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Benefits of site-specific subsoiling for cotton production in Coastal Plain soils☆

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Abstract

The negative impacts of soil compaction on crop yields can often be alleviated by subsoiling. However, this subsoiling operation is often conducted at unnecessarily deep depths wasting energy and excessively disturbing surface residue necessary for erosion control and improved soil quality. A corn (*Zea mays* L.)–cotton (*Gossypium hirsutum* L.) rotation experiment was conducted over 4 years on a Coastal Plain soil with a hardpan in east-central Alabama to evaluate the potential for site-specific subsoiling (tilling just deep enough to eliminate the hardpan layer) to improve crop yields while conserving energy. Seed cotton yield showed benefits of subsoiling (2342 kg/ha) compared to the no-subsoiling treatment (2059 kg/ha). Averaging over all years of the study, site-specific subsoiling produced cotton yields (2274 kg/ha) statistically equivalent to uniform deep subsoiling at a 45 cm depth (2410 kg/ha) while not excessively disturbing surface soil and residues. Significant reductions in draft force were found for site-specific subsoiling (59% and 35%) as compared to uniform deep subsoiling at a 45 cm depth in shallow depth hardpan plots (25 cm) and medium depth hardpan plots (35 cm), respectively. Calculated fuel use for site-specific subsoiling was found to be reduced by 43% and 27% in the shallow and medium depth hardpan plots, respectively, as compared to uniform deep subsoiling in these same plots. Producers in the Coastal Plains who can determine (or who know) the depth of their root-impeding layer and perform site-specific subsoiling can have comparable cotton yields to traditional uniform depth subsoiling with reduced energy requirements.
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1. Introduction

Crop production is decreased worldwide by soil compaction (Raper, 2005a; Hamza and Anderson, 2005) with negative environmental consequences (Soane and van Ouwerkerk, 1995). The causes of soil compaction can either be traffic-induced or naturally occurring. The most severe cases of soil compaction are often caused by large vehicles operating on soils susceptible to soil compaction.

Cotton has been found to be particularly susceptible to soil compaction with many studies indicating significant yield reductions owing to either excessive vehicle traffic or soils predisposed to hardpan conditions (McConnell et al., 1989; Reeves and Mullins, 1995; Coelho et al., 2000; Schwab et al., 2002). Cotton may be more susceptible to compaction because it is typically grown on problematic soils which are primarily silt loam or coarser-textured. Another reason

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for increased sensitivity to soil compaction could be the intensive tillage systems that have traditionally been necessary both for planting and cultivation. Vehicle traffic coupled with naturally compactable soils has contributed significantly to shallow crop rooting, drought, and reduced crop yields (Raper, 2003).

Subsoiling has often been found to reduce the ill effects of soil compaction and therefore improve soil properties and increase cotton yields (Melville, 1976; Tupper and Spurgeon, 1981; McConnell et al., 1989; Reeves and Mullins, 1995; Raper et al., 2000a,b; Schwab et al., 2002). However, the energy requirements and costs associated with subsoiling can be substantial and have been shown to increase dramatically with increased tillage depth (ASAE Standards, 2003). A reduction in tillage depth could save producers significantly if soil compaction was still eliminated (Fulton et al., 1996; Raper, 1999).

Cover crops are often used in conservation tillage systems and are particularly effective in increasing the amount of organic matter near the soil surface. The use of cover crops has also contributed to reduced effects of soil compaction, mostly by contributing to increased water infiltration and storage (Raper et al., 2000a). In these studies, reduced soil strength and higher soil moisture contributed towards higher crop yields. There are also some indications that a cover crop may reduce the need for subsoiling by increasing infiltration and water-holding capacity of the soil (Truman et al., 2003, 2005). Another positive benefit of cover crops and increased organic matter is that the soil is better able to support vehicle traffic (Ess et al., 1998). Significantly reduced bulk density was found for plots that included a cover crop as compared to bare plots in the soil surface layer (2.5–7.5 cm) following multiple machine passes. Soil compaction appeared to be reduced by the root mass of the cover crop with little benefit seen from the aboveground biomass.

Soils in the southeastern US have exhibited large amounts of variability in soil compaction (Raper et al., 2001). Soil compaction can change dramatically from an untrafficked middle to a subsoiled row and to a trafficked middle, mostly caused by vehicle traffic. Soil compaction can also naturally vary spatially across the field due to variations in soil properties and prior cropping systems which reflect previous traffic patterns and tillage practices. Using soil compaction information obtained from an on-the-go sensor or from previous measurements may offer a method of adjusting tillage depth that maintains crop productivity while conserving energy.

Therefore, the objectives of this experiment were to determine the:

(1) effect of site-specific subsoiling and cover crops on cotton yield,
(2) reductions in draft force due to site-specific subsoiling, and
(3) reductions in fuel requirements for site-specific subsoiling.

2. Methods and materials

This experiment was performed on an 8 ha field at the E.V. Smith Research and Extension Center located near Shorter, AL which is part of the Alabama Agricultural Experiment Station. The soil type was a Toccoa fine sandy loam of the Coastal Plain (coarse-loamy, mixed, active, nonacid, thermic Typic Udifluvents). This field had been annually subsoiled through 1998 to compensate for excessive soil compaction which frequently restricted plant root growth.

To facilitate appropriate crop management typical for southeastern producers, a corn–cotton rotation system was established with winter cover crops of rye (*Secale cereale* L.) cv. Wren's Abruzzi. Prior preceding cotton and crimson clover (*Trifolium incarnatum* L.) cv. AU Robin preceding corn. The entire field was split into two halves: Field 1 and Field 2. A split–split-plot experiment was conducted on these fields in a completely randomized design with four replications. Mainplot treatments were hardpan depth, subplot treatments were cover crops, and sub–subplots were subsoiling depth.

Half of each plot was planted with a cover crop and the other half left bare resulting in a natural weed winter fallow. Rye was used as a cover crop prior to planting cotton and crimson clover was used as a cover crop prior to planting corn. The management of cover crops including dates of planting and termination are included in Table 1.

The experiment was initiated during the spring of 1999 with the planting of cotton in Field 1 and corn in Field 2. No-subsoiling was used to prepare the fields with the intent of discovering the field's natural variation in soil compaction. Data obtained from this test showed dramatic variations in seed cotton yield in Field 1 from 0 to 1678 kg/ha and in corn yield in Field 2 from 0 to near 5028 kg/ha.

In the fall of 1999, a complete set of cone index measurements (ASAE Standards, 2004a,b) were obtained with the Multiple-Probe Soil Measurement System (Raper et al., 1999) using an approximate 100 m grid when the soil was near field capacity. Peak values of cone index were determined for each sampled profile.

Table 1
Dates of field activities for cover and cash crops

	Field 1 date	Field 1 action	Field 2 date	Field 2 action
2000 Crop	29/10/1999	Planted clover cover crop	29/10/1999	Planted rye cover crop
	27/03/2000	Terminated cover crop	12/05/2000	Terminated cover crop
	19/04/2000	Subsoiled	22/05/2000	Subsoiled
	20/04/2000	Planted corn (Dekalb DK687)	02/06/2000	Planted cotton (Sure-Grow 501 BG)
	29/09/2000	Harvested corn	07/11/2000	Harvested cotton
2001 Crop	28/11/2000	Planted rye cover crop	28/11/2000	Planted clover cover crop
	23/04/2001	Terminated cover crop	06/04/2001	Terminated cover crop
	02/05/2001	Subsoiled	13/04/2001	Subsoiled
	08/05/2001	Planted cotton (Sure-Grow 501 BG)	17/04/2001	Planted corn (Pioneer 34A55)
	02/11/2001	Harvested cotton	28/08/2001	Harvested corn
2002 Crop	28/11/2001	Planted clover crop crop	28/11/2001	Planted rye cover crop
	11/03/2002	Terminated cover crop	16/04/2002	Terminated cover crop
	20/03/2002	Subsoiled	26/04/2002	Subsoiled
	03/04/2002	Planted corn (Pioneer 34A55)	23/05/2002	Planted cotton (Sure-Grow 501 BG)
	09/08/2002	Harvested corn	02/10/2002	Harvested cotton
2003 Crop	05/11/2002	Planted rye cover crop	05/11/2002	Planted clover crop crop
	05/05/2003	Terminated cover crop	18/03/2003	Terminated cover crop
	13/05/2003	Subsoiled	26/03/2003	Subsoiled
	29/05/2003	Planted cotton (Delta and Pine Land Co. DPL 501 B/RR)	02/04/2003	Planted corn (Pioneer 34A55)
	31/10/2003	Harvested cotton	12/08/2003	Harvested corn

These peak values were assumed to occur at the depth of the existing soil hardpan, which is the root-restricting layer commonly found in this region. Above the depth of the hardpan, the soil had cone index values which were less than the peak value. A great deal of variation was found in this field for the soil hardpan with values mostly being noted in the 15–45 cm depth range. Plots having three distinct hardpan depths (15–25 cm, 25–35 cm, and 35–45 cm) were used. Each depth had four replicates. Not all areas within the field had defined hardpan profiles. These areas were omitted from the experimental plots.

Prior to planting in the spring of 2000, 2001, 2002, and 2003, three subsoiling treatments were imposed on each of the experimental plots:

1. no-subsoiling (zero-depth subsoiling);
2. site-specific subsoiling (25 cm, 35 cm, or 45 cm depth subsoiling);
3. deep subsoiling (45 m depth subsoiling).

Our procedure can be illustrated best by an example. In plot number 3, the hardpan depth had been established to exist at a depth of 35 cm. Therefore, the site-specific subsoiling treatment would be applied slightly below a depth of 35 cm in this plot. Two other treatments would also be applied within this area: no-subsoiling (zero-depth subsoiling) and the traditional uniform deep subsoiling (45 cm depth subsoiling).

A John Deere 955 Row Crop Ripper which had been supplied as part of a Cooperative Research and Development Agreement with Deere and Co. (Moline, IL) was used to perform site-specific and deep subsoiling treatments. This subsoiler was equipped with 7 cm wide LASERRIP^{TM} Ripper Points. Due to initial problems with this subsoiler that prevented the areas behind the shank from closing up after tillage, additional components were supplied from Yetter Mfg. (Colchester, IL) that assisted with moving soil into this zone and allowing planting immediately after subsoiling. No secondary tillage was conducted prior to planting with all systems being considered no-tillage or conservation tillage. To facilitate site-specific subsoiling, several items were manually repositioned allowing the subsoiler to function properly at various depths of tillage. The Yetter closing components, coulters, and gauge wheels were all manually adjusted for the desired three site-specific subsoiling depths. Four-row equipment was used for cotton establishment with a row spacing of 1.0 m while six-row equipment was used for corn with a row spacing of 0.76 m. Total plot width was 4.08 m for the cotton and 4.56 m for corn. Differences in plot width were accommodated by having a slightly larger border on the edge of the plots for cotton production. Plot length was 30.5 m.

Table 2
Soil moisture values (gravimetric) at time of subsoiling

Depth (cm)	Years			
	2000	2001	2002	2003
0–15	14.5	19.8	20.1	17.8
15–30	16.4	21.3	22.1	17.9

To measure draft, vertical, and horizontal subsoiling forces, the JD 955 subsoiler was mounted on a 3-dimensional dynamometer which was attached to a John Deere 8300 MFWD tractor (Raper et al., 2000a). Ground speed was measured with a Dickey-John radar gun (Auburn, IL) and averaged for each plot.

The soil moisture at time of subsoiling was targeted to be in a relatively moist state where adequate traction was achievable with the tractor and subsoiling forces should be minimized (Table 2). Over the 4 years of the experiment, values of soil moisture present at subsoiling varied by an approximate maximum amount of 5% in the 0–15 and 15–30 cm layers.

Only data collected from the cotton experiment will be discussed in this paper. The corn data was previously published in Raper et al. (2005). Cotton spatial yield information was obtained with an Agleader Technology Inc. (Ames, IA) cotton yield monitor over the middle two-row section of each plot. This information was averaged over the entire length of the plot to obtain one yield value per treatment.

A split–split plot arrangement with four replications with main plots of hardpan depth, subplots of cover crop, and sub–subplots of tillage treatment were analyzed with an appropriate GLM model using SAS (Cary, NC). A predetermined significance level of $P \leq 0.1$ was chosen to separate treatment effects.

3. Results and discussion

Discussions will be limited to main treatment effects and significant interactions between depth of hardpan and subsoiling treatments.

3.1. Cotton yields

In 2000, the effect of cover crop was the only significant treatment effect ($P \leq 0.01$) that was found (Table 3). In this year, cover crops were found to greatly benefit crop yield with the cover crop treatment out yielding the no-cover crop treatment by more than 600 kg/ha.

In 2001, the effect of subsoiling was the only significant treatment effect ($P \leq 0.03$) that was found. Deep subsoiling (45 cm) was found to yield significantly greater than the no-till treatments while site-specific subsoiling was not statistically different from either of the other two subsoiling treatments (Table 3).

Table 3
Seed cotton yields (kg/ha) averaged across hardpan depths

Treatments	2000	2001	2002	2003	Average
Subsoiling treatment					
No-till	2494	1860	1643	2240	2059
Site-specific	2334	2086	2102	2574	2274
Deep	2298	2379	2225	2739	2410
$LSD_{0.1}$	ns	314	109	154	175
Cover crop					
Cover	2682	2097	1830	2459	2267
No cover	2069	2120	2150	2576	2229
$LSD_{0.1}$	155	ns	172	117	ns

In 2002 (Table 3), significant effects on seed cotton yield were found as a result of the cover crop treatment ($P \leq 0.01$) and the subsoiling treatment ($P \leq 0.01$). Cover crops decreased crop yields as opposed to the treatment effects found in 2000. Deep subsoiling caused the greatest crop yields, followed by site-specific subsoiling, with no-tillage having the lowest crop yields. A significant interaction was also found between the subsoiling treatment and the hardpan depth ($P \leq 0.01$) for 2002 (Table 4). This interaction was likely caused by the greatest yields being found in the 35 cm hardpan depth plots as a result of site-specific subsoiling.

In 2003, significant effects on seed cotton yield (Table 3) were found as a result of cover crop treatment ($P \leq 0.05$) and subsoiling treatment ($P \leq 0.01$). The effect of the cover crop was again to cause a significant yield depression as was found in 2002. Deep subsoiling again resulted in the largest crop yield, while no-tillage resulted in the lowest crop yield with site-specific subsoiling yielding midway between the other two subsoiling treatments.

When the data were averaged across replications, depth of hardpan, and cover crop for years 2000–2003, no statistical differences were found between site-specific subsoiling and traditional deep subsoiling ($P > 0.1$). Site-specific subsoiling and deep subsoiling both had yields which were greater than no-tillage due to the yield-limiting soil compaction that was present in this Coastal Plain soil.

The depth of hardpan was not found to affect cotton yield ($P \leq 0.16$) although a significant interaction with subsoiling treatment was found ($P \leq 0.01$; Table 3). The largest differences occurred at the hardpan depths of 35 and 45 cm where no-tillage significantly

Table 4
Seed cotton yields (kg/ha) averaged across cover crops

Hardpan depth (cm)	Subsoiling treatments	2000	2001	2002	2003	Average
25	No-till	2730	2113	1837	2182	2215
	Site-specific	2718	1951	2044	2318	2258
	Deep	2624	2435	2433	2667	2540
35	No-till	2548	1732	1512	2170	1990
	Site-Specific	2504	2206	2507	2511	2432
	Deep	2462	2632	2337	2644	2519
45	No-till	2203	1736	1581	2369	1972
	Site-specific	1778	2102	1757	2893	2133
	Deep	1807	2068	1905	2906	2172
$LSD_{0.1}$		ns	ns	314	ns	395

decreased yields compared to either site-specific subsoiling or deep subsoiling. In the 45 cm hardpan depth plots, subsoiling was done at 45 cm in both site-specific as well as deep subsoiling treatments. Therefore, these two tillage treatments were statistically similar.

A trend was found with the lowest yields occurring for all of the subsoiling treatments at the deepest hardpan depth of 45 cm. It was also noted that the no-tillage plots showed a continual decrease in cotton yield as hardpan depth increased. These results were not specific to cotton, however, as the corn results were similar with greater corn yields being measured at shallower hardpan depths (Raper et al., 2005). One possible explanation for these trends may be that as hardpan depth increased, so did the magnitude of the average peak cone index measured in those plots (Fig. 1). Significantly higher peak values of cone index were found at the deepest hardpan depths of 45 cm than were found at either of the two shallower hardpan depths. In the shallower hardpan plots (25 and 35 cm), roots may not have been restricted to the same degree as was found in the 45 cm hardpan plots and were able to penetrate through the shallower hardpan plots.

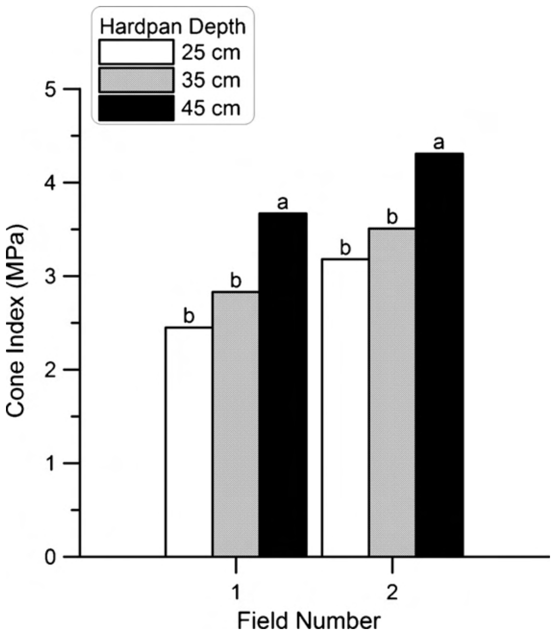

Fig. 1. Average peak cone index measured over plots prior to experiment. Letters indicate differences using $LSD_{0.1}$.

3.2. Implement draft force

Draft forces declined from the highest values which were measured at the initiation of the experiment in 2000 to the smallest values which were measured at the conclusion of the experiment in 2003. During the intermediate years of 2001 and 2002, intermediate values were also measured. One potential reason for this reduction in draft forces could be that the annual subsoiling in these plots was coupled with controlled traffic which reduced the soil's ability to form a compacted layer. However, the row spacing alternated between 1.02 and 0.76 m in successive years, so in-row subsoiling was not conducted in the same location every year.

The main effects of depth of the hardpan ($P \leq 0.01$) and the subsoiling depth ($P \leq 0.01$) both significantly affected subsoiling draft force. There was also a significant interaction between the two main effects ($P \leq 0.01$; Fig. 2). At the shallow hardpan depth of 25 cm, site-specific subsoiling resulted in a 59% draft reduction as compared to uniform deep subsoiling (45 cm depth). At the medium hardpan depth of 35 cm, site-specific subsoiling also reduced draft by 35% compared to uniform deep subsoiling at 45 cm. As a check, site-specific subsoiling and deep uniform

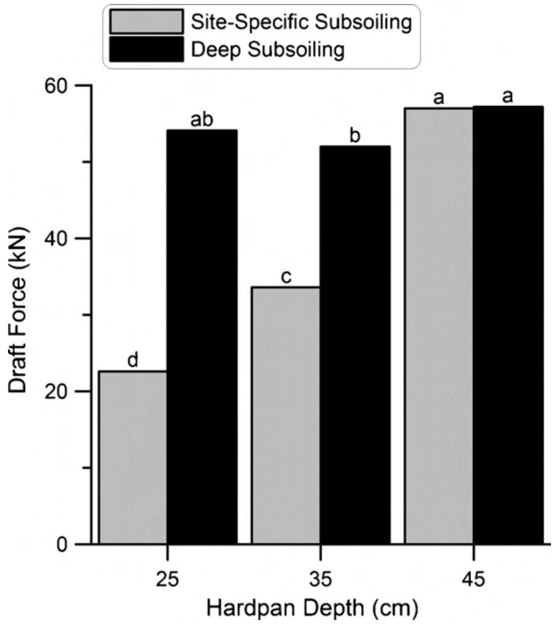

Fig. 2. Implement draft (kN) averaged across years and cover crops. Letters indicate differences using $LSD_{0.1}$.

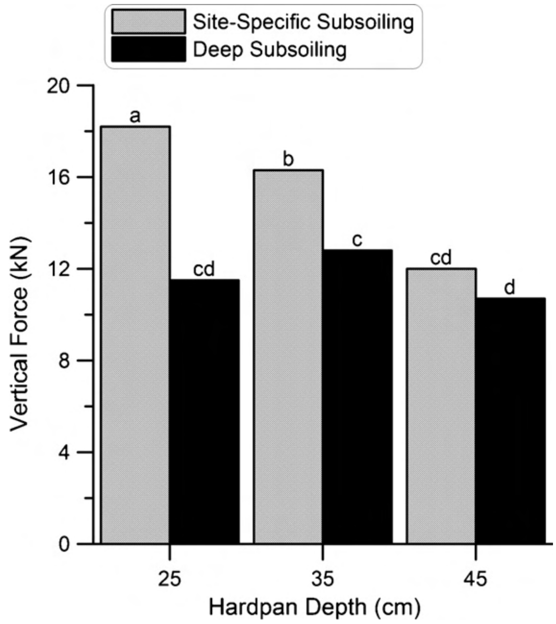

Fig. 3. Implement vertical force (kN) averaged across years and cover crops. Letters indicate differences using $LSD_{0.1}$.

subsoiling resulted in similar drafts at the deep hardpan depth of 45 cm; not surprising because site-specific subsoiling and uniform subsoiling depths were both 45 cm in these plots with a hardpan identified at the 45 cm depth.

Another surprising finding was that hardpan depths of 25, 35, or 45 cm had no effect on draft force for deep uniform subsoiling which was conducted at a 45 cm depth. The depth of the root-impeding layer did not affect draft forces except when subsoiling depth was reduced.

3.3. Implement vertical force

Relatively large amounts of vertical force were necessary to cause the JD 955 subsoiler to penetrate the soil due to the multiple soil-engaging attachments found on the frame. Vertical force was slightly decreased as the depth of subsoiling increased due to suction from the shanks operating at deeper depths. Implement vertical force was found to be affected by main effects of subsoiling depth ($P \leq 0.01$) and hardpan depth ($P \leq 0.01$). An interaction between subsoiling depth and hardpan depth was also found for vertical force ($P \leq 0.01$; Fig. 3). Significantly larger values of vertical force were found for site-specific subsoiling at hardpan depths of 25 and 35 cm. At the hardpan depth of 25 cm, 37% more vertical force was required for site-specific subsoiling. Similarly, at the hardpan depth of 35 cm, 25% more vertical force was necessary for site-specific subsoiling.

3.4. Implement power

Some variation in subsoiling speed was found, with deep subsoiling being conducted at slower speeds than site-specific subsoiling. At the shallow hardpan depth of 25 cm, site-specific subsoiling was conducted at 5.3 m/s; greater than the deep subsoiling speed of 4.8 m/s ($P \leq 0.01$). At the medium hardpan depth of 35 cm, site-specific subsoiling was conducted at a higher speed of 5.2 m/s compared to deep subsoiling which was conducted at 4.7 m/s ($P \leq 0.01$). At the deepest hardpan depth of 45 cm, no differences in subsoiling speeds were found between site-specific subsoiling (4.4 m/s) and deep subsoiling (4.6 m/s; $P \leq 0.39$).

Power requirements required for subsoiling were calculated by multiplying the draft force by the subsoiling speed (ASAE Standards, 2003). Subsoiling depth and hardpan depth were both found to significantly affect implement power ($P \leq 0.01$). The interaction of subsoiling depth and hardpan depth was also found to significantly affect implement power ($P \leq 0.01$; Fig. 4). Greatest reductions were obtained at the shallow hardpan depth of 25 cm, with site-specific subsoiling requiring 52% less power than uniform deep subsoiling. At the medium hardpan depth of 35 cm, a 26% reduction in implement power was required for

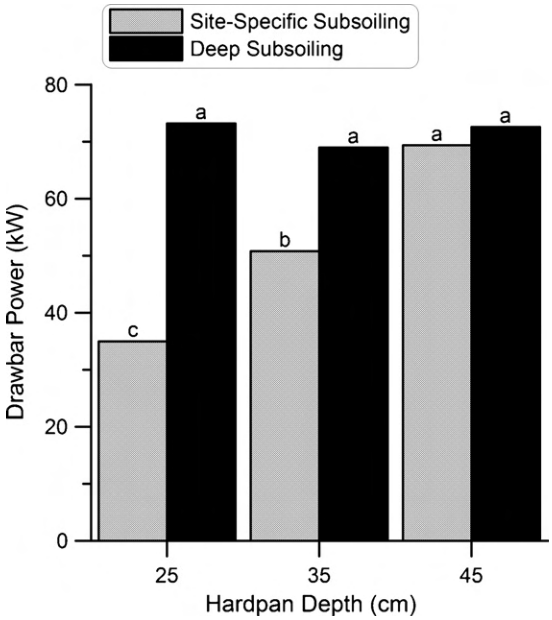

Fig. 4. Drawbar power (kW) averaged across years and cover crops. Letters indicate differences using $LSD_{0.1}$.

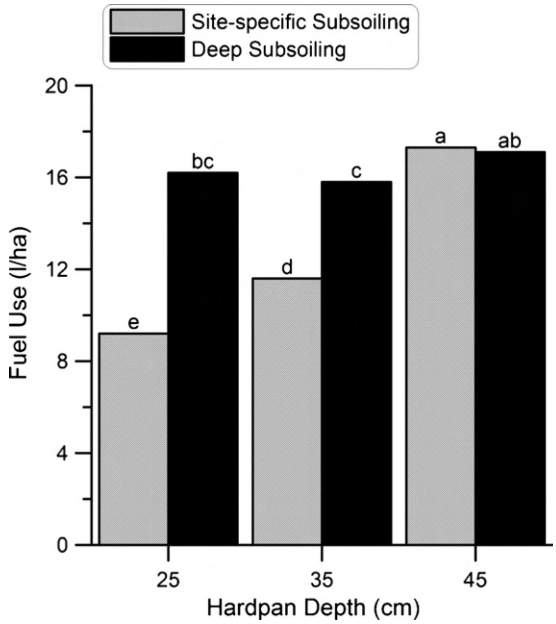

Fig. 5. Calculated fuel use (l/ha) averaged across years and cover crops. Letters indicate differences using $LSD_{0.1}$.

site-specific subsoiling compared to uniform deep subsoiling. Not surprisingly, no differences were found at the 45 cm hardpan depth layer for site-specific subsoiling and deep subsoiling.

3.5. Calculated fuel use

A procedure was developed that allowed fuel use to be calculated for subsoiling depth (Raper et al., 2005). The procedure involved converting variable power-take-off data (from the Nebraska OECD Tractor Test for a John Deere 8300 tractor (Leviticus et al., 1995)) to drawbar power by multiplying 0.73 for a mechanical front-wheel assist tractor on tilled ground (ASAE Standards, 2003). A linear relationship was created between drawbar power and fuel rate which had a correlation coefficient of 0.99:

$$\mathrm{FR} = 0.31 \times \mathrm{DP} + 9.14 \quad (1)$$

where FR is the fuel rate (l/h) and DP is the drawbar power (kW).

Information from Fig. 4 was used in Eq. (1) to determine fuel rate for the different subsoiling treatments. Fuel use was obtained by dividing fuel rate by the speed and width of the subsoiling operation.

The results for calculated fuel use were similar to results for implement power. The depth of hardpan and the subsoiling treatments were both found to be statistically significant as well as a significant interaction between the two parameters ($P \leq 0.01$ for each parameter and the interaction; Fig. 5). On the shallow hardpan plots (25 cm depth), site-specific subsoiling required 43% less fuel than deep subsoiling. On the medium depth hardpan plots (35 cm), site-specific subsoiling required 27% less fuel.

Considering the whole field used in this experiment enabled estimates to be made for total savings associated with the use of site-specific subsoiling. Of the 4.4 ha actually used for the experiment, 1.0 ha had a hardpan depth of 25 cm, 2.2 ha had a hardpan depth of 35 cm, and 1.2 ha had a hardpan depth of 45 cm. If the whole field was subsoiled to the uniform deep depth of 45 cm, it would require a total fuel amount of 71.5 l. If site-specific subsoiling were employed, the entire field could be subsoiled using only 55.5 l of fuel, saving 22% of the estimated fuel requirements for uniform deep subsoiling on this Coastal Plains soil.

As with most site-specific technologies, the cost of implementing site-specific subsoiling is currently prohibitive due to the need of obtaining site-specific soil compaction information and the cost of equipment developments and modifications. The authors are currently conducting research to develop methods of measuring site-specific soil compaction (Raper and Hall, 2003; Hall and Raper, 2005) and to develop optimum designs of subsoiler shanks that will be equally effective at all depths for site-specific subsoiling (Raper, 2005b). However, this experiment proved the feasibility of the concept; i.e., site-specific subsoiling offers potential for reducing the overall cost of the subsoiling operation while maintaining constant crop yields.

4. Conclusions

The conclusions of this experiment were:

(1) Site-specific subsoiling had similar seed cotton yields as traditional deep uniform subsoiling to 45 cm. Both subsoiling treatments yielded greater than no-tillage in this Coastal Plain soil. The effect of cover crops on seed cotton yield was varied with no overall effect seen over the 4-year period.
(2) Site-specific subsoiling resulted in 59% and 35% reduced draft force in the shallow depth hardpan plots (25 cm) and medium depth hardpan plots (35 cm), respectively, compared to uniform deep subsoiling conducted at 45 cm depth.
(3) Site-specific subsoiling resulted in 43% and 27% reduced calculated fuel use in the shallow depth hardpan plots (25 cm) and medium depth hardpan plots (35 cm), respectively, compared to uniform deep subsoiling conducted at 45 cm depth.

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