USING SITE-SPECIFIC SUBSOILING TO MINIMIZE DRAFT AND OPTIMIZE CORN YIELDS

R. L. Raper, D. W. Reeves, J. N. Shaw, E. van Santen, P. L. Mask

ABSTRACT. *Subsoiling is often required to alleviate soil compaction; however, deep tillage can be expensive and time-consuming. If this tillage operation is conducted deeper than the compacted soil layer, energy is wasted. However, if this tillage operation is conducted shallower than the compacted soil layer, energy is again wasted, and plant roots may be prevented from penetrating the compacted layer. Technologies are now available that allow subsoiling to be conducted at the specific depth of the compacted layer, which would conserve natural resources without sacrificing crop yields. An experiment was conducted over four years in a field located in southern Alabama to evaluate whether the concept of site-specific subsoiling (tilling just deep enough to eliminate the hardpan layer) would reduce tillage draft and energy requirements and/or reduce crop yields. Average corn (*Zea mays *L.) yields over this four-year period showed that site-specific subsoiling produced yields equivalent to those produced by the uniform deep subsoiling treatment while reducing draft forces, drawbar power, and fuel use.*

Keywords. *Crop yields, Draft, Precision agriculture, Site-specific, Soil compaction, Subsoiling, Tillage.*

Soil compaction can be naturally occurring or machinery-induced (Raper, 2003; Schuler et al., 2000). Naturally occurring soil compaction is often facilitated by a well-graded soil that contains many different sizes of soil particles (Craul, 1994). Poorly graded soils, which are mostly of a certain particle size, tend to be more resistant to compaction. In well-graded soils, the mixture of large and small particles fills most voids, which leave inadequate pore space for plant root expansion. Coastal plain soils tend to be particularly susceptible to this problem due to their sandy topsoils and clay subsoils. At depths where the two soil layers intersect, hardpans tend to form and restrict root growth.

Machinery-induced soil compaction is due to vehicle traffic from large and heavy equipment used in agricultural fields. Many studies have shown that soil compaction is increased under row middles that have been subjected to vehicle traffic, as opposed to traffic middles where no traffic has occurred (Hamlett et al., 1990; Kaspar et al., 1991; Raper et al., 1994; Raper et al., 1998).

Subsoiling is often used to combat soil compaction and reduce soil strength to levels that allow for root development and growth (Garner et al., 1987; Vepraskas et al., 1995; Raper, 2002, 2005). This tillage process provides increased rooting depth to withstand short-term drought conditions prevalent during the growing season in the southeastern U.S. A typical depth of annual subsoiling is between 0.3 m and 0.5 m. The depth of tillage is often chosen based on average needs of the soil and the capability of the tractor and implement.

Soil, however, varies greatly over the landscape. The depth of the root-impeding layer has been found to vary based on previous cropping systems and vehicle traffic patterns. Raper et al. (2005) found greater variation existed in fields that were subject to random traffic, as opposed to fields where traffic was segregated with a controlled traffic system. They also found that the depth of the root-impeding layer was at a shallower depth in a field that had been managed with conventional tillage than in a field that had been managed with conservation tillage.

Due to the need to eliminate the root-impeding layer and the variation that had been found in the depth of this layer, the concept of site-specific subsoiling was investigated as a potential method for adjusting subsoiling tillage depth on-the-go as a farmer traverses a field. A map created using geo-referenced soil strength data could be used to reduce subsoiling depth in areas where deep subsoiling was not needed, or a sensor could be used to make an immediate adjustment in subsoiling depth. Reducing subsoiling depth would also reduce subsoiling forces and energy requirements. If the depth of subsoiling chosen was too deep, energy would be wasted and additional surface residue would be covered by the excessively disturbed soil. If the depth of subsoiling chosen was too shallow, subsoiling would be inadequate to remove the root-restricting layer, and thus all energy used for this tillage operation would be wasted.

Site-specific measurements of hardpan depth taken in several locations in the southeastern U.S. indicate that between 25% and 75% of tillage energy could be saved if some form of site-specific tillage could be developed and used (Fulton et al., 1996; Raper, 1999). In addition, some data indicate that tillage deeper than necessary may reduce yields (Raper et al., 2000a; Raper et al., 2000b). Therefore, it is important to determine the

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Article was submitted for review in December 2004; approved for publication by the Power & Machinery Division of ASABE in October 2005.

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depth of the root-impeding layer and to till only deep enough to eliminate this layer of soil compaction. A variable-depth subsoiling (site-specific subsoiling) system is needed that considers the crop's needs and the soil's variability.

The objectives of this study were to determine the effect of site-specific subsoiling on corn yield, subsoiling forces, and subsoiling power and fuel requirements.

Methods and Materials

In 1999, an 8 ha field was selected at Alabama Experiment Station's E.V. Smith Research Station in southern Alabama that exhibited a noticeable amount of yield variability. Soils at the site developed in alluvium and varied from Dystrudepts to Hapludults. The soils in this field had excessive soil strength and required annual subsoiling. Some of the yield variability was thought to be attributed to excessive soil compaction that varied substantially throughout the field. Before plots were established within this field, background information was obtained in an attempt to understand the spatial soil variability.

One method that is often used to quickly determine soil type variability within a field is measuring soil electrical conductivity. The Veris Technologies 3100 Soil EC Mapping System (Salina, Kansas) was used on an approximately 10 m swath to examine spatial differences in electrical conductivity within this field. These sensors have been used to determine management zones for precision agriculture applications and are sensitive to differences in soil texture and clay mineralogy (Shaw and Mask, 2003), which are related to differences in soil strength. These data showed substantial spatial variation in electrical conductivity, from 0 to 20 ms/m (fig. 1).

To directly obtain differences in soil strength throughout the field, a complete set of soil cone penetrometer measurements (*ASAE Standards*, 2004a, 2004b) was obtained with the Multiple-Probe Soil Measurement System (MPSMS) (Raper et al., 1999), which simultaneously inserted three probes into the soil spaced 0.4 m apart. Cells of 100 × 100 m were created and sampled extensively for cone index. Along the middle transect of each cell, the MPSMS was inserted every 20 m.

Locating the depth of the hardpan layer requires experience and familiarity with cone index data. Usually this compacted soil layer is found when the cone index data quickly rises and then decreases. Taylor and Gardner (1963) found that when the cone index values exceeded 2 MPa, plant roots were no longer able to proliferate. However, changing moisture content can also change the depth at which 2 MPa is measured. Subsoiling at depths where 2 MPa cone index was measured could leave a compacted zone immediately below the depth of tillage. To completely eliminate the compacted zone and provide maximum soil loosening for crop production, the depth of the peak cone index value was taken as the minimum depth for subsoiling.

Cone index measurements were analyzed for differences in the depth to hardpan over the entire field using the depth to the peak value of cone index as the determining factor for location of the soil hardpan. An SAS procedure designed to search for the peak value as the criteria for the hardpan was used to sort the data and predict the depth of hardpan formation. The specific criteria used to locate these hardpan depths consisted of locating at least three consecutive data points that were 0.05 MPa greater than the previous data points while ensuring that the magnitude of cone index was greater than 1.0 MPa. Values of cone index often exceeded 2 MPa and sometimes exceeded 3 MPa, particularly in areas of the field with shallow zones of soil compaction. These data also showed significant variation in hardpan depth across the field (fig. 2). A corn crop was planted in 1999 using no deep tillage and no surface tillage. A yield monitor was used to harvest the crop to determine natural variations in the field's crop productivity previous to installing treatments. These data showed some variation in yield across the field, with values ranging from near 0 kg/ha to more than 100 kg/ha (data not shown). The yield variation data, the electrical conductivity data, and the cone index data were then used to locate the experimental plots while excluding cells that may not have had a clearly discernable hardpan or did not drain properly.

The cone index data indicated that the depth of extreme values of soil compaction that restricted root growth ranged from 15 to 45 cm over the entire field. This range of depth of compaction was split into three distinct hardpan depth ranges of 15-25 cm, 25-35 cm, and 35-45 cm, which were replicated four times within the field (fig. 3). Three subsoiling treatments were imposed within each of the test plots in the spring of 2000, 2001, 2002, and 2003:

- No subsoiling (zero-depth subsoiling).
- Site-specific subsoiling (25 cm, 35 cm, or 45 cm depth subsoiling).
- Deep subsoiling (45 cm depth subsoiling).

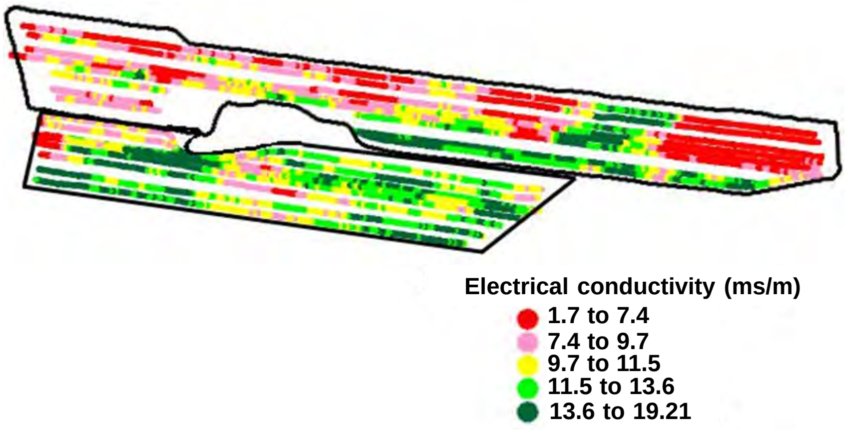

Figure 1. Map of electrical conductivity (ms/m) for the shallow depth range (0 - 30 cm) obtained with a Veris 3100 Soil Mapping System.

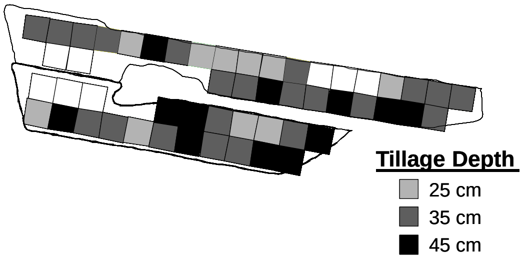

Figure 2. Map of cone index showing locations of measured hardpan depth as determined by peak cone index values. Blank areas did not have a detectable hardpan depth.

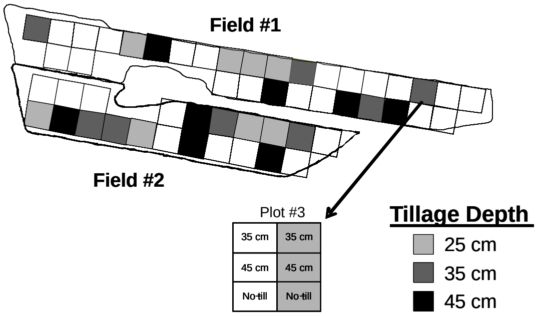

Figure 3. Experimental layout of field showing location of plots, hardpan depths, location of cover crops, and location of subsoiling treatments. Cover crops were planted in half of each plot as illustrated by the shaded portion of plot 3.

As an example, for plot 3 with the medium-depth hardpan (the 25-35 cm hardpan depth), a 35 cm tillage depth was selected for the site-specific subsoiling depth. Therefore, three tillage treatments were applied in this plot: (1) no-subsoiling, (2) site-specific subsoiling (to a depth of 35 cm), and (3) deep subsoiling (fig. 3). The darker portion (right side) of plot 3 was planted with a cover crop, while the lighter portion (left side) did not have any cover crop establishment.

The field was split into two halves (field 1 and field 2) to allow for a corn-cotton (*Gossypium hirsutum* L.) rotation. Because there were no contiguous blocks containing all hardpan depths, we chose a completely randomized design (r = 4) with a split-split-plot restriction on randomization. Hardpan depths were assigned as mainplot treatments, cover crops as subplots, and subsoiling depth as sub-subplots. Half of each plot was planted in a cover crop, and the other half was left bare. Prior to planting cotton, the cover crop was rye (*Secale cereale* L.) cv. Wren's Abruzzi (table 1). Prior to planting corn, the cover crop was crimson clover (*Trifolium incarnatum* L.) cv. AU Robin. Cotton was planted in 1.02 m rows with 4-row equipment, while corn was planted in 0.76 cm rows with 6-row equipment. Plot size was either 4 rows × 30.5 m for cotton or 6 rows × 30.5 m for corn.

Table 1. Planting rotation for cash and cover crops.

	Field 1	Field 2
Fall 1999	Crimson clover	Rye
Spring 2000	Corn	Cotton
Fall 2000	Rye	Crimson clover
Spring 2001	Cotton	Corn
Fall 2001	Crimson clover	Rye
Spring 2002	Corn	Cotton
Fall 2002	Rye	Crimson clover
Spring 2003	Cotton	Corn

Subsoiling treatments were conducted using a John Deere (JD) 955 Row Crop Ripper equipped with 7 cm wide LaserRip ripper points (fig. 4). This subsoiler was supplied as part of a cooperative research and development agreement with Deere & Co. (Moline, Ill.). Modifications were made to this implement to allow for a subsoiling depth of 25 to 45 cm and to incorporate heavy residue handling attachments, which were supplied by Yetter Manufacturing Company (Colchester, Ill.). For each particular subsoiling depth desired, the subsoiler attachments were manually adjusted to facilitate residue handling. The subsoiler was mounted on a three-dimensional dynamometer, which measured the draft, vertical, and side forces required for tillage of each plot. A radar gun was used to obtain tillage speed, which was used along with the mean draft data to obtain the power and estimate the fuel requirements necessary for subsoiling. A JD 8300 MFWD tractor was used to pull the implement.

Only corn data will be discussed in this article. An AgLeader Technology, Inc. (Ames, Iowa) PF 3000 yield monitor mounted on a JD 4435 combine with a 4-row head was used to obtain corn yield data for each of the plots at the end of the growing season. The yield data obtained over the middle 4-row section for each plot were averaged to determine a mean value for each plot.

Mixed model methodology as implemented in SAS Proc Mixed (Littell et al., 1996) was used to analyze the data based on the described design. Hardpan depth, cover crop treatment, subsoiling depth, and their interactions were considered to be fixed effects. Replicates, year, field, and all associated interactions were considered to be random effects. A significance level of $P \leq 0.1$ was chosen to separate treatment effects.

Results and Discussion

Corn Yield

Discussions will be limited to main and two-way treatment effects since no three-way interactions were significant.

Corn yield averaged across replications, depth of hardpan, and cover crop for the years 2000-2003 showed that yields varied significantly, from 5.9 Mg/ha in 2000 and 2003 to 7.8 Mg/ha in 2002 ($P \leq 0.03$). Cover crops were not found to have a significant effect on corn yield ($P \leq 0.81$) and will not be considered in further discussion.

Across all plots, subsoiling treatment and hardpan depth were found to be statistically significant effects ($P \leq 0.01$ for each treatment), with no subsoiling being found to be different from both site-specific subsoiling and deep subsoiling. Corn yields in site-specific subsoiled plots were found to be similar to those from deep subsoiled plots. Corn yields from all three hardpan depths were found to be statistically different from each other. However, an interaction also occurred between the depth of hardpan and subsoiling treatment (fig. 5; $P \leq 0.03$). In the shallow plots (hardpan depth of 25 cm), no statistical difference was found between the three subsoiling treatments. However, at the other two hardpan depths (35 and 45 cm), reduced yields were found for the no-subsoiling treatment. It was also noted that corn yield with the no-subsoiling treatment decreased in a linear manner as hardpan depth increased.

In the medium-depth hardpan plots (hardpan depth of 35 cm), deep subsoiling (8.2 Mg/ha; $P \leq 0.02$) resulted in higher yields than site-specific subsoiling (7.0 Mg/ha), which

Figure 4. John Deere 955 used for subsoiling treatments.

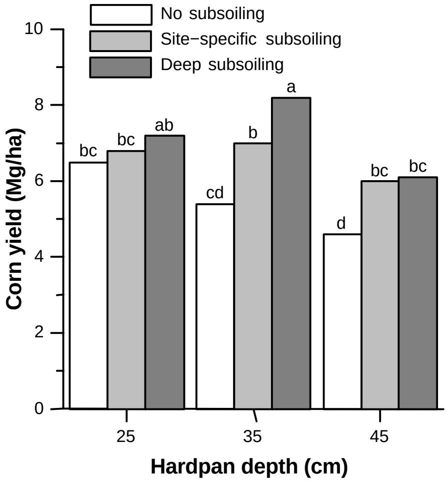

Figure 5. Corn yield (averaged from years 2000-2003) analyzed for subsoiling treatment by hardpan depth location. Letters indicate differences using P ≤ 0.10.

was also higher than no subsoiling (5.4 Mg/ha; $P \leq 0.01$). Site-specific subsoiling had similar corn yield as deep subsoiling in the deep plots (hardpan depth of 45 cm). One point should be made about the 45 cm hardpan depth plots. The site-specific subsoiling treatment and the deep subsoiling treatment were conducted at the same depth of 45 cm. In these plots, where the hardpan was 45 cm deep, the site-specific subsoiling treatment and the deep subsoiling treatment were the same treatment. As a check, the yield data for these treatments were statistically equal in these plots.

DRAFT FORCE

A subsoiling treatment effect and a hardpan depth treatment effect were found for draft force ($P \leq 0.01$ for each parameter). An interaction also occurred between the subsoiling treatment and the depth of hardpan (fig. 6; $P \leq 0.01$). At the two shallowest hardpan depths, site-specific subsoiling required significantly reduced draft forces as compared to deep subsoiling, i.e., 55% reduced draft force at the 25 cm hardpan depth and 26% reduced draft force at the 35 cm hardpan depth. At the hardpan depth of 45 cm, site-specific subsoiling and deep subsoiling were equal, having both been performed at the same depth. One interesting note is that the deep subsoiling treatment took the same amount of draft force at all hardpan depths. A deeper hardpan did not require additional draft force to disrupt the compacted soil.

VERTICAL FORCE

Only positive values of vertical force were measured, which indicated that the implement was always being pushed into the soil by the tractor. Similar to draft force, an interaction was found for vertical force between the hardpan depth and the subsoiling treatment (fig. 7; $P \leq 0.05$). Site-specific subsoiling took significantly greater vertical force than deep subsoiling at the two shallower hardpan depths. At the 45 cm hardpan depth, both values were equivalent since the site-specific subsoiling treatment and the deep subsoiling treatment were conducted at the same depth. No statistical differences were found between the vertical forces required for subsoiling at a depth of 45 cm in any of the three hardpan depths, although a trend existed of decreased vertical force with increased depth of hardpan. At some greater depth of operation, the vertical force may become negative for this subsoiler, but this depth was not achieved with our test.

ESTIMATED DRAFT ENERGY AND FUEL USE

Even though efforts were made to conduct all subsoiling operations at the same speed, some variation occurred due to the large forces required for subsoiling and increased slippage for the deep subsoiling treatment. Site-specific subsoiling was found to have slightly higher draft speeds (4.8 km/h) than deep subsoiling (4.1 km/h; $P \leq 0.01$). The depth of the hardpan was also found to have a significant effect on subsoiling speed ($P \leq 0.01$), with speed of subsoiling decreasing as hardpan depth increased (4.8, 4.6, and 4.1 km/h for the 25, 35, and 45 cm depths, respectively).

The power requirements of the subsoiling operation were calculated by multiplying the draft force by the speed of operation (*ASAE Standards*, 2003). Results were similar to those obtained for draft force, with both subsoiling depth and hardpan depth being found statistically significant ($P \leq 0.01$ for each parameter). The interaction between subsoiling treatment and hardpan depth was also found to be significant (fig. 8; $P \leq 0.01$). At the two shallow hardpan depths of 25 and 35 cm, the site-specific subsoiling treatment took 47% and 17% reduced drawbar power, respectively, compared to the deep subsoiling treatment. The drawbar power required for deep subsoiling was not affected dramatically by the subsoiling depth, while drawbar power for site-specific subsoiling increased in a linear fashion as subsoiling depth increased (fig. 8).

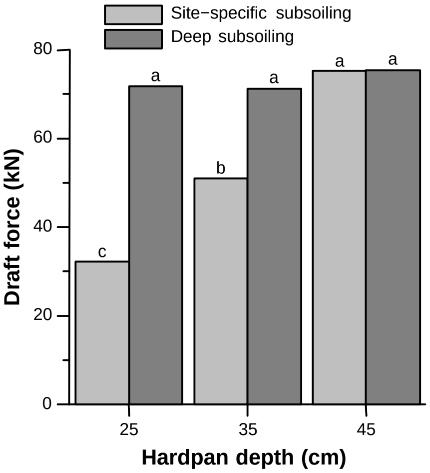

Figure 6. Draft force (averaged from years 2000-2003) analyzed for subsoiling treatment by hardpan depth location. Letters indicate differences using $P \leq 0.10$.

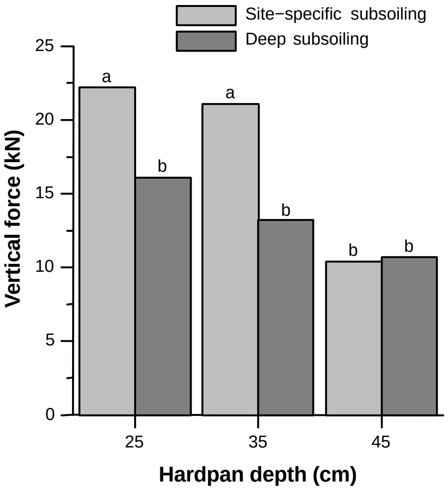

Figure 7. Vertical force (averaged from years 2000-2003) analyzed for subsoiling treatment by hardpan depth location. Letters indicate differences using $P \leq 0.10$.

The fuel usage for the subsoiling operations was estimated from the previous data and additional information provided by the Nebraska OECD Tractor Test for the JD 8300 Diesel tractor (Leviticus et al., 1995). Using data from the Nebraska Tractor Test allowed a relationship between varying power and fuel rate to be established (fig. 9). Prior to forming the relationship, however, the power-take-off data from the Nebraska Tractor Test was converted to drawbar power by multiplying by 0.73 for a mechanical front-wheel assist tractor on tilled ground (*ASAE Standards*, 2003). The fuel rate for site-specific and deep subsoiling for each hardpan depth was obtained by using the fuel rate information from figure 9 and the drawbar power information from figure 8. The fuel use was then determined by dividing the fuel rate by the speed and width of the subsoiling operation.

Subsoiling depth and depth of hardpan were both found to be statistically significant factors affecting fuel use ($P \leq 0.01$ for each parameter). In addition, a significant interaction occurred between subsoiling depth and hardpan depth for estimated fuel use (fig. 10; $P \leq 0.01$). Similar amounts of fuel (approximately 18.6 L/ha) were required for deep subsoiling

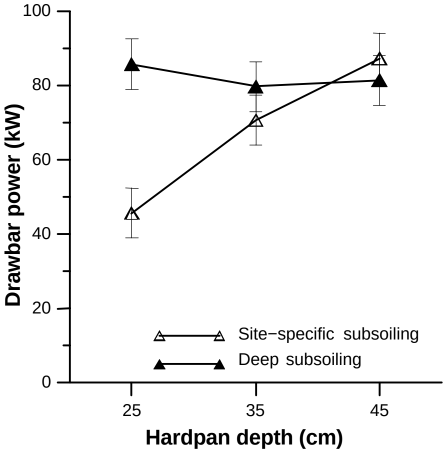

Figure 8. Drawbar power (averaged from years 2000-2003) analyzed for subsoiling treatment by hardpan depth location. Error bars indicate standard error values.

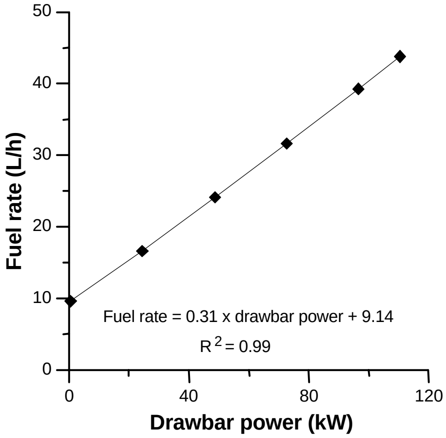

Figure 9. Linear relationship established for Nebraska Tractor Test data.

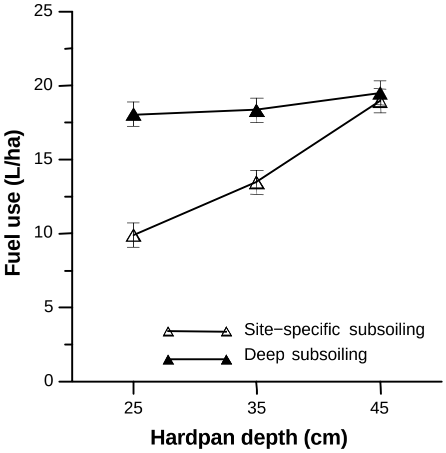

Figure 10. Estimated fuel use (averaged from years 2000-2003) analyzed for subsoiling treatment by hardpan depth location. Error bars indicate standard error values.

on all plots, with reduced values of 45% and 27% being required for site-specific subsoiling on plots with 25 and 35 cm depths of hardpan, respectively. As hardpan depth decreased, fuel use for site-specific subsoiling also decreased.

Examining figure 2 shows that 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. Using the data for estimated fuel use allows calculations to be made for overall fuel use required for subsoiling this field. If the whole field were subjected to deep subsoiling, it would require a total of 82 L of fuel, while site-specific subsoiling over the entire field would only require 62 L of fuel. Reducing subsoiling depth from 45 cm to the site-specific depth of subsoiling would reduce fuel use by 24% on this field. Savings would even be greater on fields with smaller areas in need of deep subsoiling or with shallower hardpans.

CONCLUSIONS

Statistically similar corn yields were produced by site-specific subsoiling and by uniform deep subsoiling. Both of these subsoiling treatments yielded greater than the no-subsoiling treatment. The cover crop did not affect corn yield. In addition:

- In the shallow (25 cm) and medium (35 cm) hardpan soil condition, draft force was reduced by 55% and 28%, respectively, using site-specific subsoiling compared to uniform deep subsoiling.
- In the shallow (25 cm) and medium (35 cm) hardpan soil condition, drawbar power was reduced by 47% and 17%, respectively, by site-specific subsoiling as compared to uniform deep subsoiling.
- Site-specific subsoiling reduced estimated fuel use by 45% for the 25 cm hardpan depth plots and by 27% for the 35 cm hardpan depth plots.

ACKNOWLEDGEMENT

This research was conducted as part of a Cooperative Research and Development Agreement with Deere & Co., Moline, Illinois.

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