wetting and drying cycles created by greater root activity were responsible for this increase as suggested by Bronick and Lal (2005).

No-traffic middle (fig.5) and traffic middle (fig.6) positions results followed the same trend, with no-till having highest Bd values below 15cm depth, however, significant differences were only found at 35cm depth for no-traffic middle. Cover crop effect on Bd was similar to in-row position and significant differences were found at 35cm depths for both traffic and no-traffic middle. Our results agree with those of Raper et al. (2005) (silt loam -Typic Paleudult) where no-till had the highest Bd values, however, they differ regarding the cash crop yields. In this study (sandy loam- Plinthic Paleudult), no-till produced statistically lower yields than in-row subsoiled treatments.

Soil Water Content and Hydraulic Conductivity of Saturated Soil

According to NRCS Soil Survey (2008), the field capacity of this well drained sandy loam at 25 – 45cm depth is 24.6 % by volume while its permanent wilting point is 17%. Our soil moisture results clearly showed no effect of in-row subsoiling treatment on soil moisture. Volumetric water content (Wv) means by subsoiling treatment throughout the growing season were: Strip-till (18.4%); No-till (18.8%); Paratill (19.3%) and Worksaver (20.6%). These results concur with ones of Lopez-Fando et al. (2007), when in-row subsoiling (Paraplow) increased Wv compared to no-till and residual effects were present up to 9 months after paraplowing. These results are also in part corroborated by our Bd and results where no-till exhibited the greatest compaction. Cover crop significantly increased daily volumetric water content (fig. 7). This increase ranged from 12 to 29% more water than no cover treatments.

Cover treatments accumulated 18.6% higher volumetric water content than fallow treatments during the whole crop growing period. This average difference is equivalent to 45 m^3 ha^{-1} or a 4.5 mm daily rain event, within the measured depth (28-42cm). If an extrapolation is made for a soil layer from a depth of 0-40cm the water equivalent is 128 m^3 ha^{-1} or a 12.8 mm daily rain event.

Our results differ from the ones of Fabrizzi et al. (2005) and Schwab et al. (2002) where no-till had the highest water content. Schwab et al. (2002) explained that roots under no- till condition could not colonize or grow as well as the ones where subsoiling as applied due to the increased bulk density and soil strength. Fabrizzi et al. (2005) pointed out that soil temperatures were lower under no-till during initial stages of root development, causing lower crop growth and consequently lower water use.

Even though evaporation and soil temperature readings were not taken, we believe that the cover crop had substantially diminished water loss caused by them, similarly to the findings of Fabrizzi et al. (2005). Additionally, the highly compacted (CI > 3.0MPa; Bd > 1.6g cm^{-3}) soil profile under no-till restricted normal root expansion and decreased water storage, thus reducing yields as supported by our data.

A regression analysis was conducted to establish the relation between soil moisture content and yield (table 2). However, results showed no clear correlation between cotton yield and moisture, suggesting that multiple factors were involved in yield increase provided by the use of cover crop and in-row subsoiling. The same trend was observed between K_{sat} and cotton yield, and for a multiple regression including SOC, Bd, K_{sat}, and moisture as dependent variables.

One common fear expressed by farmers is that the cover crop may lower soil moisture reserves leaving less water available for the subsequent cash crop. The solution for this issue is not standard for all farms and depends on crop, soil, and climatic conditions. In the Southeast, it is recommended to kill a rye cover crop before it matures, which is, after it begins flowering or sheds pollen (Ashford and Reeves, 2003). Also it is important to allow a window of opportunity for rainfall to replenish soil moisture reservoir. Therefore, it is recommended to kill a rye cover crop 2 to 3 weeks prior to planting the cash crop (Balkcom et al., 2007). Figure 8 illustrates this scenario. The rye cover received a substantially lower (160mm below 15 year average) rainfall amount during the months of March and April combined. As rye was terminated near the end of April, rainfall accumulated during May was able to adequately replenish soil water. In addition we believe evaporation was diminished by the flattened cover crop during the growing season, which helps to conserve soil water.

Hydraulic conductivity of saturated soil (20-40cm depth) was lower for the no-till treatment and was not affected by the cover crop (fig.9). This agrees with the reduced bulk densities and soil strength values found for the in-row subsoiled treatments regardless of implement used, also suggesting there was better soil structure under the row with these treatments allowing for better water flow and root penetration.

It is relevant to add that K_s rating for this Dothan sandy loam at 20-40 cm depth given by the NRCS Soil Survey (2008) was 43 mm h^{-1} which falls within 36 to 360 mm h^{-1} range and was classified as high. Our field measurements showed that the Paratill and strip-till fell within the same range, while the Worksaver and no-till were classified as moderate (fig.9). Reynolds et al. (2003) also proposed a K_s range of 18 to 180 mm h^{-1}, as an optimal range for agricultural production. This range of Ksat within would promote rapid infiltration and redistribution of plant available water, reduce surface runoff and erosion, and promote rapid drainage of excess water. The no-till K_s mean (17.3 mm h^{-1}) found in our study fell just a little short of the lower end of the proposed range, which may cause excessive runoff and erosion, reduced trafficability and aeration deficits caused by prolonged saturated conditions (Reynolds et al., 2007).

Our lower K_s values for no-till are in agreement with various studies but in contrast with several others. Strudley et al. (2008) presented an extensive review of tillage effects on hydraulic properties across a wide range of climates and soil types. Their review illustrated the inconsistency of results regarding tillage and residue management practices on soil hydraulic properties. Nonetheless, we reason that such a result was explained once again by the compaction or reconsolidation effects. Since K_s was heavily influenced by macroporosity, macropore volume would be drastically reduced with bulk density increases, thus reducing K_s (Mahboubi et al., 1993; Xu and Mermoud, 2001).

Cotton leaf temperature

Our leaf temperatures showed no statistical significance in three out four weeks of measurement (table 3). However, at the fourth week a cover crop effect (P<0.07) and interaction between cover and subsoiling (P<0.0008) was found (table 3). Even though statistical difference was not found for most of the readings, a trend was observed with the cover crop treatments having lower temperatures compared to the ones without the rye cover. These lower leaf temperatures can be explained by soil moisture data measured within the same growing period of the cotton crop in 2006. Cover crop treatments had 18% more volumetric water content that the ones without cover which may have contributed to a higher transpiration rate, consequently decreasing leaf temperature (table 3).

Cotton Yields

Yield results of the present study were significantly impacted by cover crop and tillage but no interaction occurred. Rye cover crop significantly increased cotton yield in 2006 by 26% (fig. 10). These findings were attributed to the higher water content found on the cover treatment (fig.7), even though a relationship between water content and yield was not found (table 3).

At the peak flowering stage (70-100 days after sowing) cotton plants are especially sensitive to water deficit and it is estimated that each stress day may result in reduction of 47 kg ha^{-1} on seed cotton yield (Hearn and Constable, 1984). Our cotton was planted on May 12, 2006 and flowering was around July 22, 2006. Observing volumetric water content during flowering (fig. 7) we noticed that the no-cover treatment had significantly lower moisture and the values were close to the suggested permanent wilting point for the Dothan soil (17%).

In the period of April to October (fig. 11) 2006, the cumulative precipitation was 505 mm which is 28% below the minimum requirement for cotton (700 mm; Brouwer, 1986). In addition, greater water content might have promoted lower soil strength allowing for superior root growth, exacerbating the effect of cover.

Yield increase promoted by in-row subsoiling can be attributed to reduction in bulk density and increase on K_{sat}. However, in-row subsoiling effects won't persist longer than a year in our climatic and edaphic conditions, revealing the necessity of annual in-row subsoiling.

Cotton yield average across all in-row subsoiled treatments (2110 kg ha^{-1}) was above the Alabama state average of 1850 kg ha^{-1} for 2006, while no-till yielded 2190 and 1500 kg ha^{-1}, respectively (NASS, 2008).

CONCLUSIONS

The cover crop only increased SOC near the surface (0-5cm) while in-row subsoiling only increased SOC at the 35cm depth. These results suggest that improvements in soil C in these soils only result with the combined use of in-row subsoiling and cover crops.

In-row subsoiling effectively reduced soil compaction as measured by bulk density and increased K_{sat}. Consequently, cash and cover productivity were also increased by in-row subsoiling regardless of the implement model.

The cover crop increased volumetric soil water content. During an especially dry year in 2006, the cover crop was responsible for significantly increasing cotton yields. Cotton leaf temperature was lower with cover crop treatment, suggesting a better hydration status in these plants compared to the no-cover treatment.

Cover crop and in-row subsoiling can effectively reduce the impact of drought and increase yields. This was illustrated by improved structure provided due to in-row subsoiling, increased water retention and surface organic matter provided by cover crop roots and the surface residue. Therefore, in southern Coastal Plain soils both management practices should be combined to minimize risk and increase yield.

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Table 1. Dothan sandy loam mean TN (total nitrogen) concentration and C/N ratio in 2006 as affected by depth. Means are averaged across tillage and cover treatments.

	No-traffic		In-row		Traffic middle	
Depth(cm)	N (g kg^{-1})	C/N	N (g kg^{-1})	C/N	N (g kg^{-1})	C/N
0-5	0.47	16	0.47	16	0.45	16
5-10	0.40	16	0.40	16	0.37	16
10-15	0.35	15	0.35	18	0.31	17
20-25	0.35	14	0.35	16	0.30	17
30-35	0.32	14	0.32	13	0.32	14

Table 2. Relationships between soil parameters and cotton yield in 2006.

Dependent Variable	Independent Variable	P>F	R^2
Yield	1609.9 + 28.01(Moisture)	0.533	0.02
Yield	2110.4 + 510.18(Log10 Ksat)	0.866	0.01
Yield	7015.08 - 3266(Bulk Density)	0.085	0.10
Yield	253.8+ 3694.8(SOC)	0.039	0.13

Table 3. Mean cotton leaf temperature 2006 at close to solar noon (from 11:00 to 1:00 PM) as affect by interaction between cover crop and subsoiling (above) and by cover crop by week (below). Different letters indicate statistical significance.

Cover	**Implement**	**Mean (°C)**
No	Paratill	31.5 a
No	Worksaver	30.8 b
No	Strip-till	30.8 b
Rye	No-till	30.7 b
No	No-till	30.4 bc
Rye	Worksaver	30.0 cd
Rye	Strip-till	29.4 de
Rye	Paratill	29.2 e

	Cover	**No-cover**	
Date	T (°C)	T (°C)	$LSD_{(0.1)}$
20-Jul	34.9	36.1	ns
28-Jul	33.3	34.6	ns
7-Aug	31.8	32.1	ns
17-Aug	29.9	30.9	0.3

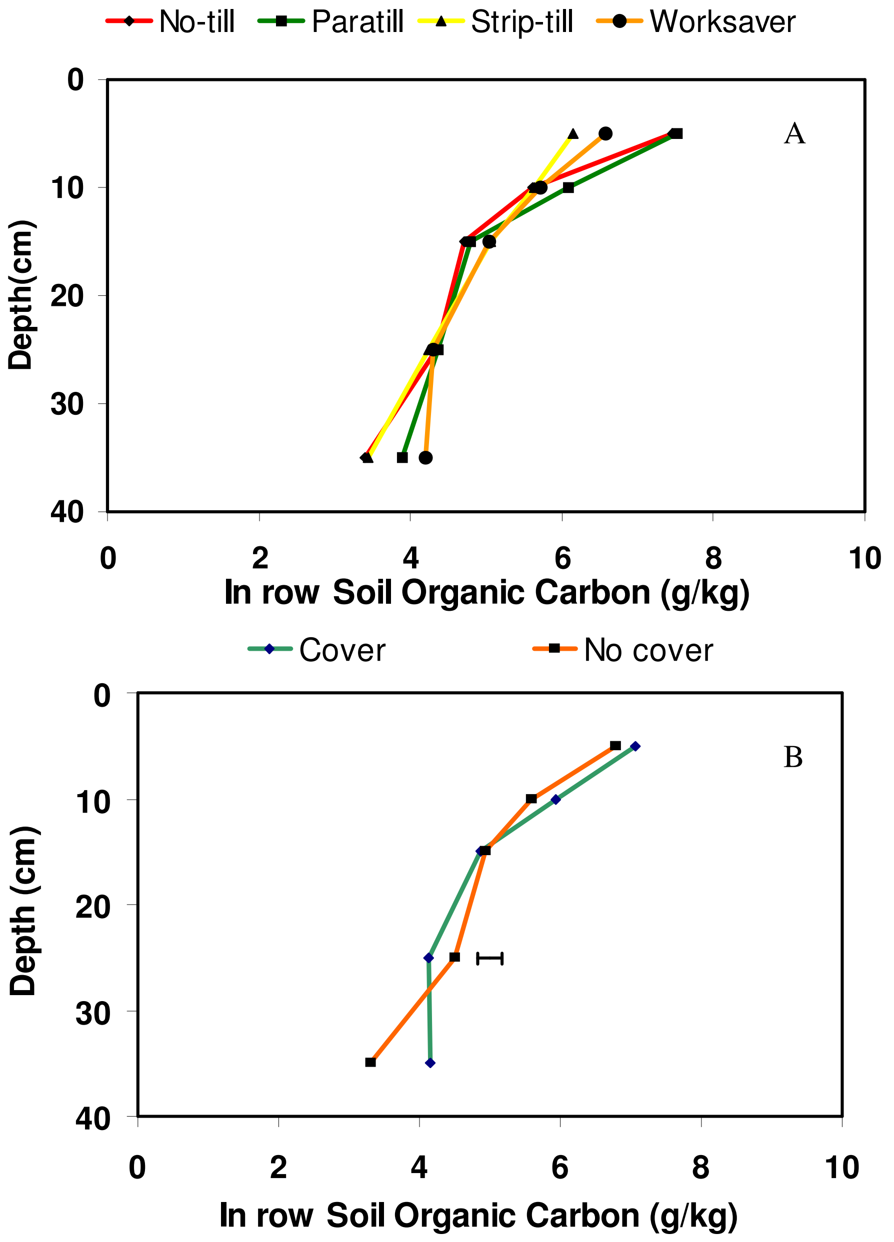


Fig. 1. SOC at in-row position concentration as affected by tillage (A) and cover crop (B) treatments in 2006. Horizontal error bars indicate statistical significance LSD $_{(0.1)}$.

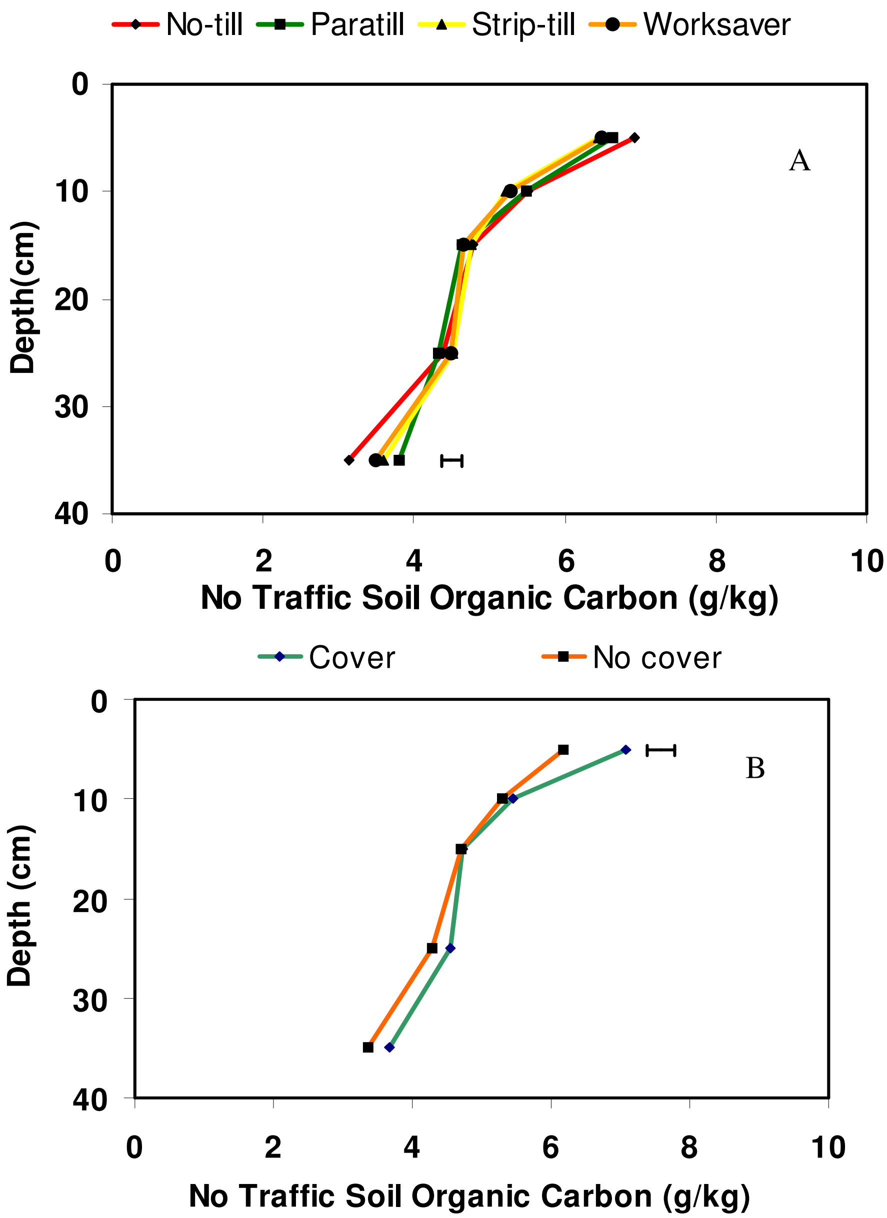


Fig. 2. SOC at no-traffic middle position concentration as affected by tillage (A) and cover crop (B) treatments in 2006. Horizontal error bars indicate statistical significance $LSD_{(0.1)}$.

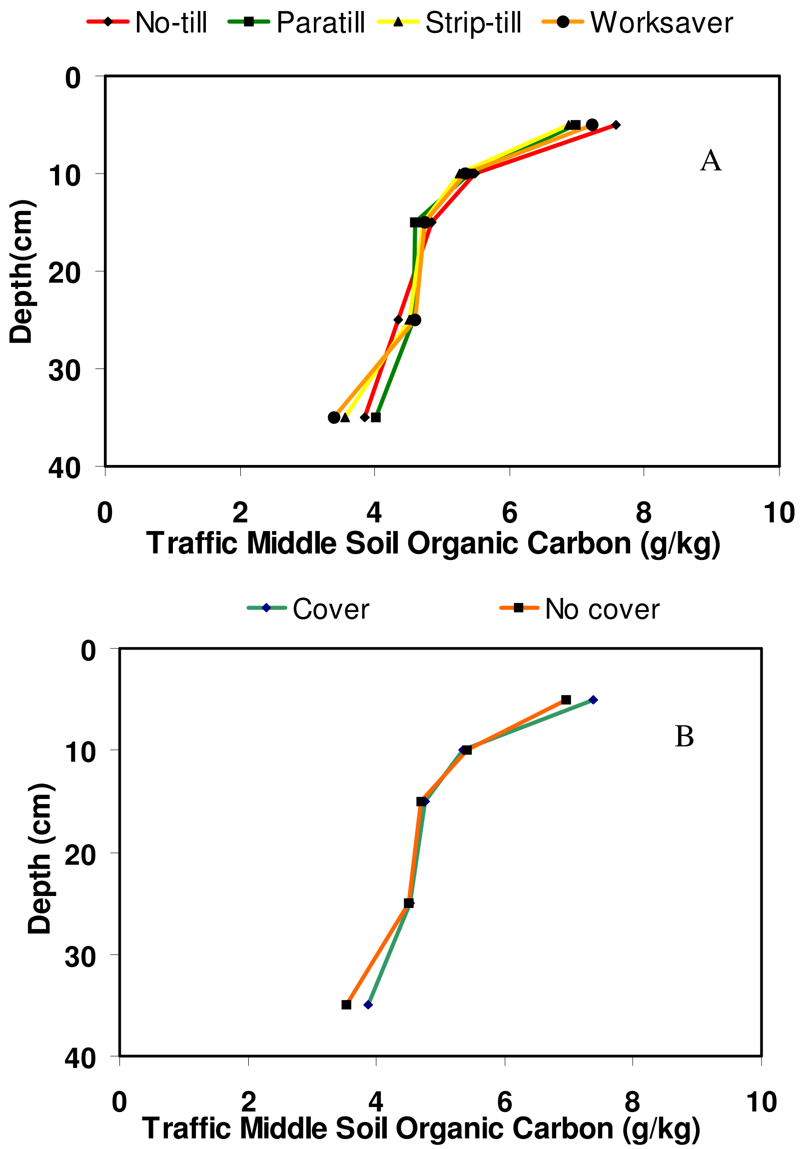


Fig. 3. SOC at traffic middle position concentration as affected by tillage (A) and cover crop (B) treatments in 2006. Horizontal error bars indicate statistical significance $LSD_{(0.1)}$.

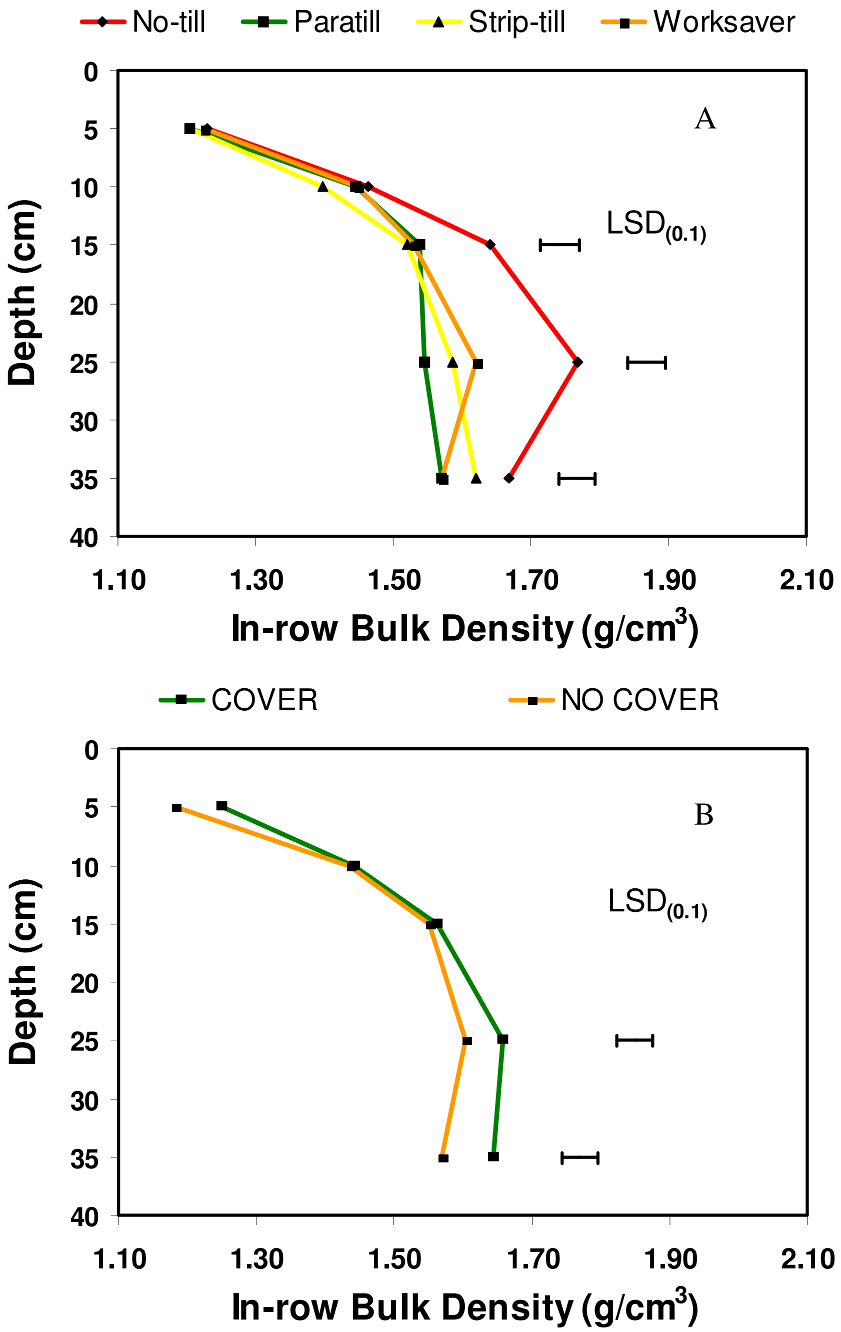


Fig. 4. Soil bulk density at in-row position as affected by tillage (A) and cover crop (B) treatments in 2006. Horizontal error bars indicate statistical significance LSD$_{(0.1)}$.

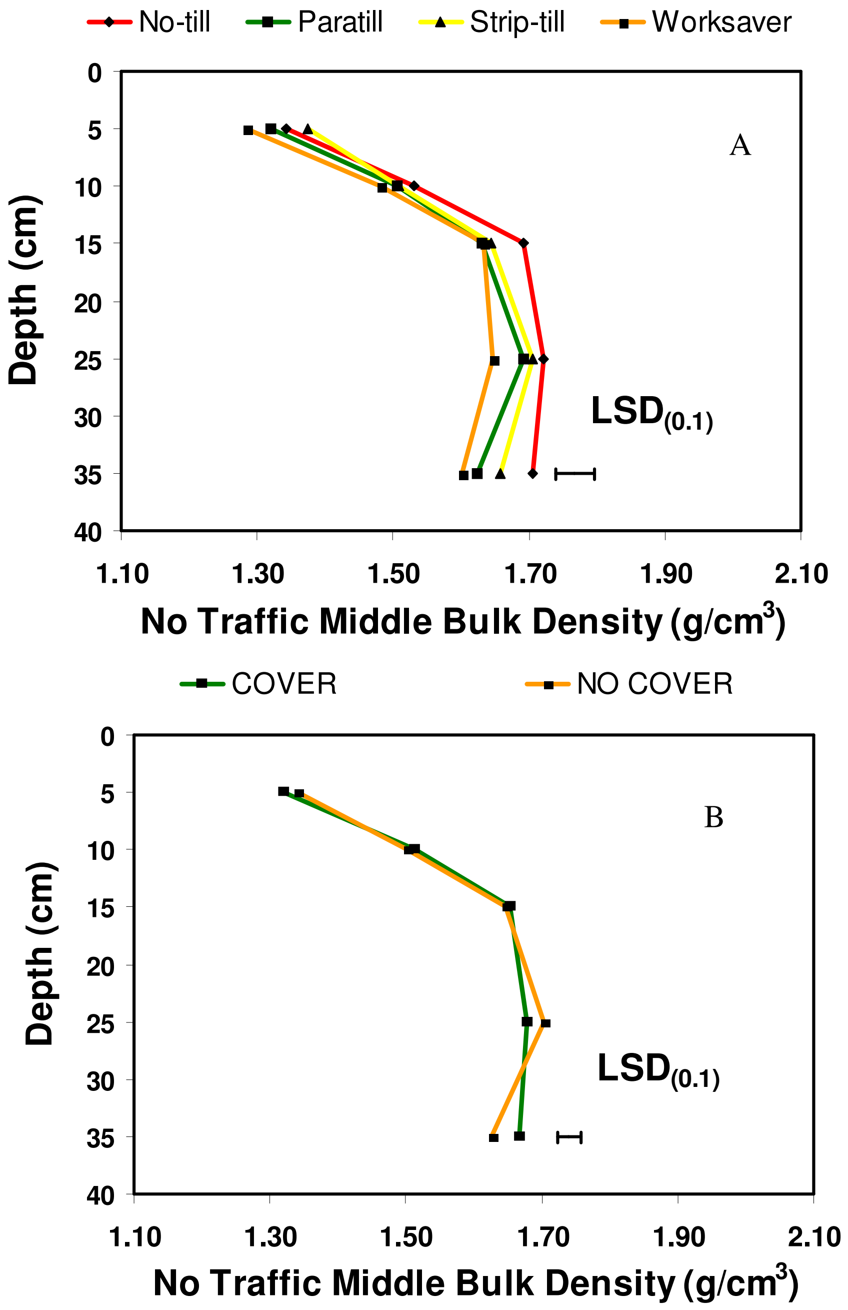
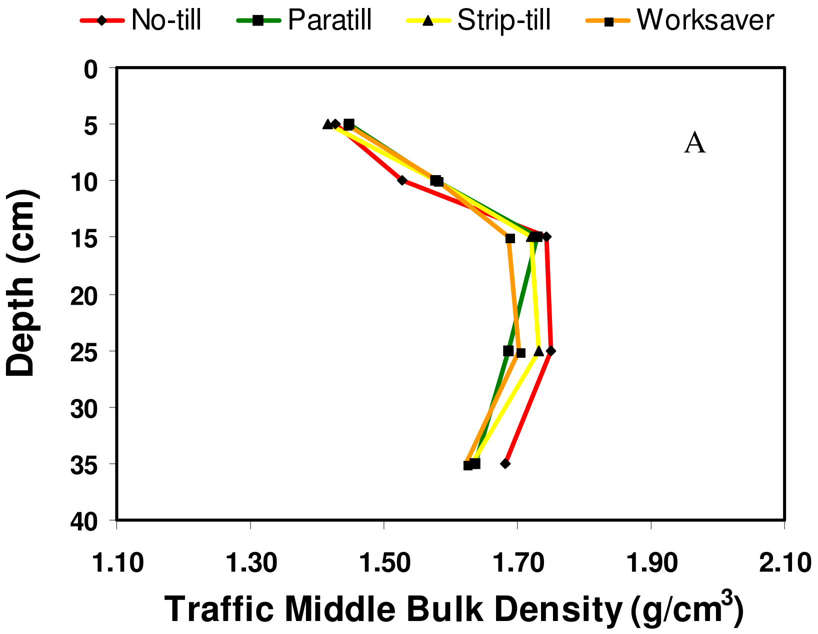


Fig. 5. Soil bulk density at no-traffic middle position as affect ed by tillage (A) and cover crop (B) treatments in 2006. Horizontal error bars indicate statistical significance LSD$_{(0.1)}$.



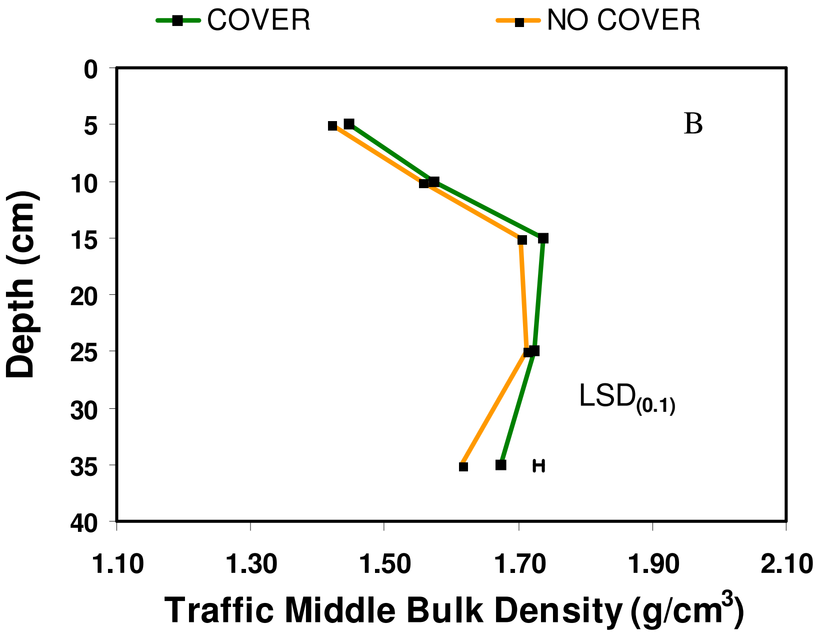


Fig.6. Soil bulk density at traffic middle position as affect by tillage (A) and cover crop (B) treatments in 2006. Horizontal error bars indicate statistical significance $LSD_{(0.1)}$.

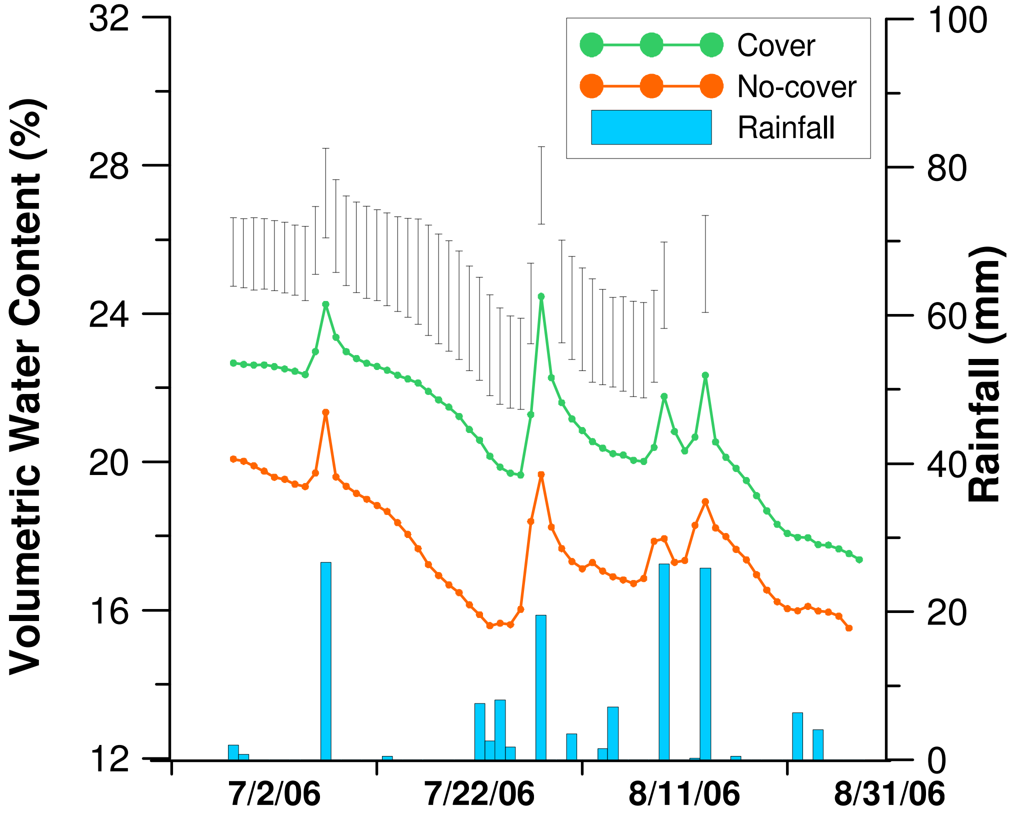


Fig. 7. Soil moisture content of a Dothan sandy loam (at 35cm depth) as affected by cover crop treatment during cotton growing season 2006. Vertical error bars represent $\mathrm{LSD}_{(0.1)}$.

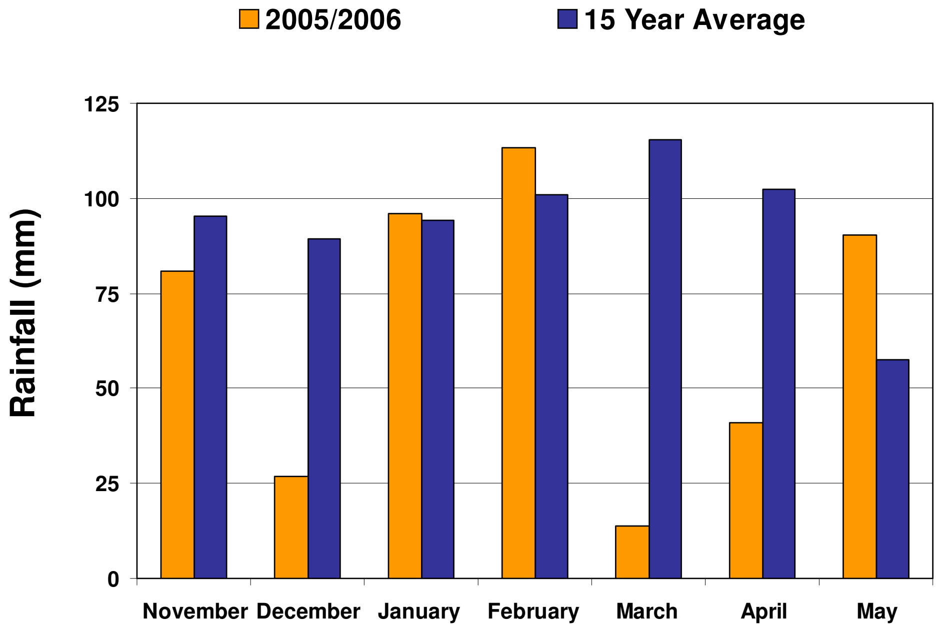


Fig. 8. Monthly precipitation during rye growing season 2005/2006 at Wiregrass research and extension center in Headland, AL.

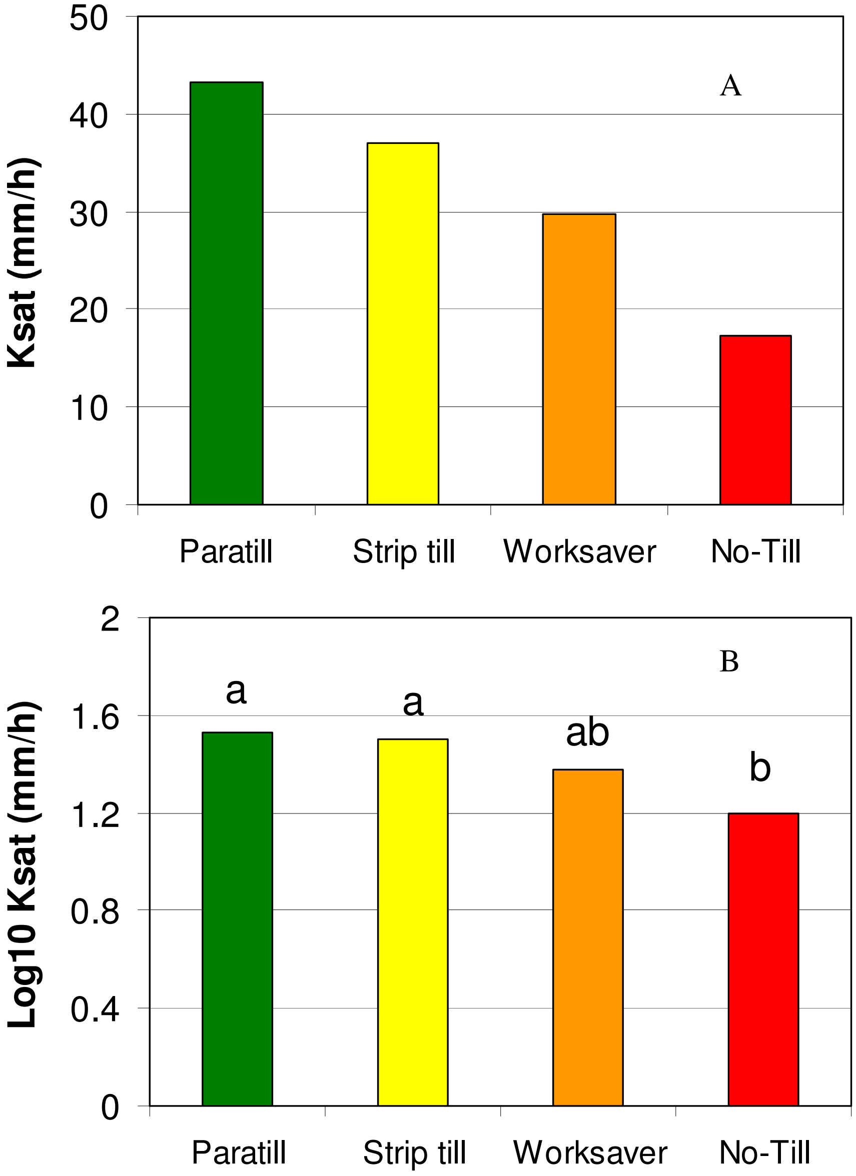


Fig. 9. Hydraulic conductivity of saturated soil Ksat (20 to 40 cm depth) as affected by tillage treatment in 2006. Tillage treatment means (A) and Log 10 of the same means (B). Log transformation required due the high variability of original data. Letters indicate $LSD_{(0.10)}$.

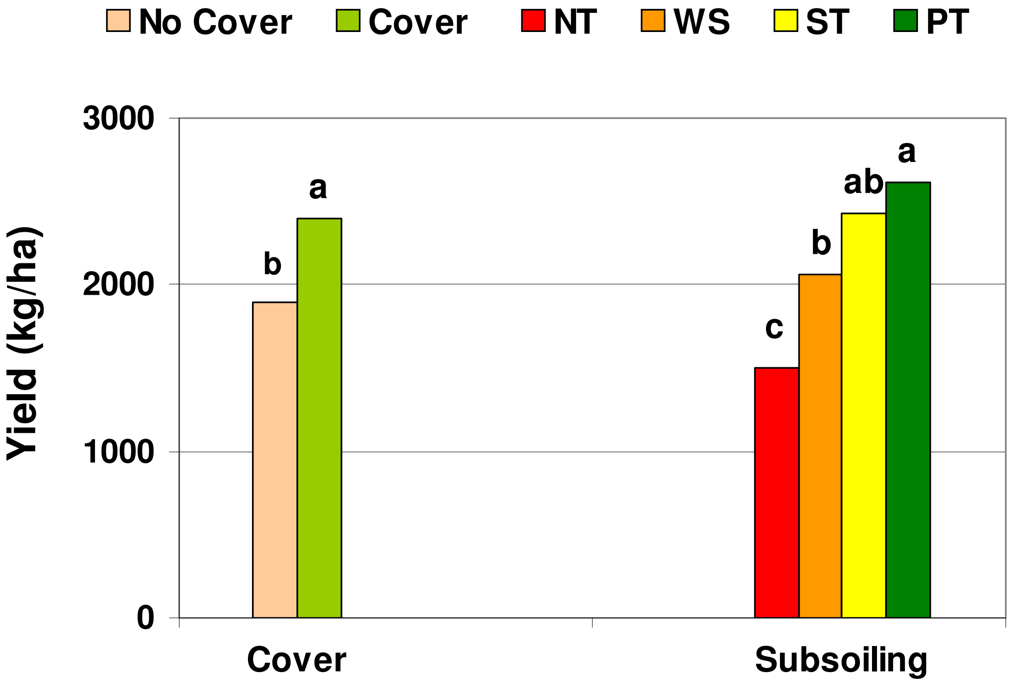


Fig. 10. Seed cotton yields as affected by cover and in-row subsoiling in 2006. Letters indicate NT-no-till; WS- Worksaver; ST- strip-till; PT- Paratill. Lower case letters indicate $LSD_{(0.1)}$.

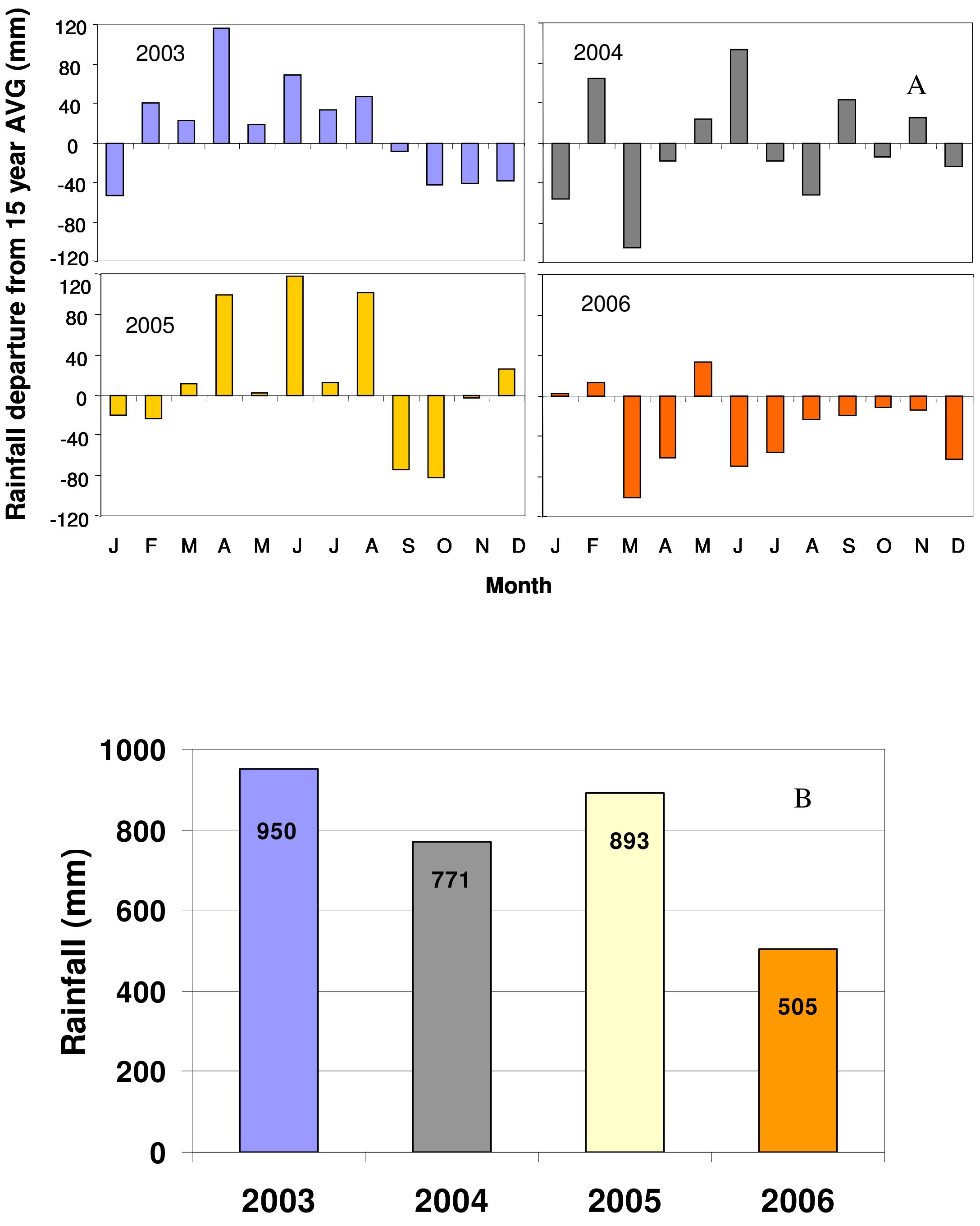


Fig. 11. Rainfall departure from 15 year average (A) and cumulative rainfall from April to October (B) for each experiment year at Wiregrass Research Station, Headland Alabama.