5-2005

Crop Yield Response to Precision Deep Tillage

Larry G. Wells
University of Kentucky, larry.wells@uky.edu

Timothy S. Stombaugh
University of Kentucky, tim.stombaugh@uky.edu

Scott A. Shearer
University of Kentucky

Repository Citation

Wells, Larry G.; Stombaugh, Timothy S.; and Shearer, Scott A., "Crop Yield Response to Precision Deep Tillage" (2005). *Biosystems and Agricultural Engineering Faculty Publications*. 146.
https://uknowledge.uky.edu/bae_facpub/146

Crop Yield Response to Precision Deep Tillage

Notes/Citation Information

Published in *Transactions of the ASAE*, v. 48, issue 3, p. 895-901.

Digital Object Identifier (DOI)

https://doi.org/10.13031/2013.18493

CROP YIELD RESPONSE TO PRECISION DEEP TILLAGE

L. G. Wells, T. S. Stombaugh, and S. A. Shearer

ABSTRACT. *Experimental precision deep tillage was applied at three sites in central Kentucky with relatively well-drained silt loam soils in no-till crop production. Fields were divided into 0.4 ha (1 ac) grid cells using DGPS mapping. Assessment of soil compaction by machinery traffic was made using multiple soil cone penetrometer measurements and expressed as cone index (CI). Corn, wheat, and soybean yields were depressed in grid cells with* $CI_{avg} \geq 1.5$ *MPa (218 psi) prior to application of tillage treatments at sites 1 and 3, whereas at site 2, where most of the highest average CI values ranged from 1.44 to 1.49 MPa (209 to 216 psi), the opposite was true. In general, deep tillage resulted in yield improvement in compacted grid cells relative to those receiving no deep tillage; however, differences were significant at the 10% level in only two of six instances. Cells tilled to 40 cm generally had higher yields than cells tilled only to the depth at which* $CI_{avg} \geq 1.5$ *MPa (218 psi) (precision deep tillage) at sites 1 and 3. However, the opposite was true for double-crop soybean subjected to limited rainfall. At site 2, tilled cells had higher yields than non-tilled cells, with precision tillage showing the maximum relative yield.*

Keywords. *Precision agriculture, Precision deep tillage, Soil compaction, Soil cone index, Variable-depth tillage.*

Field machinery traffic can result in excessive compaction of cropland. Such compaction results in reduction of soil porosity, water holding capacity, and in most cases, hydraulic conductivity. Additionally, soil strength and bulk density can increase to levels that impair root penetration. In such instances, crop yield potential is reduced and revenue is compromised.

Deep tillage is a remedy of adverse soil compaction that results in improved conditions for crop growth. Mechanical disturbance of subsoil increases water holding capacity and reduces impedance to root penetration. However, such tillage requires substantial expenditure of energy and entails significant cost to producers.

Site-specific application of variable-depth deep tillage has shown promise in alleviating adverse soil compaction in zones or areas in which it occurs, while avoiding unnecessary application of this expensive procedure. A study was initiated in 2000 to determine the feasibility of applying site-specific deep tillage in Kentucky cropland where excessive compaction of soil by machinery traffic was suspected or determined. This article presents the results of an investigation involving three sites in central Kentucky consisting of approximately 142 ha (350 ac) of cropland. The specific objectives of this study were to: (1) develop and implement a method of applying site-specific variable-depth deep tillage in cropland where excessive soil compaction is determined, and (2) determine if site-specific variable-depth deep tillage results in improved crop yield potential as compared to uniform deep tillage or no deep tillage.

BACKGROUND

Yield loss attributable to excessive soil compaction is well documented in the literature. The primary cause of such compaction is machinery traffic characterized by high axle loading. Voorhees et al. (1989) reported yield loss of 30% in corn associated with soil compacted by axle loads of 18 Mg. Bakken et al. (1987) subjected wet soil to machine traffic and reported a 25% reduction in wheat yield. Gray and Pope (1986) compacted plots of silty clay loam soil with tractor traffic. Soybean stand and yield were reduced, and incidence of root rot was increased by compaction.

Increased soil bulk density and strength resulting from soil compaction is sensed using a soil cone penetrometer (*ASAE Standards*, 2002a). Bakhsh et al. (1998) determined significant correlation between corn and soybean yield and soil cone index (CI) and several other soil parameters in a study of site-specific agriculture in Iowa. Restricted root growth in various crops has been associated with elevated levels of CI in several soil types. Blanchar et al. (1978) reported that root growth in peas decreased as CI increased from 1.0 to 2.0 MPa and ceased above 2.0 MPa (290 psi) in a silt loam soil. Taylor and Gardner (1963) measured 30% of maximum root growth in cotton at CI = 2.0 MPa (290 psi) in a fine sandy loam soil and no root growth at CI = 2.9 MPa (420 psi). Gerald et al. (1982) determined root-limiting levels of CI of 6 to 7 MPa (870 to 1015 psi) and 2.5 MPa (363 psi) for cotton root growth in fine sandy loam and clay loam soils, respectively. Vepraskas and Wagger (1989) reported root growth limiting CI levels of 1.5, 3.0, and 4.1 MPa (218, 435, and 595 psi) in sandy loam coastal plain soils with clay contents of 4%, 12%, and 20%, respectively. Henderson et al. (1989) determined

---

Article was submitted for review in February 2004; approved for publication by the Power & Machinery Division of ASAE in April 2005.

The investigation reported in this article (04-05-032) is in connection with a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director. Mention of trade names is for informational purposes and does not necessarily imply endorsement by the Kentucky Agricultural Experiment Station.

The authors are **Larry G. Wells, ASAE Member Engineer,** Professor, **Timothy S. Stombaugh, ASAE Member Engineer**, Assistant Extension Professor, and **Scott A. Shearer, ASAE Member Engineer,** Professor, Department of Biosystems and Agricultural Engineering, University of Kentucky, Lexington, Kentucky. **Corresponding author:** Larry G. Wells, 128 C. E. Barnhart Building, University of Kentucky, Lexington, KY 40546-0276; phone: 859-257-3000, ext. 219; fax: 859-257-5671; e-mail: lwells@bae.uky.edu.

that wheat yield decreased in earthy sand soils above CI = 1.0 MPa (145 psi) and reported a 40% decrease at CI = 2.0 MPa (290 psi).

Deep tillage or subsoiling has been used extensively to rehabilitate soils that have been excessively compacted by machine traffic. Subsoilers typically consist of tools spaced at 76 cm (30 in.) corresponding to conventional crop row spacing. Tillage depth ranges from 25 to 45 cm (10 to 18 in.), depending on depth of compaction.

Deep tillage has been shown to increase crop yield in compacted soils. McConnell et al. (1989) reported yield increase in cotton from 12% to 41% corresponding to subsoiling compacted silt loam soils. Busscher et al. (2000) studied the effect of subsoiling of loamy sand soil compacted by traffic on yield of wheat and soybean. Yield increased in wheat by 1.5 to 1.7 Mg/ha (26.0 to 29.6 bu/ac) for each 0.1 MPa (14.5 psi) decrease in CI from 1.55 to 0.85 MPa due to subsoiling. Soybean yield increased from 1.1 to 1.8 Mg/ha (19.1 to 31.3 bu/ac) per 0.1 MPa decrease from 2.1 to 1.0 MPa.

The advent of precision agriculture has resulted in variable-rate control of fertilizer and pesticide application and seed population in crop production. Owing to the inherent variability of soil compaction in fields and the substantial energy requirement and cost associated with deep tillage, site-specific and variable-depth tillage may offer potential for increased crop production efficiency. Gorucu et al. (2001) reported a 28% reduction in fuel use for variable-depth tillage compared with uniform-depth tillage in a coastal plain soil with variable clay content, with no difference in seed cotton yield. Raper et al. (2003) reported approximate energy savings of 20% with no loss of cotton yield when applying variable-depth tillage.

EXPERIMENTAL METHODS

STUDY SITES

Three sites were identified in central Kentucky cropland where excessive compaction of soil by machinery traffic was suspected. Site 1 was a contiguous field of approximately 36.4 ha (90 ac) located north of Shelbyville, Kentucky. Alfalfa production prior to 1999 involved use of high axle load equipment at high soil water contents, resulting in soil compaction. The site included Shelbyville and Lowell silt loam soils that are described as varying from well-drained to moderately well-drained.

Site 2 was a field of approximately 21 ha (52 ac) located on the University of Kentucky Animal Research Center near Versailles, Kentucky. Low yields and nominal observations of compacted soil were attributed to disking the soil at high water content during tobacco production prior to 2000. The predominant soil type was a well-drained Maury silt loam.

Site 3 was approximately 90.6 ha (224 ac) of cropland involving five fields separated by roadways, fences, and streams located south of Shelbyville, Kentucky. Corn silage production at this site prior to 2000 involved the use of high axle load traffic, resulting in soil compaction. The predominant soil types at this site were also Shelbyville and Lowell silt loams. Sites 1 and 3 were operated by Worth and Dee Ellis Farms.

Corn, soybean, and wheat were produced at these sites using "no-till" practices, i.e., applying herbicide and leaving crop residue on the soil surface with minimal mechanical disturbance of soil. All fields were divided into 0.4 ha (1 ac) grid cells using DGPS mapping. All crops were harvested using combines equipped with DGPS and yield monitors. Precision farming methods were utilized at sites 1 and 3 for variable-rate application of lime, potassium, and phosphorous as determined by soil sampling from the 0.4 ha (1 ac) grid cells. Recommendations of the University of Kentucky Cooperative Extension Service (UKCES, 2004) were followed for determining fertilizer application rates. Fertilizer was applied uniformly on site 2 following the same recommendations indicated by soil sampling from the entire field.

ASSESSMENT OF SOIL COMPACTION

A five-probe recording soil cone penetrometer was designed and fabricated for use in this study (fig. 1). Stainless steel shafts and 20.3 mm (0.798 in.) base diameter cones were fabricated as specified by *ASAE Standards* (2002a). Penetration force was measured using 4.48 kN (1000 lb_f) strain gauge load cells (Interface, Inc., Scottsdale, Ariz.) with specified accuracy of $\pm$0.05% of full scale. An Instacal data acquisition and control board (Measurement Computing Corp., Middleboro, Mass.) converted analog signals to digital values for each of the five load cells at 200 Hz. Data acquisition code computed average readings for the load cells at approximately 0.8 s intervals and recorded them in a spreadsheet as the penetrometers were pushed into the soil at the prescribed rate of 3 cm (1.2 in.) per second (*ASAE Standards*, 2002b). Thus, five measurements of CI versus depth were recorded simultaneously at depth intervals of approximately 2.5 cm (1 in.).

Three probings were recorded in each grid cell, resulting in a total of 15 recordings per cell. Probings were generally made traversing diagonally across cells at approximately equal intervals of separation. This is fewer than the number of observations suggested by Cassel (1982) to estimate average CI within 10% of the true mean at the 10% level of significance. However, it was impractical to take more measurements over the large number of grid cells investigated in this study. The average CI was calculated for each nominal 2.5 cm (1 in.) depth increment in each cell. CI measurements were recorded during March 2000 with soil water content near field capacity (approximately 25% d.b.) in the B and lower A horizons at sites 1 and 2. Measurements were made and recorded in the same manner at site 3 in March 2001.

APPLICATION OF DEEP TILLAGE

Based on the various studies cited in the Background section, deep tillage was deemed beneficial at CI $\geq$ 1.5 MPa (218 psi). Deep tillage was applied using an Ecolo-til 2500 subsoiler manufactured in 2000 by Case-IH Corporation (fig. 2). The implement consisted of five shanks spaced 76 cm (30 in.) apart with 20 cm (8 in.) "no-till" shanks and points reaching a maximum depth of 40 cm (16 in.). Tillage depth was adjusted by moving the gauge wheels between 15 and 40 cm (6 and 16 in.) as indicated by the respective tillage treatments applied to grid cells.

At site 1, all grid cells were divided randomly into three deep tillage treatments: (1) tillage to maximum depth of 40 cm (16 in.), (2) tillage to the maximum depth for which

Figure 1. Tractor-mounted, multi-probe recording soil cone penetrometer equipped with DGPS.

average cell CI ≥ 1.5 MPa (218 psi), i.e., precision tillage, and (3) a no-tillage control. Because not all cells were characterized by average CI ≥ 1.5 MPa (218 psi), random assignment of the above treatments resulted in the following categories of cells: (1) average maximum CI < 1.5 MPa (218 psi) not tilled, (2) average maximum CI < 1.5 MPa (218 psi) tilled to maximum depth of 40 cm (16 in.), (3) average maximum CI ≥ 1.5 MPa (218 psi) not tilled, (4) average maximum CI ≥ 1.5 MPa (218 psi) tilled to maximum depth of 40 cm (16 in.), and (5) tilled to precise maximum depth of <40 cm (16 in.) for which average CI ≥ 1.5 MPa (218 psi) (precision tillage).

Unfortunately, at site 1, the average CI ≥ 1.5 MPa (218 psi) was determined at less than maximum tillage depth in only 13 of 67 cells. After random assignment of the experimental treatments, only four of these cells received the precision tillage treatment, with 15 cells tilled to the maximum depth and 19 cells assigned to the no-tillage control treatment. Tillage was applied during late October 2000 with soil water content near the wilting point. Table 1 is a compilation of cell compaction and tillage treatments applied at site 1.

As a result of the dearth of cells in which precision tillage was applied at site 1, the experimental protocol was revised

Figure 2. Case-IH Ecolo-til 2500 subsoiler (2000 model) with five shanks spaced at 76 cm (30 in.) with a maximum tillage depth of 40 cm (16 in.).

Table 1. Categorization of 0.4 ha (1 ac) cells comprising experimental site 1 based on average maximum CI measured prior to application of deep tillage treatments and type of deep tillage applied.

CI Range and Treatment	No. of Cells
Before tillage	
CI_{avg} < 1.5 MPa (218 psi)	29
CI_{avg} > 1.5 MPa (218 psi)	38
After tillage	
CI_{avg} < 1.5 MPa (218 psi) not tilled	13
CI_{avg} < 1.5 MPa (218 psi) tilled to 40 cm (15.75 in.)	16
CI_{avg} > 1.5 MPa (218 psi) precision tilled to <40 cm (15.75 in.)	4
CI_{avg} > 1.5 MPa (218 psi) tilled to 40 cm (15.75 in.)	15
CI_{avg} > 1.5 MPa (218 psi) not tilled	19

Table 2. Categorization of 0.4 ha (1 ac) cells comprising experimental site 2 based on average maximum CI measured prior to application of deep tillage treatments and type of deep tillage applied.

CI Range and Treatment	No. of Cells
Before tillage	
CI_{avg} < 1.5 MPa (218 psi)	31
CI_{avg} > 1.5 MPa (218 psi)	14
After tillage	
CI_{avg} < 1.5 MPa (218 psi) not tilled	16
CI_{avg} < 1.5 MPa (218 psi) tilled to 40 cm (15.75 in.)	15
CI_{avg} > 1.5 MPa (218 psi) precision tilled to <40 cm (15.75 in.)	7
CI_{avg} > 1.5 MPa (218 psi) tilled to 40 cm (15.75 in.)	4
CI_{avg} > 1.5 MPa (218 psi) not tilled	3

Table 3. Categorization of 0.4 ha (1 ac) cells comprising experimental site 3 based on average maximum CI measured prior to application of deep tillage treatments and type of deep tillage applied.

CI Range and Treatment	No. of Cells
Before tillage	
CI_{avg} < 1.5 MPa (218 psi)	119
CI_{avg} > 1.5 MPa (218 psi)	86
After tillage	
CI_{avg} < 1.5 MPa (218 psi) not tilled	119
CI_{avg} > 1.5 MPa (218 psi) precision tilled to <40 cm (15.75 in.)	26
CI_{avg} > 1.5 MPa (218 psi) tilled to 40 cm (15.75 in.)	28
CI_{avg} > 1.5 MPa (218 psi) not tilled	32

for site 2. Grid cells were divided into two categories: (1) cells with an average CI $\geq$ 1.5 MPa (218 psi), and (2) cells with an average CI < 1.5 MPa (218 psi). Cells in category 1 were then randomly assigned to three treatments: (1) tillage to maximum depth of 40 cm (16 in.), (2) tillage to the precise depth for which average CI $\geq$ 1.5 MPa (218 psi) (precision tillage), and (3) a non-tilled control. Cells in category 2 were randomly assigned to two treatments: (1) tillage to maximum depth of 40 cm (16 in.), and (2) a non-tilled control. Deep tillage treatments were applied to site 2 during early December 2000 with topsoil water content relatively high and subsoil water content relatively dry. Table 2 is a compilation of cell compaction and tillage treatments applied at site 2. At site 3, deep tillage treatments were applied in both March and October 2001. Grid cells with an average CI $\geq$ 1.5 MPa (218 psi) were randomly assigned to the same treatments as site 2, with treatments applied in half of the cells in March, when subsoil water content was relatively high, and the remainder applied in October, when subsoil water content was near the wilting point. Because preliminary analysis of site 1 indicated minimal effect of tillage on yield in cells with average CI < 1.5 MPa (218 psi), such cells were not tilled at site 3. Table 3 is a compilation of cell compaction and tillage treatments applied at site 3.

CROP PRODUCTION

Assessment of soil compaction, application of tillage treatments, and crop production after application of tillage treatments at the various sites is compiled in table 4. Site 1 was planted in corn in 2001; however, potassium deficiency resulted in a severe outbreak of Stewart's wilt at two concentrated areas within the field. Because the resulting yield loss was not attributable to soil compaction, yield data from 2001 was omitted from the study. Winter wheat was planted in late 2001 and harvested in June 2002. Double-crop soybean was planted and harvested in 2002. A severe shortage of rainfall from July through October 2002 resulted in poor yield.

Corn was grown at site 2 in 2001. Yield was relatively good (8.6 Mg/ha; 157 bu/ac) for this soil and location. Corn was grown again in 2002, and lack of rainfall after June was even more severe at this site. Yield was very poor (0.9 Mg/ha; 16 bu/ac), and yield data were unavailable for 22 of 45 grid cells. Thus, the 2002 crop was not considered in the analysis.

Full-season soybean was produced at site 3 in 2001. Deep tillage treatments were applied to only half of the compacted grid cells in spring 2001, thus yields in non-treated compacted cells were likely depressed. Winter wheat was planted in late 2001, after applying the remaining deep tillage treatments, and was harvested in June 2002. Double-crop soybean was planted thereafter and was adversely affected by the aforementioned lack of rainfall after June 2002.

YIELD MEASUREMENT

Crop yield was measured at all sites using combines equipped with DGPS and yield monitors. The software used utilized a standard time delay of 12 s to coordinate yield measurement with location as measured using GPS. The

Table 4. Compaction assessment, tillage, and post-tillage crop production schedule at the various study sites.

Year	Site 1	Site 2	Site 3
2000	CI measured in March; wheat; double-crop soybean; tillage applied in October.	CI measured in March; full-season soybean; tillage applied in December.	Corn
2001	Corn (wilt infestation, data not included in study).	Corn	CI measured in March; tillage applied in half of compacted cells in March. Full-season soybean; tillage applied in half of compacted cells in October.
2002	Winter wheat; double-crop soybean.	Corn (drought, data not included in study).	Winter wheat; double-crop soybean.

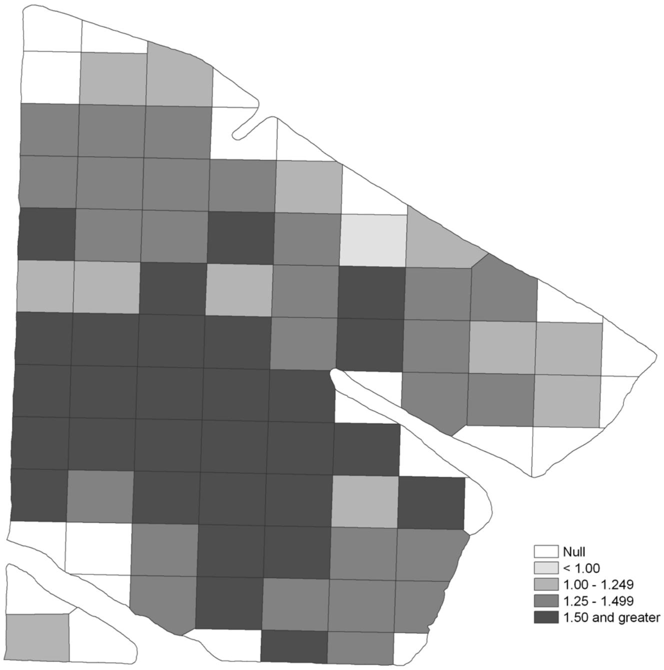

Figure 3. Average maximum soil cone index measured at or above maximum tillage depth of 40 cm (16 in.) in 0.4 ha (1.0 ac) cells at site 1 prior to the application of tillage treatments.

yield monitor data were analyzed as "point data," i.e., all measurements associated with GPS coordinates that were contained within a cell were assigned to that cell. No provision was made for measurement error resulting from the combine header overlapping cell boundaries, such as "trimming" or discarding yield data collected near cell boundaries. Thus, mean yield was computed for each 0.4 ha (1 ac) grid cell from observations recorded within its boundaries, and error associated with this phenomenon was regarded as experimental error.

Total yield for all crops at all sites was measured separately by weighing grain carts filled while harvesting crops from each site. These data were used as a cumulative check of the calibration of the yield monitors, which were re-calibrated as needed. The resulting yield map shape files were processed using ArcGIS (2003) software.

RESULTS AND DISCUSSION

Figure 3 illustrates the maximum average CI measured in each grid cell at or above 40 cm (15.75 in.) depth at site 1. Average CI was computed for the 15 measurements taken in each cell at 2.5 cm (1 in.) depth increments, with the maximum average CI and corresponding depth determined for each cell. A corresponding determination was made in each cell of the maximum depth, $\leq$40 cm (15.75 in.), for which average CI was $\geq$ 1.5 MPa (218 psi). These and corresponding measurements at sites 2 and 3 provided the basis for the deep tillage application protocol outlined in tables 1 to 3. CI was quite variable within cells at each depth of measurement, with coefficients of variation (CV) ranging from approximately 20% to 50%.

Since the experimental factors could not be equally replicated in all experimental fields, because of the history of the cells within fields, the design of the experiment was an incomplete randomized block design with unequal observations. Therefore, the statistical analysis of the treatment means and modeling of data was accomplished using the SAS Proc Mixed procedure (SAS, 1999). Effects of the state of soil compaction before and after tillage on relative crop yield are reported at the 10% level of significance.

Table 5 presents mean crop yield at site 1 for 1999, 2000, and 2002. Relative yield for each crop, i.e., average cell yield divided by average site yield, was computed for each cell. Relative yields of corn in 1999 and of wheat in 2000 indicate that cells with $CI_{avg} \geq 1.5$ MPa (218 psi) had significantly

Table 5. Relative crop yields at site 1 for 1999, 2000, and 2002 showing effects of pre-tillage soil compaction and tillage treatments applied in November 2000. Relative cell yield is yield in each 0.4 ha (1 ac) cell divided by average yield at the site, i.e., all cells.

Treatment	1999 Corn	2000 Wheat	2000 Double-Crop Soybean	2002 Wheat	2002 Double-Crop Soybean
$CI_{avg} < 1.5$ MPa (218 psi) not tilled	1.18 b[a]	1.06 b	0.67 b	0.95 a	1.21 a
$CI_{avg} \geq 1.5$ MPa (218 psi) not tilled	0.86 a	0.97 a	1.25 a	0.97 ab	0.86 bcd
$CI_{avg} \geq 1.5$ MPa (218 psi) precision tilled to $\leq$40 cm (15.75 in.)	--	--	--	0.97 ab	1.31 ac
$CI_{avg} \geq 1.5$ MPa (218 psi) tilled to 40 cm (15.75 in.)	--	--	--	1.13 b	0.63 d
$CI_{avg} < 1.5$ MPa (218 psi) tilled to 40 cm (15.75 in.)	--	--	--	1.02 ab	1.16 a
Average yield in Mg/ha (bu/ac)	2.23 (35.7)	3.58 (53.5)	0.39 (5.8)	2.97 (44.4)	0.48 (7.2)

[a] Mean relative yields in any column denoted by the same letter are not different at the 10% level of significance.

Table 6. Mean relative crop yields at site 2 for 1996 through 2001 showing effects of pre-tillage soil compaction and precision tillage treatments applied in December 2000. Relative cell yield is yield in each 0.4 ha (1 ac) cell divided by average yield at the site, i.e., all cells.

Treatment	1996 Corn	1997 Corn	1998 Full-Season Soybean	1999 Corn	2000 Full-Season Soybean	2001 Corn
$CI_{avg} < 1.5$ MPa (218 psi) not tilled	0.98 a[a]	1.00 a	1.00 a	0.99 a	0.94 a	0.99 a
$CI_{avg} \geq 1.5$ MPa (218 psi) not tilled	1.04 a	1.01 a	1.01 a	1.03 a	1.00 a	0.94 a
$CI_{avg} \geq 1.5$ MPa (218 psi) precision tilled to $\leq$40 cm (15.75 in.)	--	--	--	--	--	1.06 b
$CI_{avg} \geq 1.5$ MPa (218 psi) tilled to 40 cm (15.75 in.)	--	--	--	--	--	1.04 ab
$CI_{avg} < 1.5$ MPa (218 psi) tilled to 40 cm (15.75 in.)	--	--	--	--	--	1.02 ab
Average yield in Mg/ha (bu/ac)	1.87 (30)	5.42 (86.9)	1.97 (29.5)	4.74 (76)	3.75 (56.1)	8.59 (137.7)

[a] Mean relative yields in any column denoted by the same letter are not different at the 10% level of significance.

lower yield. The opposite was true, however, with double-crop soybean in 2000. Both corn yield in 1999 and soybean yield in 2000 were well below average yield of all fields harvested by Worth and Dee Ellis Farms for these crop years.

Wheat yield in 2002 indicates a substantial increase (although not significant at the 10% level) in compacted cells that were subsoiled. This benefit was not found in the relatively small number (4) of cells that received the precision deep tillage treatment. Double-crop soybean yield in 2002 shows the opposite effect of compaction that was seen prior to tillage in 2000. Cells that were not compacted or that received precision tillage showed substantially higher yield, although again not different at the 10% level of significance. Cells with compaction of deeper subsoil had the greatest depression of yield during this season of relatively low rainfall.

Table 6 shows relative yields from site 2 for years 1996 through 2001. Prior to the application of tillage treatments in December 2000, yields were highest in cells with $CI_{avg} \geq$ 1.5 MPa (218 psi), although differences in relative yield between cells with $CI_{avg} \geq 1.5$ MPa (218 psi) and $CI_{avg} <$ 1.5 MPa (218 psi) were not significant at the 10% level. McKyes et al. (1979) reported that optimum yield of silage corn yield on a clay soil was dependent on soil bulk density and rainfall availability. As rainfall decreased, optimum bulk density increased. Such a phenomenon may have occurred in the pre-tillage yield measurements at site 2. Relative corn yield in 2001 for cells with $CI_{avg} \geq 1.5$ MPa (218 psi) was highest for cells tilled only to depths for which $CI_{avg} \geq$ 1.5 MPa (218 psi), but only higher at the 10% level than compacted cells that were not tilled. Although not shown in tables 2 or 6, the maximum depth for which $CI_{avg} \geq 1.5$ MPa (218 psi) at site 2 ranged from 15 to 22.5 cm (5.9 to 8.9 in.). Thus, tillage to 40 cm (16 in.) provided no benefit.

All grid cells receiving tillage treatments had higher corn yields in 2001 than non-tilled cells. Cells receiving precision deep tillage treatments had the highest yields (higher than compacted cells not tilled at the 10% level of significance), indicating that precision deep tillage may be most beneficial when adverse compaction is relatively shallow. On the other hand, since these cells also had the highest yield before tillage, other factors may be more responsible for the difference.

Table 7 shows relative yields from site 3 for years 2000 through 2002. Prior to tillage, grid cells with $CI_{avg} \geq 1.5$ MPa (218 psi) had lower yield than those with $CI_{avg} < 1.5$ MPa (218 psi), and the difference was significant at the 10% level. After application of deep tillage treatments in spring 2001, yield in cells receiving tillage increased relative to cells with $CI_{avg} \geq 1.5$ MPa (218 psi) receiving no tillage, although not significantly different at the 10% level, and were approximately equivalent to cells with $CI_{avg} < 1.5$ MPa (218 psi). After application of the remainder of deep tillage treatments in fall 2002, grid cells receiving tillage continued to show increased yields relative to compacted cells receiving no tillage. This difference was most pronounced for double-crop soybean in 2002 subjected to severely limited rainfall. Relative yield in cells with $CI_{avg} < 1.5$ MPa (218 psi), not tilled, and those with $CI_{avg} \geq 1.5$ MPa (218 psi), tilled to 40 cm, was greater than those with $CI_{avg} \geq 1.5$ MPa (218 psi), not tilled, at the 10% level of significance. Relative yield in cells tilled only to the maximum depth, $\leq$40 cm (16 in.), at which $CI_{avg} \geq 1.5$ MPa (218 psi) (precision-tilled) were not different at the 10% level of significance than in cells with $CI_{avg} \geq 1.5$ MPa (218 psi) which were not tilled.

Corn, wheat, and soybean yields were significantly depressed (10% level) in grid cells with $CI_{avg} \geq 1.5$ MPa (218 psi) prior to application of tillage treatments at sites 1 and 3, whereas at site 2, where most of the highest average CI values ranged from 1.44 to 1.49 MPa (209 to 216 psi) and compaction was relatively shallow, the opposite was true. In three of five crops analyzed at sites 1 and 3, deep tillage to 40 cm (16 in.) of compacted grid cells resulted in higher yield than in compacted cells receiving no deep tillage. However, the difference was significant at the 10% level in only one instance. Cells receiving precision deep tillage had greater

Table 7. Mean relative crop yields at site 3 for 2000 through 2002 showing effects of pre-tillage soil compaction and precision tillage treatments applied in March and November 2001. Relative cell yield is yield in each 0.4 ha (1 ac) cell divided by average yield at the site, i.e., all cells.

Treatment	2000 Corn	2001 Full-Season Soybean	2002 Wheat	2002 Double-Crop Soybean
$CI_{avg} < 1.5$ MPa (218 psi) not tilled	1.02 b[a]	1.01 a	1.01 a	1.02 b
$CI_{avg} \geq 1.5$ MPa (218 psi) not tilled	0.97 a	0.98 a	0.99 a	0.93 a
$CI_{avg} \geq 1.5$ MPa (218 psi) precision tilled to $\leq$40 cm (15.75 in.)	--	0.99 a	1.01 a	1.01 ab
$CI_{avg} \geq 1.5$ MPa (218 psi) tilled to 40 cm (15.75 in.)	--	1.02 a	0.95 a	1.08 b
Average yield in Mg/ha (bu/ac)	5.92 (94.9)	2.65 (39.6)	3.81 (61.1)	0.67 (10.0)

[a] Mean relative yields in column denoted by different letters are different at the 10% level of significance.

yields than compacted cells not tilled in five of six crops, but in only one case was the difference significant at the 10% level. At site 2, cells receiving tillage had higher yields than cells receiving no tillage (both compacted and not compacted), with cells receiving precision tillage significantly greater than compacted cells receiving no tillage. However, some of the difference at this site may be attributable to factors other than tillage.

CONCLUSIONS

Experimental precision deep tillage was applied at three sites in central Kentucky with relatively well-drained silt loam soils in no-till crop production. Fields were divided into 0.4 ha (1 ac) grid cells using DGPS mapping. Assessment of soil compaction by machinery traffic was made using multiple soil cone penetrometer measurements.

Precision deep tillage produced increased yield relative to compacted cells receiving no deep tillage in five of six crops studied. However, the difference was significant at the 10% level in only one instance in which soil compaction was quite shallow. Although yields were significantly depressed (10% level) in cells with CI > 1.5 MPa in all crops analyzed prior to application of tillage at sites 1 and 3, even deep tillage to 40 cm (16 in.) significantly increased yield in only one of five crops grown after application of tillage. Thus, it appears that a higher threshold for applying deep tillage is indicated, perhaps 2.0 MPa (290 psi). Clearly, significant yield improvement will be required before any system of applying precision deep tillage can be profitable. Research will continue to determine the circumstances in which application of precision deep tillage will result in a probable increase of net crop revenue that is greater than can be achieved with uniform-depth deep tillage.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of Mr. Jeff Norkus, Mr. Carl King, and Mr. Steve Higgins, Department of Biosystems and Agricultural Engineering, University of Kentucky, and of Mr. Mike Ellis, Worth and Dee Ellis Farms, Inc.

REFERENCES

ArcGIS. 2003. ArcGIS version 8.3. Redlands, Cal.: Environmental Systems Research Institute.

ASAE Standards, 49th ed. 2002a. S313.3: Soil cone penetrometer. St. Joseph, Mich.: ASAE.

ASAE Standards, 49th ed. 2002b. EP542: Procedures for using and reporting data obtained with the soil cone penetrometer. St. Joseph, Mich.: ASAE.

Bakhsh, A., T. S. Colvin, D. B. Jaynes, R. S. Kanwar, and U. S. Tim. 1998. Using soil attributes and GIS for interpretation of spatial variability in yield. *Trans. ASAE* 43(4): 819-828.

Bakken, L. R., T. Borresen, and A. Njos. 1987. Effect of soil compaction by tractor traffic on soil structure, denitrification, and yield of wheat. *J. Soil Sci.* 38(3): 541-552.

Blanchar, R. W., C. R. Edmonds, and J. M. Bradford. 1978. Root growth in cores from fragipan and B2 horizons of Hobson soil. *SSSA J.* 42(3): 437-440.

Busscher, W. J., J. R. Frederick, and P. J. Bauer. 2000. Timing effects of deep tillage on penetration resistance and wheat and soybean yield. *SSSA J.* 64(3): 999-1003.

Cassel, D. K. 1982. Tillage effects on soil bulk density and mechanical impedance. In *Predicting Tillage Effects on Soil Physical Properties and Processes*, ch. 4: 45-67. ASA Special Publication 44. D. M. Dral, ed. Madison, Wisc.: ASA.

Gerald, C. J., P. Sexton, and G. Shaw. 1982. Physical factors influencing soil strength and root growth. *Agron. J.* 74(2): 875-879.

Gorucu, S., A. Khalilian, Y. Han, R. B. Dodd, F. J. Wolak, and M. Keskin. 2001. Variable-depth tillage based on geo-referenced soil compaction data in coastal plain region of South Carolina. ASAE Paper No. 011016, St. Joseph, Mich.: ASAE.

Gray, L. E., and R. A. Pope. 1986. Influence of soil compaction on soybean stand, and yield and phytophthora root rot incidence. *Agron. J.* 78(1): 189-191.

Henderson, C. W. L. 1989. Using a penetrometer to predict the effects of soil compaction on the growth and yield of wheat on uniform sandy soils. *Australian J. Agric. Res.* 40(3): 497-508.

McConnell, J. S., J. S. Frizzell, and W. H. Wilkerson. 1989. Effects of soil compaction and subsoil tillage of two alfisols on the growth and yield of cotton. *J. Prod. Agric.* 2(2): 140-146.

McKyes, E., S. C. Negli, R. J. Godwin, and J. R. Ogilvie. 1979. The effect of machinery traffic and tillage operations on the physical properties of a clay and on yield of silage corn. *J. Agric. Eng. Res.* 24(2): 143-148.

Raper, R. L., D. W. Reeves, J. Shaw, E. van Santen, P. L. Mask, and T. E. Grift. 2003. Reducing draft and maintaining crop yields with site-specific tillage. In *Proc. 16th ISTRO Conf.*, 961−965. Wageningen, The Netherlands: International Soil Tillage Research Organization.

SAS. 1999. The SAS system for Windows. Release 8.02. Cary, N.C.: SAS Institute, Inc.

Taylor, H. M., and H. R. Gardner. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content, and strength of soil. *Soil Sci.* 96(3): 153-156.

UKCES. 2004. Lime and nutrient recommendations, 2004-2005. Bulletin AGR-1. Lexington, Ky.: University of Kentucky Cooperative Extension Service.

Vepraskas, M. J., and M. G. Wagger. 1989. Cone index values diagnostic of where subsoiling can increase corn root growth. *SSSA J.* 52(4): 1117-1121.

Voorhees, W. B., J. F. Johnson, G. W. Randall, and W. W. Nelson. 1989. Corn growth and yield as affected by surface and subsoil compaction. *Agron. J.* 81(2): 294-303.