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# Using conservation systems to alleviate soil compaction in a Southeastern United States ultisol☆

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ABSTRACT

Coastal Plain soils are prone to compaction layers 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 the cost of the operation. We evaluated three subsoiling implements against a non-subsoiled treatment with and without a rye (*Secale cereale* L.) cover crop on a 4-year cotton (*Gossypium hirsutum* L.)–peanut (*Arachis hypogaea* L.) rotation experiment in Headland, AL on a Dothan loamy sand (Plinthic Kandiudult). 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 (1.5–4.0 MPa) in less than a year due to natural reconsolidation and normal vehicle traffic. On average, in-row subsoiling returned $698/ha/year for cotton and $612/ha/year more for all in-row subsoiling than non-subsoiled treatments. No differences between implements were found. A conservation system consisting of annual paratilling combined with a winter cover crop proved to be the most productive and profitable system.

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## 1. Introduction

Crops grown in the Southeastern United States often suffer from short-term (2–3 week) droughts which are prevalent during the typical growing season. Coastal Plain soils found in this region are usually highly weathered, erodible, carbon-depleted, and have low water holding capacity. Research has shown, however, that conservation systems in this region can increase water retention and organic matter, and improve soil structure (Reeves, 1994; Ess et al., 1998; Raper et al., 2000).

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

However, the successful implementation of a conservation system for a cotton–peanut rotation faces several obstacles. A cotton–peanut rotation is desirable from an economic standpoint, but until the mid-1980s was not recommended in southeastern US 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 tomato spotted wilt virus that is vectored by thrips (*Frankiniella 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) and low effectiveness (Marois and Wright, 2003). Spotted wilt virus has been managed by controlling production strategies such as: choice of resistant cultivars, planting dates, increasing seeding 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.

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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 lack of 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, which represents approximately 2.5% of cotton production costs for the southeastern US.

While there is 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.

## 2. Materials and methods

### 2.1. Study site

This experiment was conducted at Wiregrass Research and Extension Center (WGS) (31°21′N, 85°19′W) located in Headland, AL which is the southeastern part of the state. The 0.4 ha site consists of a Dothan soil series on a 0–1% 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). In-row subsoiling was conducted every spring prior to cash crop planting at a 38 cm depth using the following implements: Ripper-Stripper Strip-till (Unverferth Manufacturing Co, Inc., Kalida, OH); Paratill (Bigham Brothers, Inc., Lubbock, TX); and Terramax Worksaver (Worksaver Inc., Litchfield, IL). Each plot had 4 (8 m long) rows spaced at 0.92 m. To ensure correct row position, a Trimble AgGPS Autopilot (Trimble, Sunnyvale, CA) steering system was used for subsoiling and planting.

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. 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 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/m (116,000 plants/ha) 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/m (197,000 plants/ha) and received no fertilization. Peanuts are typically rotated with cotton because of disease pressures.

### 2.2. Data collection

#### 2.2.1. 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 in-row subsoiling and planting in 2005; and 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 non-trafficked middle, and (v) 46 cm (midway) from the row in the non-trafficked middle. A cone with a base area of 130 $mm^2$ was used on each of the penetrometers (ASABE Standards, 2004a,b). Three sets of measurements were taken per plot continuously (25 data points per second) throughout the soil profile to a depth of 50 cm. The cone index data were then averaged every 5 cm for statistical analysis (SAS Institute, 1988). These data were then used to create contour graphs using Kriging point interpolation (linear variogram; Golden Software Inc., Golden, CO). Soil samples were taken from 0–15 cm and 15–30 cm and oven-dried at 105 °C until constant weight to determine soil moisture at the time of penetrometer readings.

#### 2.2.2. Crop yield

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

#### 2.2.3. 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 38 cm for all experiments.

#### 2.2.4. Cover crop biomass, total nitrogen, and carbon

Rye was sampled using 2 (0.25 m square) frames per plot. 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 1 mm sieve and sub-samples were taken to determine total N and C content using a dry combustion method with a TruSpec analyzer (Leco Corporation, St. Joseph, MI).

*2.2.5. Data analysis*

Data were subjected to ANOVA (GLM procedure) using Statistical Analysis System (SAS Institute, 1988), where they were 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 $P < 0.1$.

## 3. Results and discussion

### 3.1. Cover crop biomass

The use of a winter cover can have a positive impact on soil quality by increasing soil organic matter, aggregate stability, water retention, and consequently reducing soil bulk density and soil strength (Reeves, 1994). Our results showed 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 in 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 GDD requirements for rye 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.

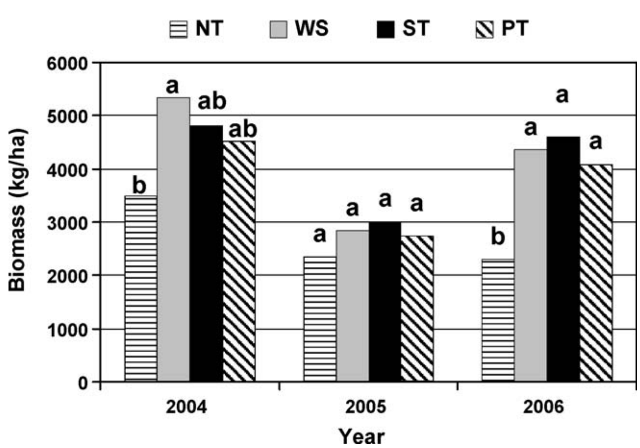


**Fig. 1.** Annual winter rye cover crop biomass production as affected by in-row susbsoiling (NT—no-till; WS—worksaver; ST—strip-till; PT—paratill). Different lower case letters indicate statistical significance $LSD_{0.1}$ within year.

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

| Month | 2003/2004* | | 2004/2005** | | 2005/2006*** | |
|---|---|---|---|---|---|---|
| | 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).

In 2006, in-row subsoiling increased cover crop production from 76% (Paratill) up to 99% (strip-till) compared to strict no-till (Fig. 1). Another important point is that in-row subsoiled plots were able to produce more than 4500 kg/ha 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 experiment. 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. (2007) 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 the 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 to 1) 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.

### 3.2. Soil strength

Position and depth factors were found to be significant ($P \leq 0.01$), therefore the analyses of variance were conducted by row position and by depth levels. Statistical significance was found 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 and 4). 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 and 4). The cover crop factor or the interaction between in-row susbsoiling and cover crop showed little significance depending on the year.

**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 | | |
| 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 |
| $LSD_{0.1}$ | 7.3 | 2.1 | 3.2 |

**Table 3**
Significance level of cover crop, tillage, and their interactions on soil strength by row position (Spring 2005). Letters indicate cover (C), subsoiling (S) and interaction cover × subsoiling (C × S). Numbers in bold are significant at the 0.1 significance level.

| Depth | No-traffic | | | In-row | | | Traffic | | |
|---|---|---|---|---|---|---|---|---|---|
| cm | *P*-value | | | | | | | | |
| | C | S | C × S | C | S | C × S | C | S | C × 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 | 0.48 | 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 |

The CI means were plotted on contour graphs establishing penetration isolines or lines of equal resistance (Figs. 2–4). Moisture at time of CI measurement showed little variation range among treatments; the differences were attributed to treatment effects. Moisture at time of CI sampling is presented by depth (Table 5). 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 from 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 (Figs. 2–4). It is important to notice that we have two sets of readings for 2006 (Figs. 3 and 4). The first one shows CI values after terminating the rye cover on 2006, 11 months after the 2005 readings (Fig. 2). 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 (3–4 fold) after this period, with much of the area above 2 MPa. Even for the no-till treatment an enlargement of the compacted layer occurred, also there were no significant differences among treatments (Table 4). Another set of CI data for 2006 (Fig. 4) taken 1 day after the first set of readings (Fig. 3) illustrates how in-row subsoiling breaks most of the compacted profile significantly reducing CI values (Table 4). These results show the necessity of in-row susbsoiling and how reconsolidation happens in warm, humid conditions combined with highly weathered C depleted soils.

**Table 4**
Significance level of cover, tillage, and their interactions on soil strength by row position during Spring 2006, before and after tillage. Letters indicate cover (C), subsoiling (S) and interaction (C × S). Numbers in bold are significant at the 0.1 significance level.

| Depth | No-traffic | | | In-row | | | Traffic | | |
|---|---|---|---|---|---|---|---|---|---|
| cm | *P*-value | | | | | | | | |
| | C | S | C × S | C | S | C × S | C | S | C × S |
| Before tillage | | | | | | | | | |
| 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 |
| After tillage | | | | | | | | | |
| 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 5**
Mean gravimetric water content (GWC) of the soil (Dothan sandy loam) at the time of penetrometer readings by depth.

| Depth (cm) | Year | | | |
|---|---|---|---|---|
| | 2003 Fall | 2004 Fall | 2005 Spring | 2006 Spring |
| | GWC (kg/kg) | | | |
| 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 |

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).

### 3.3. Tillage energy

Drawbar power results were not significantly different by year or cover crop. Therefore, 2005 and 2006 data were pooled to produce drawbar power means by implement. The results showed statistical significance with the Paratill having lower power requirements of 7.75 kW/shank compared to Strip-till (8.61 kW/shank) and Worksaver (8.94 kW/shank) and 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 10.1 kW/shank, respectively. These differences can be explained mainly by different speeds of operation since soil type and moisture conditions were similar to our experiment. Our speed was maintained at 4 km/h while the other two experiments had speed targeted to 7 km/h.

All other energy parameters were analyzed by year, as this factor was significant (Table 6). 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,b).

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.

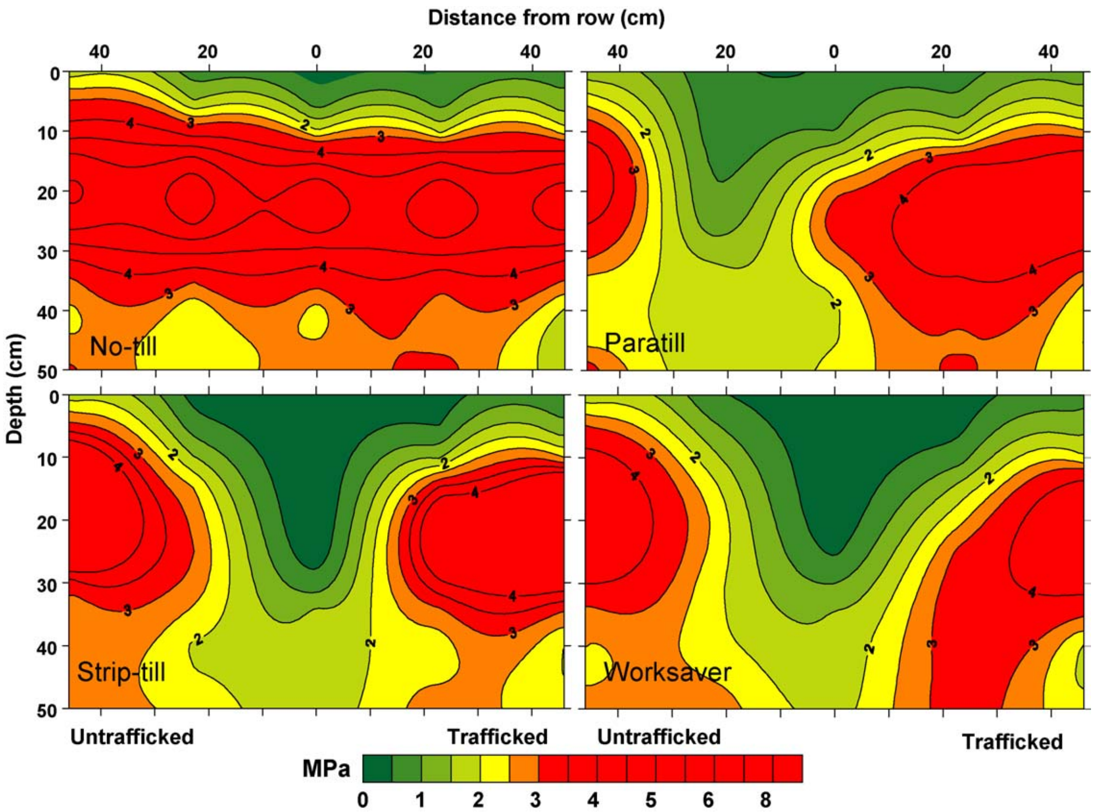


**Fig. 2.** Spring 2005 soil strength of a Dothan sandy loam in southeastern AL after planting the peanut crop. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

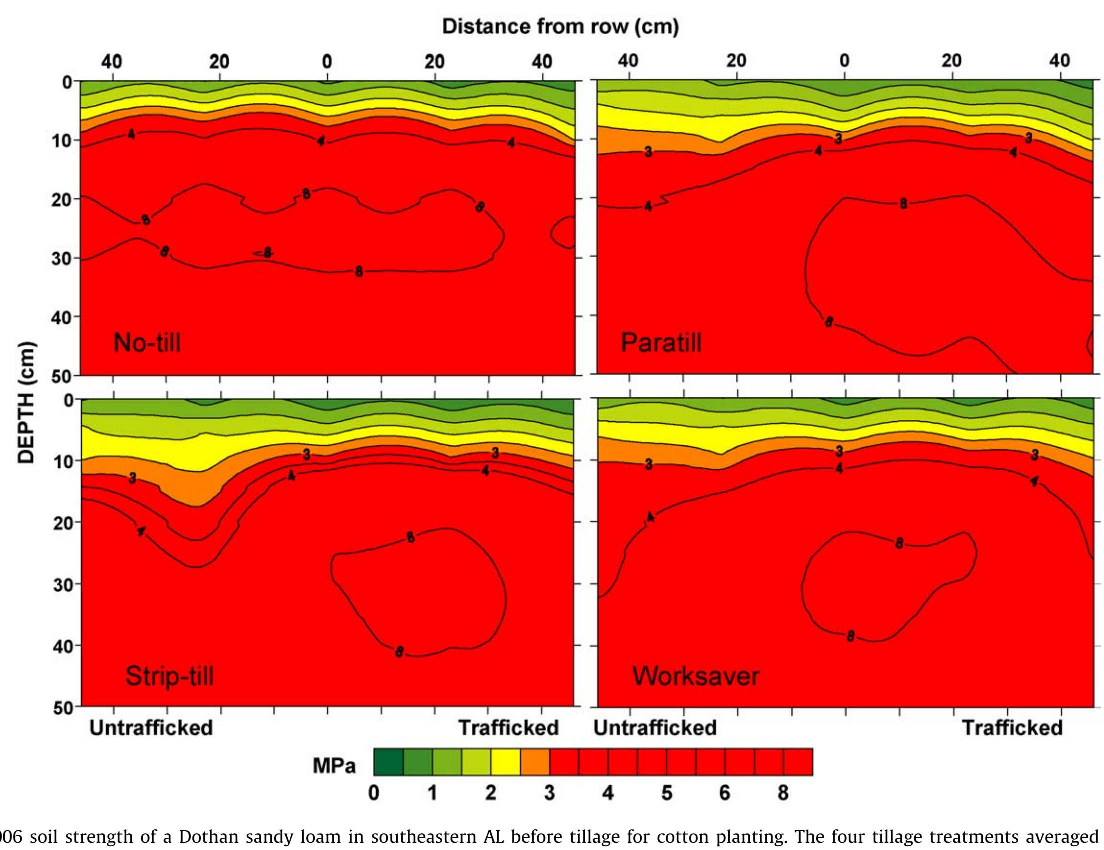


**Fig. 3.** Spring 2006 soil strength of a Dothan sandy loam in southeastern AL before tillage for cotton planting. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

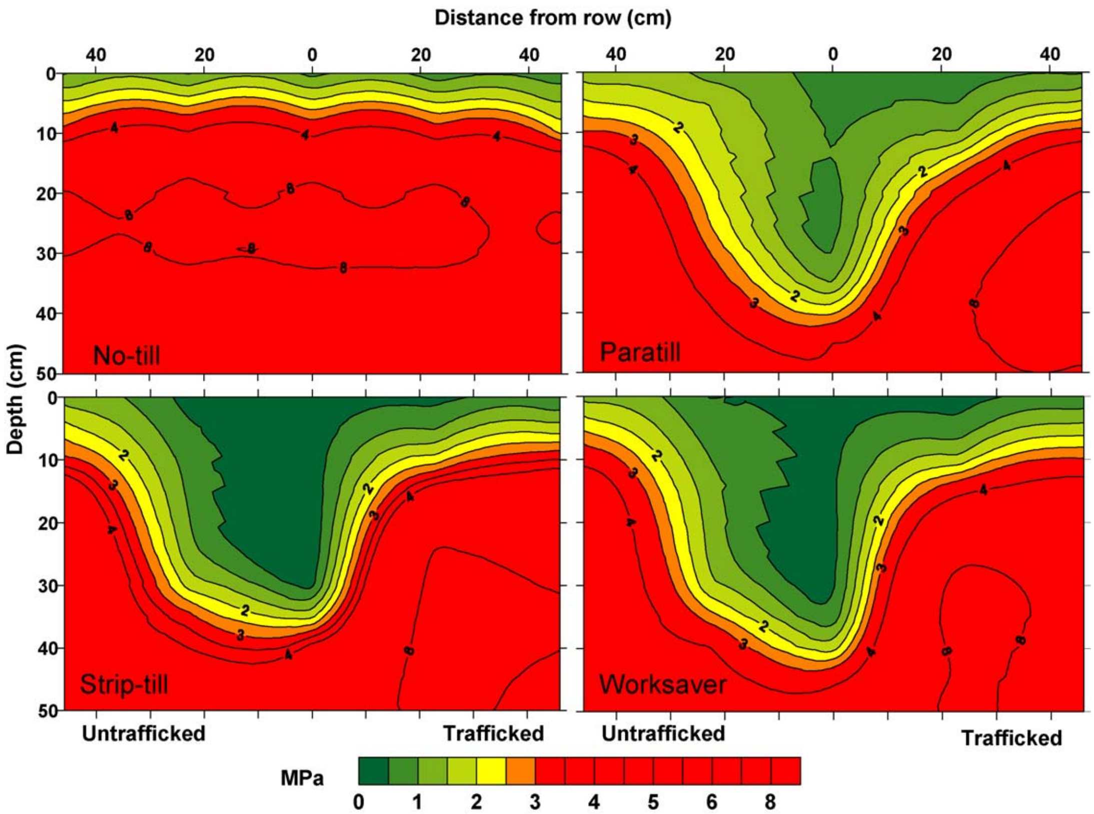


**Fig. 4.** Spring 2006 soil strength of a Dothan sandy loam in southeastern AL after tillage for cotton planting. The four tillage treatments averaged across cover crop treatments as influenced by row position and depth. Isolines created by Kriging interpolation.

### 3.4. 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 two 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. 5). 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 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.

**Table 6**
Draft, vertical and side forces means by subsoiler for 2005 and 2006. Means are averaged across cover crop treatment. Letters indicate statistical significance.

| Implement | Draft (kN) | | Vertical (kN) | | Side (kN) | | Speed (km/h) | |
|---|---|---|---|---|---|---|---|---|
| | Year | | | | | | | |
| | 2005 | 2006 | 2005 | 2006 | 2005 | 2006 | 2005 | 2006 |
| Paratill | 26 a | 37 | 2.9 b | −1.1 c | 0.7 | 0.6 | 4.0 | 3.2 a |
| Strip-till | 31.4 b | 40 | 14.1 a | 11.6 a | 0.6 | 0.4 | 4.0 | 3.1 b |
| Worksaver | 30.5 b | 40.1 | 3.8 b | 1.4 b | 0.7 | 0.9 | 4.2 | 3.2 a |
| $LSD_{0.1}$ | 2.7 | ns | 1.0 | 0.8 | ns | ns | ns | 0.04 |

During 2006, a severe drought hit the Southeastern states and Alabama farmers suffered great losses. In the period of April to October 2006 (Fig. 6), 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. 7). 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 950 mm

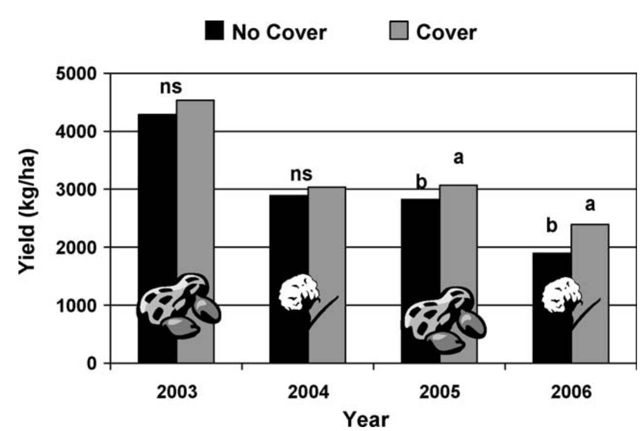


**Fig. 5.** Peanuts and cotton yields by year as affected by cover crop on a Dothan sandy loam in southeastern Alabama. Different letters indicate $LSD_{0.1}$.

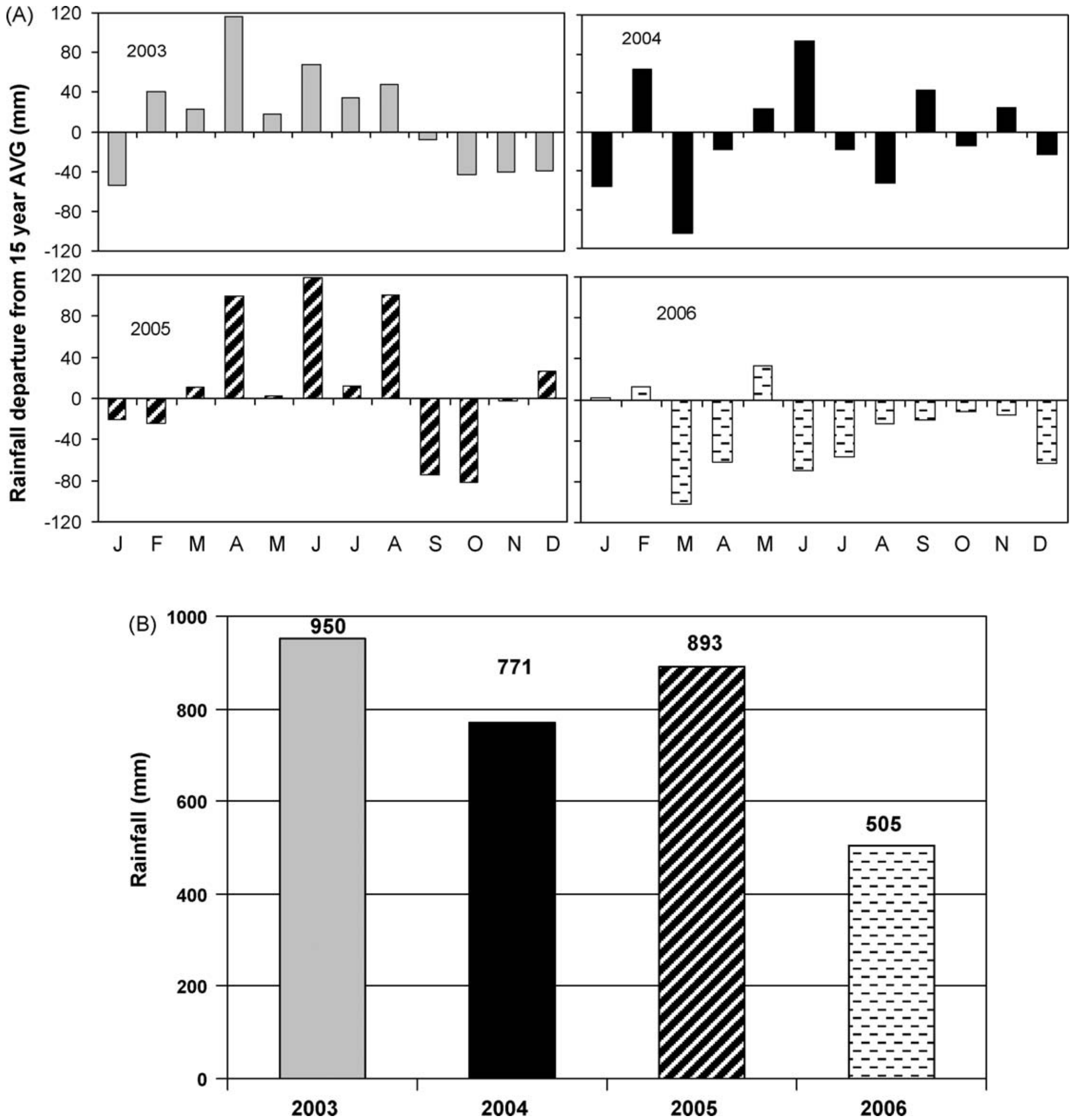


**Fig. 6.** Rainfall departure from 15 year average (AVG) (A) and cumulative rainfall from April to October (B) for each experiment year at Wiregrass Research Station, Headland Alabama.

(Fig. 6). Optimal peanut production water requirements are normally approximately 500–750 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. 7). Yield increases can be attributed to reduced soil strength. However, as seen in the soil strength results, the benefits of in-row 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. Our 2003 yields were at least 1000 kg/ha greater for all treatments. In 2005, only the in-row subsoiled treatments produced yields above 3080 kg/ha, while no-till yielded 1145 kg/ha less than state average. Average cotton yield for all in-row subsoiled treatments (3220 and 2110 kg/ha) were above the state average of 2300 and 1850 kg/ha for 2004 and 2006, while no-till yielded 2190 and 1500 kg/ha respectively. It is important to note that the state averages cover a diverse set of soil and climate conditions.

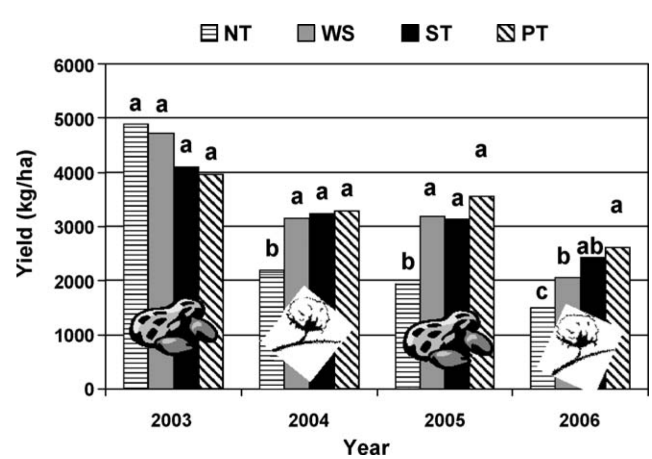


**Fig. 7.** Peanuts and cotton yields as affected by in-row subsoiling. Letters indicate NT—no-till; WS—worksaver; ST—strip-till; PT—paratill. Different lower case letters indicate statisticalificance $LSD_{0.1}$.

**Table 7**
Estimated costs and economic return for peanut crop in 2005.

| | Peanut yield | Yield increase | Revenue increase* | Cost increase** | Net increase | Net return*** |
|---|---|---|---|---|---|---|
| | kg/ha | | US $/ha | | | |
| 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 | 25 | 139 | 74 | 64 | 7 |

Source (ACES, 2008).
†← No-till and no-cover are the base comparison.
* Peanut price at $550/M.
** (Fuel $0.8/L; 0.66 h/ha; 135hp tractor $47/h; Ripper-Bedder $17/h; cover crop $74/ha).
*** Net return over total production costs 2008 ($1611/ha).

**Table 8**
Estimated costs and economic return for cotton crops in 2004 and 2006.

| | Seed cotton yield | | Average increase | Revenue increase* | Cost increase** | Net increase | Net return*** |
|---|---|---|---|---|---|---|---|
| | 2004 | 2006 | | | | | |
| | kg/ha | | US $/ha | | | | |
| 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 |

Source (ACES, 2008).
†← No-till and no-cover are the base comparison.
* Based on 40% lint yield. Lint $1.65/kg; seed cotton $0.2/kg.
** (Fuel $0.8/L; 0.66 h/ha; 135hp tractor $47/h; Ripper-Bedder $17/h; cover crop $74/ha).
*** Net return over total production costs 2008 ($1654/ha).

### 3.5. Economic return

Subsoiling costs are estimated to be approximately $32 to $43/ha (Raper and Bergtold, 2007; Alabama Cooperative Extension System (ACES) 2008). Our yield increase for each in-row subsoiling treatment versus no-till is shown in Tables 7 and 8. Using ACES (2008) current production costs of peanuts ($1611/ha) no-till treatment would result in net loss of $546/ha, 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 at $550/Mg 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 8). 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 $74/ha (ACES, 2008), cover crops were a worthy investment, especially when cotton was affected by drought resulting in approximately $370/ha increase in net return.

## 4. 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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