Soil Moisture Effects on Energy Requirements and Soil Disruption of Subsoiling a Coastal Plain Soil

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Abstract. *An experiment was conducted to determine the optimum moisture content to subsoil based on tillage forces and soil disruption. Two different shanks, a straight shank and a "minimum−tillage" shank, were tested in a Coastal Plain soil in the soil bins of the National Soil Dynamics Laboratory in Auburn, Alabama. A three−dimensional dynamometer measured tillage forces, and a laser profilometer measured soil disruption. Tillage forces and soil disruption measured in the driest soil condition were greatest. The "minimum−tillage" shank required more energy and disrupted less surface soil than the straight shank. An index, the trench specific resistance (TSR), was developed to aid in determining the minimum amount of draft force necessary for maximally disrupting a deeper soil profile. Reduced values of TSR were found for the straight shank compared to the "minimum−tillage" shank, as minimum draft produced maximum soil disturbance. Reduced values of TSR were also found for subsoiling operations conducted at all soil conditions other than the driest. Based on this research, subsoiling should not be conducted at the extreme driest soil condition due to increased draft forces and increased aboveground soil disruption.*

Keywords. *Draft, Energy, Soil compaction, Soil moisture, Subsoiling, Tillage.*

Compaction of agricultural soils can have devastating effects on crop growth and overall productivity. This has been particularly true in the southeastern U.S., where soils have been proven to be highly compactable by natural forces and vehicle traffic (Cooper et al., 1969; McConnell et al., 1989). Numerous techniques have been used to minimize soil compaction. Controlled traffic (Dumas et al., 1973), reduced tire inflation pressure (Raper et al., 1995a, 1995b), reduced vehicle size (Cooper et al., 1969), and cover crops (Reeves et al., 1992) have all been used to reduce the negative effects of soil compaction.

One technique commonly used to alleviate the effects of soil compaction is subsoiling (Campbell et al., 1974; Reid, 1978; Garner et al., 1987). This tillage practice disrupts compacted soil profiles to depths of up to 0.5 m; however, it is not a permanent solution because of natural reconsolidation and vehicle traffic. Consequently, it is a common practice in Coastal Plain soils to subsoil on an annual basis (Tupper et al., 1989; Busscher et al., 1986). Some research has indicated that subsoiling could be performed less frequently, but a higher risk of reconsolidation often results (Colwick et al., 1981; Smith, 1985; Reeder et al., 1993).

Primarily because of the significant draft forces required to subsoil compacted profiles, many different types of subsoilers have been designed and tested (Nichols and Reaves, 1958; Upadhyaya et al., 1984; Reeder et al., 1993; Choa and Chancellor, 1973; Mielke et al., 1994; Tupper, 1974; Sakai et al., 1993; Smith and Williford, 1988). Subsoilers have also been designed to minimize soil inversion in order to maximize residue cover after subsoiling (Pidgeon, 1982, 1983). Many U.S. manufacturers (Deere and Co., Moline, Ill.; Case IH, Racine, Wisc.; Kelley Manufacturing Co., Tifton, Ga.; Worksaver Inc., Litchfield, Ill.; Bigham Brothers, Inc., Lubbock, Tex.) now promote the ability of their subsoiler shanks to disrupt compacted profiles while maintaining surface residue coverage.

Timing of subsoiling is often determined by the convenience and time available to complete the operation. Many subsoiling operations are performed in the fall when time is usually more plentiful, but some soils reconsolidate so quickly that subsoiling must be performed in the spring for the full benefit to be realized by the summer crop (Touchton et al., 1986; Vaughan et al., 1992). Another consideration for reducing energy consumption of subsoilers has been to target tillage times when soil moisture reduces soil−metal sliding friction. However, some soils adhere to metals when soil moisture is increased, thereby increasing draft force (Nichols, 1925, 1931; Chancellor, 1994).

Another consideration concerning subsoiling that has not been extensively studied is how to maximize soil disruption, thereby increasing the long−term benefits of subsoiling. Subsoiling is routinely recommended when the soil is driest to maximize disruption, but few data exist to support this recommendation (Schuler et al., 2000). In an effort to quantify the soil condition that results in the maximum amount of belowground soil disruption while not excessively disturbing the soil surface, this study was conducted to measure draft forces and soil disruption. Therefore, the objectives of this study are:

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- Determine the force required to subsoil a Coastal Plain soil at several levels of soil moisture.
- Determine soil disruption caused by subsoiling at each moisture level.
- Evaluate the differences in draft and disruption caused by a straight subsoiler and a subsoiler designed for "minimum tillage."

MATERIALS AND METHODS

An experiment was conducted in the soil bins at the USDA−ARS National Soil Dynamics Laboratory in Auburn, Alabama, to determine: (1) the force necessary to disrupt a hardpan profile in a Norfolk sandy loam soil (Typic Paleudults), and (2) the amount of soil disruption caused by the subsoiling event. Norfolk sandy loam soil is a Coastal Plain soil commonly found in the southeastern U.S. and along the Atlantic Coast. This soil was selected because it is found in many locations where subsoiling is commonly used to disrupt compacted soil layers. It was contained in indoor soil bins, which facilitated the maintenance of constant moisture content for an extended period of time.

A hardpan condition was formed in the soil bins to simulate a condition that is commonly found in the southeastern U.S. This naturally occurring, and sometimes traffic−induced, hardpan has been found 0.1 to 0.3 m below the soil surface and is quite impervious to root growth, particularly at low moisture levels. The hardpan in the soil bins was created by using a moldboard plow to laterally move the soil, followed by a rigid wheel to pack the soil left exposed in the furrow. This entire procedure was then repeated until the entire width of the bin had been traversed.

The shanks used for the experiment were manufactured by Deere & Co. (fig. 1). The straight shank was 31.8 mm thick and was equipped with a 127 mm LASERRIP ripper point. It is currently used on the John Deere 955 row crop ripper. The "minimum−tillage" shank was 19 mm thick and had a 178 mm Min−till point. This shank is used on the John Deere 2100 minimum−till ripper.

These shanks were mounted on a 3−dimensional dynamometer with an overall draft load capacity of 44 kN. Draft, vertical force, side force, speed, and depth of operation were recorded continuously for each test. The speed of tillage for all tests was held constant at 0.45 m/s. Depth of operation was 33 cm.

The soil bin was partitioned into four blocks along the length of the bin. Eight plots of dimensions 1.5 m wide by 5 m long were created within each block to test the two shanks at four different moisture contents. A total of 32 plots were arranged in a randomized complete block design with four moisture contents, two shank types, and four replications. Spacing across the bin was sufficient to ensure that disturbed soil resulting from a previous tillage operation would not affect another test. The force values obtained from each plot were averaged so as to create one value per plot of draft, vertical force, and side force. Preplanned single degree of freedom contrasts were used to compare shanks across soil conditions and different soil conditions across shanks. Fisher's protected least significant difference (LSD) was used for mean comparison among shanks and soil conditions. A significance level of 0.10 was assumed to test the null hypothesis that no differences existed between soil moisture levels or between shanks.

The soil bin was wet to a completely saturated soil condition prior to the first set of experiments. After these tests were conducted, the soil was left uncovered for several days to obtain a different soil moisture condition. Daily measurements of soil moisture between 0 and 20 cm were obtained with a time−domain reflectrometry (TDR) probe to determine when the targeted soil moisture level was achieved, and hence when the next set of tests could be conducted. This

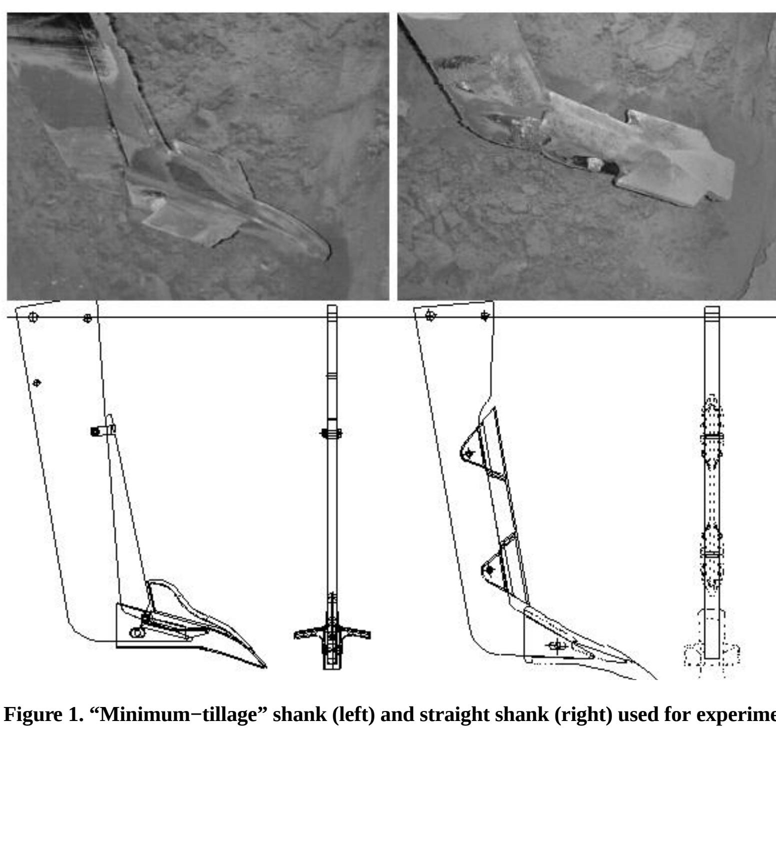

Figure 1. "Minimum−tillage" shank (left) and straight shank (right) used for experiment.

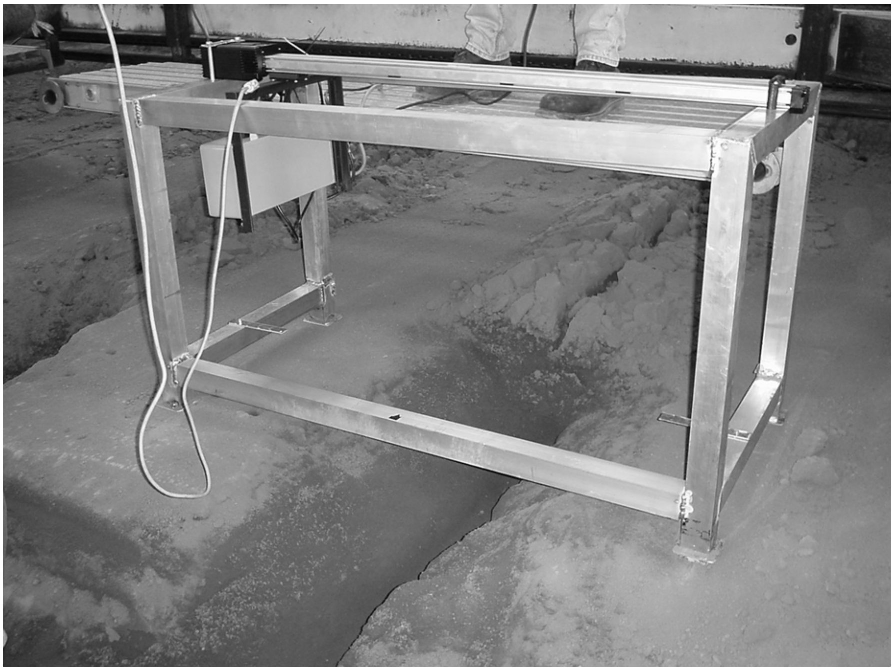

Figure 2. Laser profilometer used to measure cross−sectional area of spoil and trench.

procedure was repeated twice more to allow four distinct levels of soil moisture to be obtained.

Before the shank tests were conducted in each plot, three cone index measurements were acquired (*ASAE Standards*, 1999a, 1999b). Soil moisture was determined in undisturbed regions of each plot. Gravimetric moisture contents were determined at depths of 0 to 15 cm immediately after each experiment was completed. Bulk density values were taken at depths of 5 to 10 cm, 20 to 25 cm, and 30 to 35 cm in each replication at the end of test.

After each set of tillage experiments was conducted, a laser profilometer (Raper et al., 2004) was used to determine the width and volume of soil disturbed by each tillage event (fig. 2). Disturbed soil was manually excavated from each subsoiled zone for approximately 1 m along the travel path to allow five independent measurements of the subsoiled zone. Care was taken to ensure that only soil loosened by tillage was removed.

RESULTS AND DISCUSSION

The gravimetric moisture content for the Norfolk sandy loam soil for the 0 to 15 cm depth was found to be statistically different for the first three test conditions (wet, moist, and dry) with the last two (dry and very dry) being statistically similar (table 1). The volumetric moisture content of the Norfolk sandy loam soil determined by TDR showed each of the four moisture levels to be statistically different from the previous moisture level. The entire soil moisture range was representative for this soil type from saturation to wilting coefficient. The cone index measurements were analyzed for the peak value over the entire sampling depth at the various moisture levels. There were no statistical differences between the peak values.

Bulk density values showed the approximate location of the hardpan that was created in the soil bins (table 2). The soil within the hardpan, at a depth of 20 to 25 cm, had the highest bulk density (1.93 Mg/m^3) compared to the surface bulk density (1.58 Mg/m^3) for a depth of 5 to 10 cm, or for the soil below the hardpan (1.80 Mg/m^3) at a depth of 30 to 35 cm.

Within each of the soil moisture levels, the peak cone index values were found in the hardpan depth (table 2). The values of peak cone index within or below the hardpan layer did not increase appreciably over the period of the experiment, despite changes in soil moisture nearer the surface. The hardpan depth is where the peak cone index values were measured (table 1). For the 5 to 10 cm depth, cone index values mostly increased with increased drying.

Vertical force measurements showed a statistically significant effect of soil moisture (table 3). Vertical force from the very dry soil condition was found to differ from all other

Table 1. Soil moisture levels and soil strength for different soil moisture levels. Within a column, different letters indicate statistical differences at the 0.10 level.

Soil Moisture Level	Gravimetric Soil MC (% d.b.)	Volumetric Soil MC (%)	Peak Cone Index (MPa)
Wet	11.2 a	16.3 a	4.21
Moist	9.9 b	13.3 b	4.09
Dry	6.5 c	8.3 c	4.07
Very dry	6.1 c	5.8 d	3.92
$LSD_{0.10}$	0.5	0.9	ns

Table 2. Bulk density and peak cone index values before tillage for different soil moisture levels. Within a column, different letters indicate statistical differences at the 0.10 level.

Depth (cm)	Bulk Density (Mg/m^3)	Peak Cone Index (MPa) at			
		Wet MC	Moist MC	Dry MC	Very Dry MC
5−10	1.58 c	0.78 b	0.68 b	1.06 c	3.28 b
20−25	1.93 a	4.21 a	4.09 a	4.07 a	3.92 a
30−35	1.80 b	4.08 a	3.69 a	2.98 b	3.22 b
$LSD_{0.10}$	0.004	0.52	0.79	0.48	0.48

Table 3. Vertical and draft forces for straight and "minimum−tillage" shanks at different soil moisture levels. Numbers in parentheses indicate standard deviation.

Moisture Level	Vertical Force (kN)			Draft Force (kN)		
	Straight	Min.−Till.	Avg.	Straight	Min.−Till.	Avg.
Wet	2.02 (0.14)	1.06 (0.32)	1.54	5.88 (0.63)	5.54 (2.09)	5.71
Moist	2.30 (0.18)	1.56 (0.20)	1.94	5.41 (0.53)	8.24 (1.31)	6.81
Dry	2.34 (0.33)	1.27 (0.39)	1.81	5.30 (0.99)	7.48 (1.69)	6.37
Very Dry	3.34 (0.70)	2.54 (0.47)	3.00	7.10 (1.66)	11.09 (2.14)	8.79
Average	2.50	1.55	2.04	5.92	7.87	7.00

treatments: 3.00 kN vs. 1.81 kN ($P \leq 0.001$) for the dry soil condition, 1.94 kN ($P \leq 0.001$) for the moist soil condition, and 1.54 kN ($P \leq 0.001$) for the wet soil condition. The vertical force from the moist soil condition (1.94 kN) was found to be statistically greater ($P \leq 0.063$) than the vertical force from the wet soil condition (1.54 kN). The straight shank was found to have greater vertical force requirements than the "minimum−tillage" shank: 2.50 kN vs. 1.55 kN ($P \leq 0.001$) across all moisture levels. At each soil condition, the straight shank required greater vertical force than the "minimum−tillage" shank (fig. 3), with the greatest forces occurring at the driest soil condition.

Draft force measurements also showed a significant statistical effect of soil moisture (table 3). Draft force from the very dry soil condition was found to differ from all other soil moisture treatments: 8.79 kN vs. 6.37 kN ($P \leq 0.003$) for the dry soil condition, 6.81 kN ($P \leq 0.009$) for the moist soil condition, and 5.71 kN ($P \leq 0.004$) for the wet soil condition. Draft measurements from other than the very dry soil condition were not found to be statistically different from each other.

Draft force measurements were found to differ between shanks ($P \leq 0.001$; table 3). The straight shank required 5.92 kN of draft force averaged over all moisture contents, while the "minimum−tillage" shank required an average of 7.87 kN of draft force. Only in the wet soil moisture treatment did the "minimum−tillage" shank have a lesser but statistically insignificant requirement for draft force (5.52 kN vs. 5.88 kN; fig. 4). In all other soil moisture conditions, the draft force from the "minimum−tillage" shank exceeded the draft force of the straight shank.

Two measures of soil disruption were obtained with the laser profilometer. The aboveground cross−sectional area, or the spoil area, provided a measure of the amount of soil displaced upward above the original soil surface by the tillage process. Another measure of a shank's effectiveness is the cross−sectional area of soil, known as the trench area, that was disrupted below the soil surface. Figures 5 and 6 show averaged profiles of the cross−sectional spoil and trenched areas for each shank tested at each moisture content. These figures show enlargement of the trench cross−sectional area near the soil surface and also of the spoil resulting from subsoiling at drier soil conditions, with the maximum spoil and trench cross−sectional area being found for the very dry soil condition.

Decreased soil moisture contributed to increased soil disruption above the surface (table 4). The very dry condition had the greatest spoil cross−sectional area, with a value of 40.9×10^{-3} m^2 as compared to 35.4×10^{-3} m^2 for the dry condition ($P \leq 0.020$), 33.6×10^{-3} m^2 for the moist condition ($P \leq 0.003$), and 25.2×10^{-3} m^2 for the wet condition ($P \leq 0.001$). The "minimum−tillage" shank (31.4×10^{-3} m^2) had a smaller spoil cross−sectional area than the straight shank (36.1×10^{-3} m^2; $P \leq 0.006$). However, this difference in spoil was statistically significant only at the very dry condition (fig. 7). At all other soil conditions, greater but statistically similar amounts of spoil were generated by the straight shank as compared to the "minimum−tillage" shank.

Decreased soil moisture also contributed to the enlargement of the trench cross−sectional area (table 4). The trench area was greatest for the very dry condition (91.6×10^{-3} m^2 as compared to 77.2×10^{-3} m^2 for the dry condition ($P \leq$

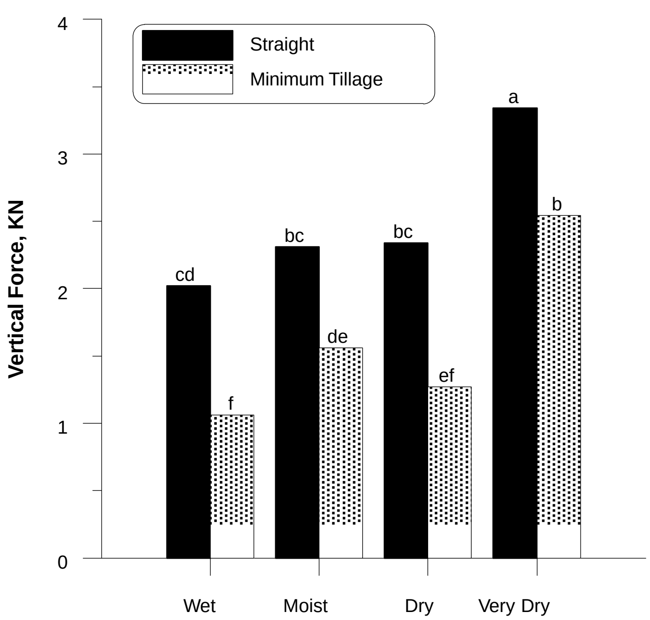

Figure 3. Vertical forces from shanks. Different letters indicate statistical differences at the 0.10 level.

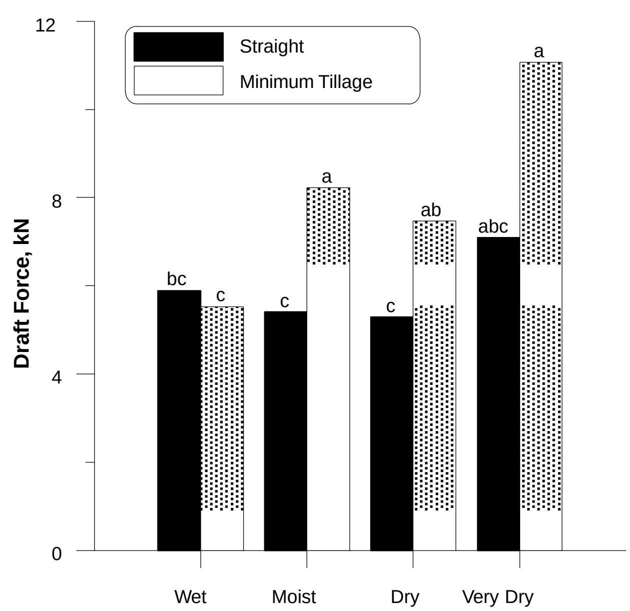

Figure 4. Draft forces from shanks. Different letters indicate statistical differences at the 0.10 level.

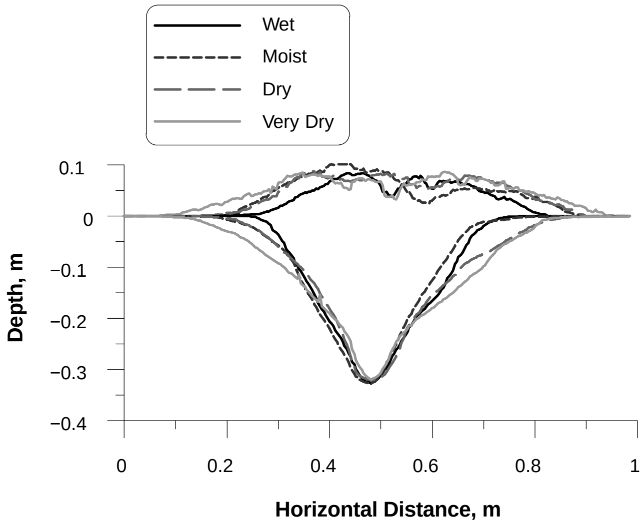

Figure 5. Spoil and trench profiles for the straight shank as measured with the laser profilometer.

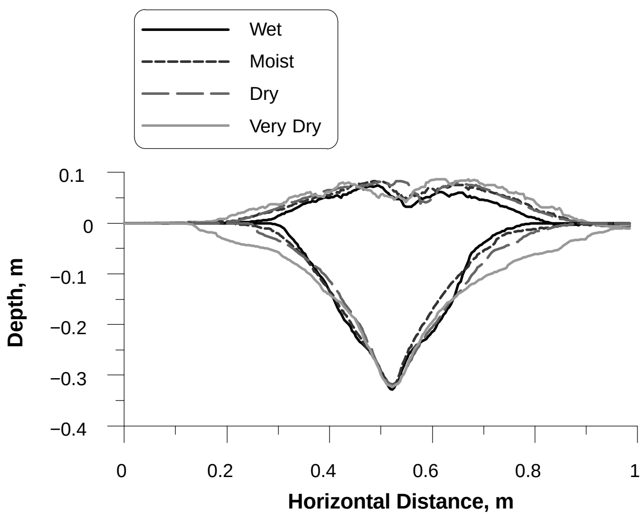

Figure 6. Spoil and trench profiles for the "minimum−tillage" shank as measured with the laser profilometer.

Table 4. Spoil and trench areas for straight and "minimum−tillage" shanks at different soil moisture levels. Numbers in parentheses indicate standard deviation.

Moisture Level	Spoil Area × 10^{-3} (m^2) Straight	Min.−Till.	Avg.	Trench Area × 10^{-3} (m^2) Straight	Min.−Till.	Avg.
Wet	27.3 (2.3)	23.1 (2.3)	25.2	74.1 (8.3)	69.5 (9.0)	71.8
Moist	35.8 (2.9)	31.3 (1.6)	33.6	72.8 (8.2)	68.3 (3.3)	70.6
Dry	37.6 (5.9)	33.1 (3.7)	35.4	80.7 (9.8)	73.7 (4.2)	77.2
Very Dry	43.8 (7.7)	38.0 (2.9)	40.9	90.7 (9.6)	92.6 (23.3)	91.6
Average	36.1	31.4	33.8	79.6	76.0	77.8

0.025), 70.6 × 10^{-3} m^2 for the moist condition ($P \leq 0.002$), and 71.8 × 10^{-3} m^2 for the wet condition ($P \leq 0.003$). No statistical differences were found between the two shanks across moisture levels (table 4; $P \leq 0.413$). The trench areas caused by the two shanks were similar among different soil conditions (fig. 8).

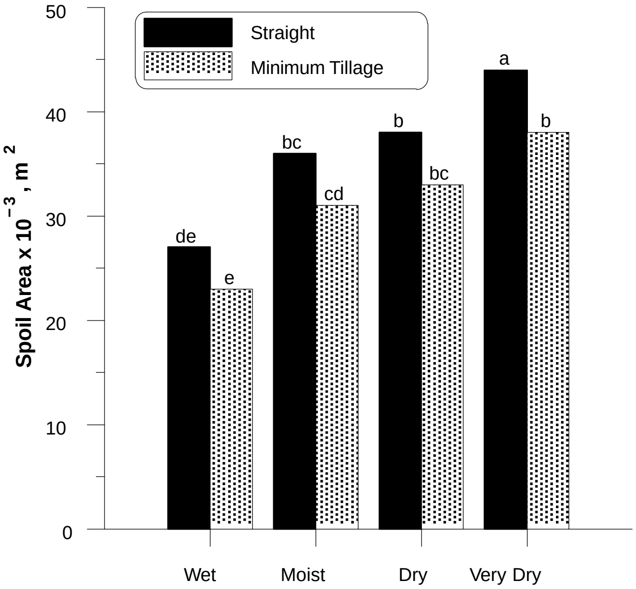

Figure 7. Spoil area measured with profilometer. Different letters indicate statistical differences at the 0.10 level.

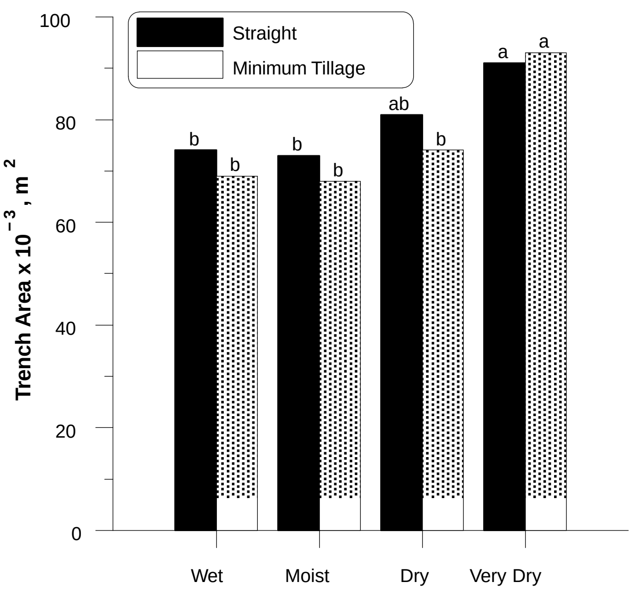

Figure 8. Trench area measured with profilometer. Different letters indicate statistical differences at the 0.10 level.

In an effort to reduce the number of parameters that must be considered when selecting the soil moisture to perform subsoiling operations, the trench specific resistance (TSR) considers both the draft force and the trenched cross−sectional area:

$$TSR = \frac{D}{TCA} \tag{1}$$

where
TSR = trench specific resistance (kN/m^2)
D = draft (kN)
TCA = trench cross−sectional area (m^2).

It is advantageous for the TSR to be small because this indicates small values of draft coupled with large values of belowground disruption.

Table 5. Trench specific resistance for straight and "minimum−tillage" shanks at different soil moisture levels. Numbers in parentheses indicate standard deviation.

Moisture Level	Trench Specific Resistance (kN/m^2)		
	Straight	Minimum−Tillage	Average
Wet	80.6 (14.6)	78.3 (22.5)	79.1
Moist	75.2 (12.5)	120.7 (13.5)	98.0
Dry	65.8 (11.5)	102.3 (26.9)	84.0
Very dry	77.4 (10.5)	130.1 (58.0)	104.1
Average	74.9	107.9	91.3

Across all soil conditions, the TSR for the straight shank was 74.9 kN/m^2, while the TSR for the "minimum−tillage" shank was 107.9 kN/m^2 (table 5). These differences were statistically different ($P \leq 0.001$). These results indicate that the straight shank was more efficient, resulting in a lower input force for equivalent trench disruption, compared to the "minimum−tillage" shank. Only at the wet condition did the "minimum−tillage" shank have similar values of TSR as the straight shank (fig. 9). At every other soil condition, statistically greater values of TSR were found for the "minimum−tillage" shank.

Differences in TSR ($P \leq 0.061$) were found between extremes in soil moisture (79.1 kN/m^2 vs. 104.1 kN/cm^2, respectively, for the wet soil condition vs. the very dry soil condition). Hence, more energy was required for disruption at the very dry soil condition, compared to the energy required for equivalent disruption at the wet soil condition.

Based on the results from this experiment, three parameters were important for choosing the most appropriate soil moisture condition to perform subsoiling: draft force, surface disruption (spoil), and belowground disruption (trench). Minimizing draft force will result in energy and time savings. Based on draft force considerations, subsoiling operations should be conducted in dry soil conditions only when draft

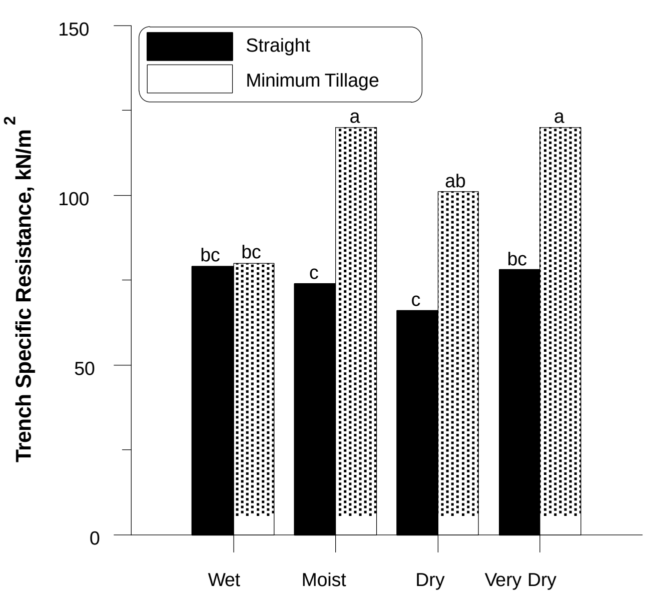

Figure 9. Trench specific resistance, defined as draft force divided by cross−sectional area of trench. Different letters indicate statistical differences at the 0.10 level.

forces are not significantly different from those in wet and moist soil conditions. Draft forces increased significantly when the soil continued to dry to the very dry soil condition. The straight shank was found to require reduced draft force and should be the more energy efficient choice.

The second parameter, spoil area, was important because decreasing the amount of residue that was buried by the subsoiling operation is important for conservation tillage systems. Subsoiling when the soil is in a very dry condition should be avoided, as increased spoil resulted from subsoiling in this soil condition. The "minimum−tillage" shank reduced the amount of spoil and should be the correct choice for producers who want to leave the maximum amount of residue undisturbed on the soil surface.

The third parameter, trench area, was important because increasing the amount of belowground disruption also increases the soil volume that roots are able to penetrate to find available moisture. Increased trench area was found for the very dry soil condition. However, the results from the other parameters indicate that subsoiling under very dry conditions should be avoided because spoil and draft were both increased.

An additional parameter, TSR, which considers both draft force and trench area, was created. Minimal values of TSR are desirable as they indicate low values of draft force coupled with maximum trench. The straight shank was the most efficient, with smaller TSR values than the "minimum−tillage" shank. Subsoiling operations in very dry soil conditions should be avoided, as this practice results in larger TSR values, which indicate high draft forces and/or decreased trench areas.

Conclusions

The conclusions that can be drawn from this experiment were:

- Draft and vertical tillage forces obtained from the driest soil condition were statistically greater than tillage forces obtained from all other soil conditions.
- Increased draft forces were measured for the "minimum−tillage" shank as opposed to the straight shank.
- The "minimum−tillage" shank reduced aboveground soil disruption (spoil) compared to the straight shank.
- The driest soil moisture level had significantly increased amounts of spoil and trench area compared to all other soil moisture levels.
- Reduced values of TSR, which indicated minimal values of draft combined with maximum values of belowground disruption, were found for the straight shank compared to the "minimum−tillage" shank.
- Elevated values of TSR, which are undesirable, were found for subsoiling in the very dry soil condition.

References

ASAE Standards. 45th ed. 1999a. EP542: Procedures for obtaining and reporting data with the soil cone penetrometer. St. Joseph, Mich.: ASAE.

ASAE Standards. 45th ed. 1999b. S313.2: Soil cone penetrometer. St. Joseph, Mich.: ASAE.

Busscher, W. J., R. E. Sojka, and C. W. Doty. 1986. Residual effects of tillage on coastal plain soil strength. *Soil Sci.* 141(2): 144−148.

Campbell, R. B., D. C. Reicosky, and C. W. Doty. 1974. Physical properties and tillage of Paleudults in the southeastern Coastal Plains. *J. Soil Water Cons.* 29(5): 220−224.
Chancellor, W. 1994. Friction between soil and equipment materials. ASAE Paper No. 941034. St. Joseph, Mich.: ASAE.
Choa, S. L., and W. J. Chancellor. 1973. Optimum design and operation parameters for a resonant oscillating subsoiler. *Trans. ASAE* 16(6): 1200−1208.
Colwick, R. F., G. L. Barker, and L. A. Smith. 1981. Effects of controlled traffic on residual effects of subsoiling. ASAE Paper No. 811016. St. Joseph, Mich.: ASAE.
Cooper, A. W., A. C. Trouse, and W. T. Dumas. 1969. Controlled traffic in row crop production. In *Proc. 7th Int. Congress of CIGR*, 1−6. Baden−Baden, Germany: CIGR.
Dumas, W. T., A. C. Trouse, L. A. Smith, F. A. Kummer, and W. R. Gill. 1973. Development and evaluation of tillage and other cultural practices in a controlled traffic system for cotton in the southern Coastal Plains. *Trans. ASAE* 16(5): 872−876.
Garner, T. H., W. R. Reynolds, H. L. Musen, G. E. Miles, J. W. Davis, D. Wolf, and U. M. Peiper. 1987. Energy requirement for subsoiling coastal plain soils. *Trans. ASAE* 30(2): 343−349.
McConnell, J. S., B. S. Frizzell, and M. 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.
Mielke, L. N., R. D. Grisso, L. L. Bashford, and A. M. Parkhurst. 1994. Bi−level subsoiler performance using tandem shanks. *Applied Eng. in Agric.* 10(3): 345−349.
Nichols, M. L. 1925. The sliding of metal over soil. *Agric. Eng.* 6(4): 80−84.
Nichols, M. L. 1931. The dynamic properties of soil. *Agric. Eng.* 12(8): 1−4.
Nichols, M. L., and C. A. Reaves. 1958. Soil reaction: to subsoiling equipment. *Agric. Eng.* 39(6): 340−343.
Pidgeon, J. D. 1982. 'Paraplow' − A rational approach to soil management. In *Proc. 9th Conf. Int. Soil Tillage Res. Org.*, 633−638. Osijek, Yugoslavia: ISTRO.
Pidgeon, J. D. 1983. Paraplow − A new approach to soil loosening. ASAE Paper No. 832136. St. Joseph, Mich.: ASAE.
Raper, R. L., A. C. Bailey, E. C. Burt, T. R. Way, and P. Liberati. 1995a. Inflation pressure and dynamic load effects on soil deformation and soil−tire interface stresses. *Trans. ASAE* 38(3): 685−689.
Raper, R. L., A. C. Bailey, E. C. Burt, T. R. Way, and P. Liberati. 1995b. The effects of reduced inflation pressure on soil−tire interface stresses and soil strength. *J. Terra.* 32(1): 43−51.
Raper, R.L., T.E. Grift, and M.Z. Tekeste. A portable tillage profiler for measuring subsoiling disruption. *Trans. ASAE* 47(1): 23−27.
Reeder, R. C., R. K. Wood, and C. L. Finck. 1993. Five subsoiler designs and their effects on soil properties and crop yields. *Trans. ASAE* 36(6): 1525−1531.
Reeves, D. W., H. H. Rogers, J. A. Droppers, S. A. Prior, and J. B. Powell. 1992. Wheel−traffic effects on corn as influenced by tillage system. *Soil Till. Res.* 23(1−2): 177−192.
Reid, J. T. 1978. A comparison of the energy input of some tillage tools. ASAE Paper No. 781039. St. Joseph, Mich.: ASAE.
Sakai, K., S. I. Hata, M. Takai, and S. Nambu. 1993. Design parameters of four−shank vibrating subsoiler. *Trans. ASAE* 36(1): 23−26.
Schuler, R. T., W. W. Casady, and R. L. Raper. 2000. Soil compaction. In *Conservation Tillage Systems and Management*, 70−76. R. C. Reeder, ed. Ames, Iowa: Midwest Plan Service.
Smith, L. A., and J. R. Williford. 1988. Power requirements of conventional, triplex, and parabolic subsoilers. *Trans. ASAE* 31(6): 1685−1688.
Smith, P. 1985. Subsoil every fourth year. *Successful Farming* 83(1): 23.
Touchton, J. T., D. H. Rickerl, C. H. Burmester, and D. W. Reeves. 1986. Starter fertilizer combinations and placement for conventional and no−tillage cotton. *J. Fert. Issues* 3(3): 91−98.
Tupper, G. R. 1974. Design of the Stoneville parabolic subsoiler. *MAFES Research Highlights* 37: 3. Mississippi State, Miss.: Mississippi Agricultural and Forestry Experiment Station.
Tupper, G. R., J. G. Hamill, and H. C. Pringle, III. 1989. Cotton response to subsoiling frequency. In *Proc. Beltwide Cotton Prod. Res. Conf.*, 10. Nashville, Tenn.: National Cotton Council.
Upadhyaya, S. K., T. H. Williams, L. J. Kemble, and N. E. Collins. 1984. Energy requirements for chiseling in coastal plain soils. *Trans. ASAE* 27(6): 1643−1649.
Vaughan, D. H., J. M. Luna, C. A. Laub, and D. R. Ess. 1992. Strip tillage in reduced chemical input corn production. ASAE Paper No. 921559. St. Joseph, Mich.: ASAE.