IN-ROW SUBSOILERS THAT REDUCE SOIL COMPACTIONAND RESIDUE DISTURBANCE

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ABSTRACT. *Aboveground soil disruption prior to planting is avoided in conservation tillage systems due to the need to keep plant residue in place. However, belowground disruption is necessary in many Southeastern U.S. soils to ameliorate soil compaction problems. For use in conservation tillage systems, belowground soil disruption should be maximized while aboveground disruption should be minimized. To assist in choosing the best shank for strip-tillage systems which accomplish both objectives, comparisons were made between several shanks commonly used for conservation tillage systems to provide in-row subsoiling prior to planting. A tractor-mounted three-dimensional dynamometer was used to measure draft, vertical, and side forces in a Coastal Plain soil in Alabama. Three subsoiler systems were evaluated at different depths of operation: (i) Paratill ™ bentleg shanks, (ii) Terramax ™ bentleg shanks, and (iii) KMC straight shanks. A portable tillage profiler was used to measure both above- and belowground soil disruptions. Shallower subsoiling resulted in reduced subsoiling forces and reduced surface soil disturbance. The bentleg subsoilers provided maximum soil disruption and minimal surface disturbance and allowed surface residue to remain mostly undisturbed. Bentleg shanks provide optimum soil conditions for conservation systems by disrupting compacted soil profiles while leaving crop residues on the soil surface to intercept rainfall and prevent soil erosion.*

Keywords. *Draft force, Drawbar power, Cone index, Bulk density, Residue, Bentleg shanks, Subsoiler, soil compaction.*

Disruption of compacted soils by subsoilers is a common practice and provides additional soil volume for expansion of plant roots (Box and Langdale, 1984; Busscher and Sojka, 1987; Busscher et al., 1988; Bernier et al., 1989; Barber, 1994; Raper et al., 1998). Maximum growth of plant roots is critical to ensuring maximum yields, particularly in the southeastern United States, where short-term droughts are common during the growing season (Doty and Reicosky, 1978; Reicosky et al., 1977). The ability of a crop to have 1 to 3 extra weeks of moisture availability provided by loosened soil profiles improves drought resistance and crop yields (Doty and Reicosky, 1978). Therefore, the main objective of the subsoiling process is to disrupt compacted soil profiles throughout the rooting depth and provide a maximum volume of soil for plant roots to grow into.

For these anticipated benefits, most Coastal Plains soils in the southeastern United States have been annually subsoiled using a variety of shanks (Dumas et al., 1973; Campbell et al., 1974; Raper, 2005). Much tillage energy is annually expended on this soil-loosening process throughout this region. However, many producers are currently modifying their management systems to include strategies to leave large amounts of crop residue on the soil surface. These crop residues are either from the last cash crop or from specially grown winter cover crops. To achieve maximum benefits from these crop residues, they must be left on the soil surface where crop residues can intercept rain drops and prevent soil erosion (Laflen and Colvin, 1980; Cogo et al., 1984; Dickey et al., 1984; Blough et al., 1990). Increased infiltration and reduced evaporation of rainfall has also been found when crop residues are left on the soil surface (Jones et al., 1994; Potter et al., 1995; Allmaras and Wilkins, 1997). Both of these factors increase the available moisture for cash crops to use later in the growing season.

A predicament exists when a tillage process is necessary to achieve maximum productivity from a naturally compacted soil profile and this same tillage process buries crop residue which is also crucial to maximizing infiltration and water storage. Little research has been conducted to determine optimum methods of subsoiling that maximally disturb compacted soil profiles while leaving the soil surface relatively undisturbed. Raper (2005) examined several shanks used in this region in a soil bin study which contained a Coastal Plain soil. His study revealed that bentleg subsoilers required the least amount of draft force for the maximum area disturbed while minimally disturbing the soil surface.

The objectives of this study were therefore to compare several bentleg shanks and straight shanks and their effect on the resulting soil condition in a field experiment. The evaluations will be based upon:

- degree of loosening provided by subsoiling,
- subsoiling forces and energy necessary for soil disruption,
- area and shape of disturbed soil profiles, and
- amount of residue buried by the subsoiling operation.

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METHODS AND MATERIALS

An experiment was conducted at the E.V. Smith Research Center near Shorter, Alabama to determine the force necessary to disrupt a hardpan profile in a southeastern U.S. soil, a Compass loamy sand soil (*coarse-loamy, siliceous, subactive, thermic Plintic Paleudults*) and to determine the amount of soil disruption caused by the subsoiling event. Compass loamy sand soil is a Coastal Plain soil commonly found in the southeastern United States and along the Atlantic Coast of the United States. The soil is easily compacted and a hardpan condition is often found at depths of 20 to 30 cm.

The shanks used for the experiment were from three different manufacturers (table 1) and were mounted on 4-row toolbars. The only straight shank was an angled in-row subsoiler shank which was manufactured by Kelley Manufacturing Company (table 1; fig. 1). The shank design used had an angle of 45° with the horizontal. This shank had a width of 25-mm and used a wear tip of 44-mm width. Wear plates were used with the shanks to simulate conditions of actual use.

Two bentleg-type shanks were also included in the study (fig. 1; table 1). Bigham Brothers Inc. manufactured the Paratill™ shank which was formerly manufactured by Howard Rotovator and ICI (Harrison, 1988). This shank is bent to one side by 45° and with the leading edge rotated forward by 25°. As the shank travels forward, it contacts the soil over a 216-mm width. The Paratill™ has a 57-mm wide point. The other bentleg shank used in the study was manufactured by Worksaver Inc. and is referred to as the Terramax™ (table 1; fig. 1). This shank is rolled about a 0.43-m radius and is rotated forward by 15°.

All shanks were attached to a three-dimensional three-point hitch dynamometer which was mounted on a JD 8300 tractor. The dynamometer was used to measure tillage forces and had a capacity of 90 kN. Draft force, vertical force, side force, speed, and depth of operation were recorded continuously for each shank test. The speed of tillage for all tests was held approximately constant at 4.4 km/h. Each set of force values obtained from each plot was averaged to create one specific value per plot of draft, vertical force, and side force. Drawbar power was calculated using speed of tillage and draft force.

A 3 × 3 randomized block experiment with two factors and four replications was conducted on 4-row plots (0.76-m row spacing) which were 9.1 m long × 3.0 m wide. The two factors were subsoiler shank (KMC subsoiler, Paratill™ subsoiler, and Terramax™ subsoiler) and tillage depth (0.2, 0.3, and 0.4 m).

Before shank tests were conducted in each plot, a set of five cone index measurements was acquired with a multiple-probe soil measurement system (MPSMS) (Raper et al., 1999). This set of measurements was taken with all five-cone index measurements being equally spaced at a 0.19-m distance across the soil with the middle measurement being directly in the path of the shank. As soon as the shank had been tested in each plot, another set of five cone index measurements was also taken in the disturbed soil in close proximity to the original cone index measurements.

Table 1. Description of shanks used in the experiment.

Common Name	Shank Type	Manufacturer	Shank Thickness (mm)
KMC subsoiler	Straight	Kelley Manufacturing Co. (Tifton, Ga.)	25
Paratill™ subsoiler	Bentleg	Bigham Brothers Inc. (Lubbock, Tex.)	25
Terramax™ subsoiler	Bentleg	Worksaver Inc. (Litchfield, Ill.)	15

Figure 1. Side and front views of individual shanks used in the experiment.

Using the frame of the MPSMS, bulk density measurements were taken directly in the path of the shank before and after tillage. Cores obtained with the MPSMS were sliced into 5-cm depth increments. Before tillage, one core was taken to quantify the original values of bulk density. These samples from the undisturbed plots were difficult to obtain before tillage because soil tended to fall out of the sampling tube. For this reason, bulk density samples were only obtained near the surface prior to subsoiling. After the experiment was completed and additional rainfall had occurred, the final measurements of bulk density were easily obtained throughout the entire soil profile. After tillage, three cores were taken to quantify the disturbed soil profile.

Six digital photographs were taken of a random plot within each replication before any subsoiling treatments were performed. These photographs were displayed on a computer monitor with a grid superimposed. Intersection points that were covered by residue were counted as were the intersection points where no residue was present (Laflen et al., 1981). The initial percent residue coverage was calculated using this procedure. After subsoiling was completed, another set of six digital photographs was taken of each plot and analyzed to determine the percent residue remaining.

After each set of tillage experiments was conducted, a portable tillage profiler (Raper et al., 2004; Raper, 2005) was used to determine the width and volume of soil that was disturbed by the tillage event in each plot. This measurement is referred to as the 'spoil.' The disturbed soil was then manually excavated from the trenched zone for each plot for approximately 1 m along the path of tillage to allow five independent measurements of the area of the subsoiled or trenched zone. This measurement is referred to as the 'trench.' Care was taken to ensure that only soil loosened by tillage was removed.

In an effort to understand the effects of draft force on the trenched cross-sectional area, an equation was created that considered these parameters (Raper, 2005).

$$TSR = D / TCA \qquad (1)$$

where

TSR = trench specific resistance (kN/m^2),
D = draft (kN), and
TCA = trench cross-sectional area (m^2).

It is advantageous for TSR to be small because this would indicate small values of draft coupled with large values of below-ground disruption.

Preplanned single degree of freedom contrasts and Fisher's protected least significant difference (LSD) were used for mean comparison. Discussions will focus on main effects except where significant interactions occurred between subsoiler and depth of operation. A probability level of 0.05 was assumed to test the null hypothesis that no differences existed between shanks or between tillage depths.

RESULTS AND DISCUSSION

SOIL PROPERTY DATA

Before subsoiling, bulk density was found to be affected by the depth at which it was measured within the row position (fig. 2; $p \le 0.001$). Bulk density was found to be reduced near the soil surface probably due to past surface tillage treatments. It rapidly increased down to a 0.05-m depth and then stabilized.

After subsoiling, bulk density measurements showed loosening of the soil profile compared to bulk density measurements obtained near the soil surface before subsoiling (fig. 2). Averaging across subsoiling depths, at depths of 0.02 m and 0.38 cm the KMC subsoiler was found to have a trend toward reduced bulk density compared to the Paratill™ ($p \le 0.052$). The KMC subsoiler also exhibited a trend toward reduced bulk density at 0.02-m depth compared to the Terramax™ ($p \le 0.092$). At depths of 0.33, 0.38, and 0.48 m, the Paratill™ had lower bulk density than the Terramax™ ($p \le 0.085$, $p \le 0.029$, $p \le 0.039$, respectively) with the bottom two depths having significant differences. It appears that near the soil surface, the KMC subsoiler reduces bulk density better than the other shanks while at the deeper depths, the Paratill™ excels in loosening the soil profile.

Before subsoiling, measurements of cone index were found to be affected by the row position at which they were measured (fig. 3A; $p \le 0.001$). Down to depths of 0.2 m, the trafficked position showed maximum values of cone index. Minimum values of cone index were measured in the no-trafficked row position down to depths of 0.15 m. From 0.15- to 0.35-m depths, the in-row position exhibited the minimum values of cone index, probably resulting from in-row subsoiling practices in previous years.

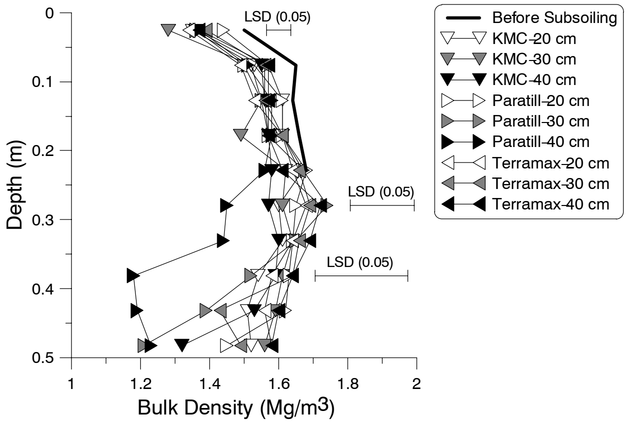

Figure 2. Bulk density measurements obtained after subsoiling at different depths in the center of the row plotted with bulk density obtained near the surface prior to subsoiling.

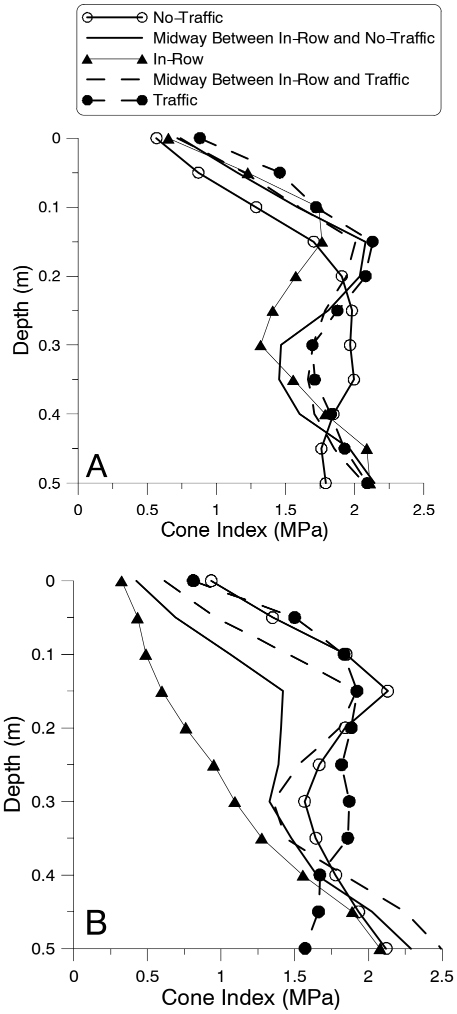

Figure 3. Cone index measurements averaged over all plots (A) prior to subsoiling, and (B) after subsoiling.

After subsoiling, measurements of cone index showed differences depending upon the relative distance from the row and with depth (fig. 3B; $p \le 0.001$) but did not vary based on type of subsoiler. Measurements of cone index obtained directly in the row exhibited minimum values of cone index as compared to other distances from the row, at least through the depth of subsoiling (0.4 m). Little change in soil cone index was seen at other distances from the row due to subsoiling.

MACHINERY DATA

After the soil had been excavated from the trenched zone, a ruler was used to determine the final subsoiling depths of each implement. Depths of subsoiling were found to be statistically different from each other (table 2; $p \le 0.001$) with targeted tillage depths of 20, 30, and 40 cm resulting in statistically different depths of 23, 30, and 37 cm. Average depths of tillage for the Paratill™ (30 cm) and the Terramax™ (29 cm) were also found to be slightly different ($p \le 0.090$) though not statistically different.

No differences in draft force were found among subsoilers, but statistically different values of draft force were found for different subsoiling depths (table 2). Subsoiling at a 20-cm depth was found to have reduced draft force (11.5 kN) compared to subsoiling at a 30-cm depth (17.2 kN; $p \le 0.007$)

and subsoiling at a 40-cm depth (33.7 kN; $p \leq 0.001$). Subsoiling at a 30-cm depth was also found to be statistically different than subsoiling at a 40-cm depth ($p \leq 0.001$).

Linear regressions of draft force on measured depth showed only slight differences between the subsoilers with the Terramax having a slightly reduced slope as compared to the KMC or the Paratill which were similar (fig. 4). The reduced slope for the Terramax and the reasonable fit for the data (R^2 = 0.78) indicated that this subsoiler required somewhat reduced draft forces, particularly at deeper depths.

Speed was not found to be significantly different among subsoilers but was found to be different between a 40-cm subsoiling depth (table 2; 4.13 km/h) and either a 30-cm subsoiling depth (4.37 km/h; $p \leq 0.001$) or a 20-cm subsoiling depth (4.35 km/h; $p \leq 0.001$). Some minimal slowing occurred at the deepest subsoiling depth, possibly due to increased tire slippage.

Similar results as found for draft force were also found for drawbar power (table 2). Implements were not found to be statistically different when operated at similar depths. However, differences did exist between the various depths of operation. Averaging across subsoiler implements, minimal power requirements were needed for the shallow depth of subsoiling of 20 cm (13.9 kW) compared to the 30-cm depth (20.8 kW; $p \leq 0.004$) or the 40-cm depth (38.6 kW; $p \leq 0.001$). Drawbar power was also found to be statistically different between the 30-cm depth and the 40-cm depth ($p \leq 0.001$) with dramatically increased drawbar power necessary for the deepest subsoiling depth.

SOIL DISRUPTION DATA

Averaged across all depths, the width of spoil on the soil surface as measured with the portable tillage profiler was found to be slightly greater for the KMC subsoiler (table 3; 0.69 m) than for the Paratill™ (0.62 m; $p \leq 0.072$). No other differences in shanks were found. The only significant difference that was determined was that subsoiling at a 40-cm depth disturbed more surface soil (0.69 m) than subsoiling at a 20-cm depth (0.62 m; $p \leq 0.049$) when averaging across subsoiler implements.

Similar statistical results were found for the width of the trench as were reported for the width of the spoil (table 3). The only difference that was found among shanks when averaging across depths was between the KMC subsoiler (0.62 m) and the Paratill™ (0.56 m; $p \leq 0.024$). A very interesting and unexpected result occurred regarding the trench width and the depth of subsoiling. The depth of subsoiling was found to have an affect on trench width. Averaging across subsoiler implements, subsoiling at a depth of 20 cm resulted in a trench width of 0.66 m which was significantly different than the trench widths which resulted from subsoiling at depths of 30 cm (0.58 m; $p \leq 0.003$) or 40 cm (0.54 m; $p \leq 0.001$). Increased depth of subsoiling resulted in decreased trench widths, which was contrary to popular belief that increased subsoiling depth resulted in wider trench widths. The soil used for this experiment could be partially responsible for this finding with severe compaction near the surface resulting in narrower trench widths when subsoiling depth was increased.

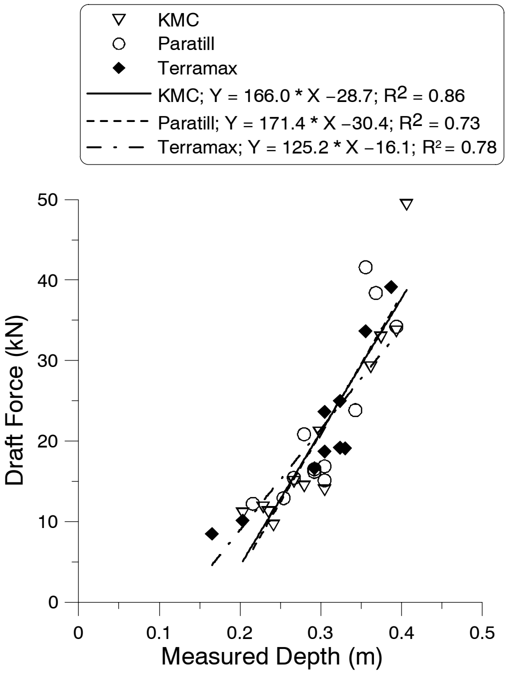

Figure 4. Linear regression of draft force on measured depth for the three subsoilers tested.

Averaging over depths of subsoiling, differences in spoil cross-sectional area were found between the KMC subsoiler (table 3; 0.026 m^2), the Paratill™ (0.021 m^2; $p \leq 0.014$), and the Terramax™ (0.021 m^2; $p \leq 0.016$). Greater surface soil disturbance was found with the KMC subsoiler which was a straight-leg subsoiler compared to the two bentleg subsoilers. Differences in spoil cross-sectional area were also found as

Table 2. Tillage depth, forces measured with three-dimensional dynamometer, speed, and drawbar power for 4-row implements.

Implement – Targeted Subsoiling Depth (cm)	Actual Subsoiling Depth (cm)[a]	Draft Force (kN)	Vertical Force (kN)	Side Force (kN)	Speed (km/h)	Drawbar Power (kW)
KMC – 20	22.7 fg	10.8 cd	-1.3 cd	0.2	4.3 ab	13.0 c
KMC – 30	28.8 de	16.0 bcd	-0.1 bc	0.4	4.3 abc	19.0 bc
KMC – 40	38.5 a	36.2 a	1.6 a	0.2	4.1 c	40.9 a
Paratill™ – 20	25.7 ef	14.2 bcd	-1.7 d	0.0	4.3 ab	17.3 bc
Paratill™ – 30	29.5 d	17.2 bc	-0.4 bc	-0.5	4.4 ab	20.9 b
Paratill™ – 40	36.5 ab	34.5 a	0.2 b	-0.2	4.2 bc	40.2 a
Terramax™ – 20	20.6 g	9.3 d	-1.1 cd	0.2	4.4 a	11.4 c
Terramax™ – 30	31.3 cd	18.4 b	0.3 b	0.2	4.4 ab	22.4 b
Terramax™ – 40	34.3 bc	30.3 a	0.8 ab	0.1	4.1 c	34.8 a
$LSD_{0.05}$	1.4	7.0	1.2	na	0.2	7.9

[a] Differences in letters indicate LSD_{005}.

Table 3. Soil disruption parameters per row.

Implement – Targeted Subsoiling Depth (cm)	Spoil Width (m)[a]	Spoil Cross-sectional Area ($m^2 \times 10^{-3}$)	Trench Width (m)	Trench Cross-sectional Area ($m^2 \times 10^{-3}$)	Trench Specific Resistance (kN/m^2)
KMC – 20	0.64 ab	19.6 bc	0.75 a	28.6 e	100.5 b
KMC – 30	0.69 ab	28.9 a	0.57 bc	53.6 cd	76.8 b
KMC – 40	0.73 a	29.5 a	0.55 bc	60.0 bc	165.0 a
Paratill™ – 20	0.58 b	20.5 bc	0.61 bc	43.0 d	83.4 b
Paratill™ – 30	0.57 b	18.5 c	0.55 bc	53.8 cd	82.0 b
Paratill™ – 40	0.73 a	25.0 ab	0.52 c	85.8 a	100.1 b
Terramax™ – 20	0.65 ab	18.6 c	0.63 b	28.8 e	95.4 b
Terramax™ – 30	0.70 a	21.5 bc	0.61 b	57.2 bc	80.4 b
Terramax™ – 40	0.62 ab	24.2 abc	0.55 bc	67.8 b	111.1 b
$LSD_{0.05}$	0.12	6.2	0.10	13.5	47.4

[a] Differences in letters indicate $LSD_{0.05}$.

a function of operating depth. Averaging across subsoiler implement, subsoiling at a depth of 20 cm resulted in spoil cross-sectional area of 0.020 m^2 which was slightly reduced from subsoiling at a depth of 30 cm (0.023 m^2; $p \leq 0.065$) and significantly reduced from subsoiling at a depth of 40 cm (0.026 m^2; $p \leq 0.001$). Subsoiling at a depth of 30 cm was also found to result in slightly reduced spoil cross-sectional area compared to subsoiling at a depth of 40 cm ($p \leq 0.067$).

Averaging across subsoiler depths, the trench cross-sectional area resulting from subsoiling with the Paratill™ (table 3; 0.061 m^2) was greater than subsoiling with the Terramax™ (0.051 m^2; $p \leq 0.018$) or the KMC subsoiler (0.048 m^2; $p \leq 0.002$). Differences in trench cross-sectional area resulted from different depths of subsoiling. Averaging across subsoiler implement, subsoiling at depths of 20 cm resulted in trench cross-sectional areas of 0.034 m^2 which was significantly reduced from subsoiling at depths of 30 cm (0.055 m^2; $p \leq 0.001$) or 40 cm (0.071 m^2; $p \leq 0.001$). Different trench cross-sectional areas also resulted from subsoiling at depths of 30 and 40 cm ($p \leq 0.001$). It is interesting to note that the decreased trench width with increased subsoiling depth did not cause a reduction in trench cross-sectional area when subsoiling depth was increased. The increased subsoiling depth compensated for the decreased width and allowed an overall increase in trench cross-sectional area.

Averaging across subsoiler depths, the Paratill™ was found to have the minimum TSR (table 3; 88.5 kN/m^2) which was somewhat greater as compared to the KMC's TSR (114.1 kN/m^2; $p \leq 0.065$). The Terramax™ had a smaller TSR (95.6 kN/m^2) than the KMC but was not statistically different. The minimal TSR associated with the Paratill™ concurred with previous research conducted by Raper (2005) which found minimal values of TSR for this shank in a sandy loam soil bin experiment. Averaging across subsoiler implements, subsoiling at a depth of 40 cm produced the maximum values of TSR (125.4 kN/m^2) compared to subsoiling at depths of 20 cm (93.1 kN/m^2; $p \leq 0.018$) or 30 cm (79.7 kN/m^2; $p \leq 0.002$). The optimal depth of subsoiling that produced maximum disruption per unit energy was subsoiling at 30 cm. Subsoiling shallower than 30 cm reduced draft force but also reduced disruption. Subsoiling deeper than 30 cm required excessive draft force for slightly increased disruption.

RESIDUE BURIAL DATA

Before the experiment was begun, 92% of the soil was found to be covered by crop and weed residue by using the digital photograph technique. After subsoiling, the Paratill™ was found to leave the maximum amount of crop residue on the soil surface at all depths of operation (fig. 5; 87%) which was statistically greater than the KMC subsoiler (68%; $p \leq 0.001$). The Terramax™ was also found to leave a greater amount of crop residue on the soil surface (85%) compared to the KMC subsoiler (68%; $p \leq 0.001$). No difference in crop residue remaining on the soil surface was found between the two bentleg subsoilers. Also, no differences were found depending upon depth of tillage.

The percent residue cover data for each subsoiler treatment were examined to determine if there were any correlations with any other measurement variable, including depth of tillage, spoil width, spoil cross-sectional area, trench width, or trench cross-sectional area. The only significant correlation occurred for the KMC subsoiler which indicated that the percent residue cover was highly correlated with the trench width ($p \leq 0.001$). A negative correlation between percent residue cover and trench width indicated that reduced amounts of residue were left on the soil surface as trench width increased.

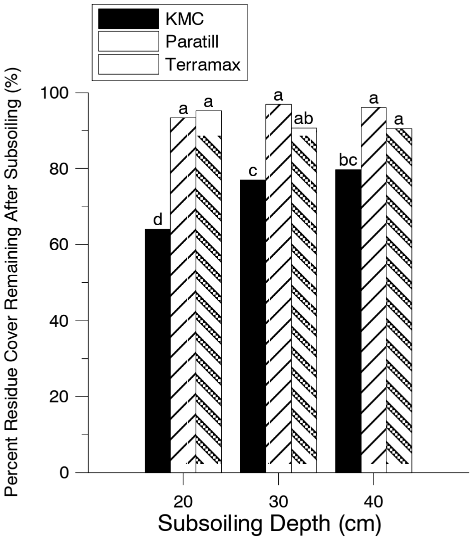

Figure 5. Percent coverage of soil surface by crop and weed residue after subsoiling experiments. Differences in letters indicate $LSD_{0.05}$ = 11.6%.

CONCLUSIONS

- Adjacent to the soil surface, the KMC subsoiler reduced bulk density better than the other shanks while at deeper depths, the Paratill™ excelled in loosening the soil profile.
- Reduced subsoiling forces were found for reduced depths of subsoiling. No differences in draft force or drawbar power were found for the different implements under consideration.
- Greater surface spoil cross-sectional area was found with the KMC subsoiler than was found with the Paratill™ or the Terramax™ subsoilers. Decreased spoil cross-sectional area was also found with decreased depth of subsoiling. An increased trench cross-sectional area was found with the Paratill™ than with the Terramax™ or the KMC subsoiler. Subsoiling at depths of 20 cm also resulted in decreased trench cross-sectional areas as compared to subsoiling at depths of 30 or 40 cm.
- The bentleg shanks retained greater amounts of crop residue on the soil surface than the straight shank subsoiler.

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