IN-ROW SUBSOILING AND CONTROLLED TRAFFIC EFFECTS ON COASTAL PLAIN SOILS

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ABSTRACT. *Soil compaction is an acute problem in the southeastern U.S., requiring periodic subsoiling to alleviate densely compacted soils. Controlling vehicle traffic is one method that has been recommended for reducing the negative effects of vehicle traffic. The objective of this study was to determine the differences in soil bulk density and cone index resulting from the interactions of surface tillage, subsoiling, and controlled traffic in a long-term corn-soybean cropping system experiment in a Coastal Plain soil in the southeastern U.S. Traffic or no-traffic treatments were accomplished using an experimental wide-frame tractive vehicle (WFTV), which enabled operations without traffic on 6.1 m wide growing zones. Subsoiling treatments included no subsoiling, annual in-row subsoiling, and initial one-time subsoiling on 25 cm centers to completely disrupt the soil to the 40 cm depth. Surface tillage treatments were no-tillage or disking and field cultivation. Soil measurements were taken after the treatments were imposed for five years. Bulk density and cone index measurements were taken at three positions in the plots: the trafficked row middle, the in-row position, and the non-trafficked row middle. Four significant conclusions from this study can be drawn: (1) vehicle traffic increased soil bulk density nearest the surface in all row positions, with the greatest increases occurring directly in the trafficked row position where equipment traffic was applied; (2) no-tillage caused significantly increased bulk density values near the soil surface in all three row positions; (3) annual in-row subsoiling effectively relieved soil compaction, while the initial complete disruption subsoiling treatment had similar bulk density and cone index values as the no-subsoiling treatment; and (4) in-row subsoiling also loosened the non-trafficked row middle, thereby compensating for the negative effects of vehicle traffic in the trafficked row middle. Consequently, crop yields were increased by in-row subsoiling but were not affected by vehicle traffic. Therefore, the influence of annual in-row subsoiling was greater on crop productivity for Coastal Plain soils than was the influence of controlled traffic.*

Keywords. *Cone index, Soil compaction, Subsoiling.*

Soil compaction is an acute problem in the southeastern U.S., with hardpan profiles restricting root growth (Kashirad et al., 1967; Cooper et al., 1969; Reicosky et al., 1977). Roots are unable to grow during short-term drought conditions, which are frequently present during the growing season.

This root-limiting condition can be alleviated by subsoiling (Tupper and Spurgeon, 1981; Busscher and Sojka, 1987; Bernier et al., 1989; Reeves and Mullins, 1995; Raper et al., 1998). Subsoiling densely compacted soil allows deeper rooting that enables crops to withstand short-term droughts. Typically, soils in this region are annually subsoiled to depths of 0.3 to 0.5 m. Annual subsoiling is recommended because soils recompact quickly due to natural consolidation processes and random wheel traffic (Busscher et al., 1986; Tupper et al., 1989; Clark et al., 1994). In a few cases, researchers have recommended subsoiling on a less frequent basis (Colwick et al., 1981; Smith, 1985; Reeder et al., 1993); however, the risk of not subsoiling during a year of intense drought is great enough to convince most producers to revert to annual subsoiling.

Another method that has shown promise of reducing soil compaction is using winter cover crops (Reeves, 1994; Thomas et al., 1996; Hollis, 1999; Raper et al., 2000a, 2000b; Kaspar et al., 2001). The use of these crops in the southeastern U.S. increases infiltration during winter periods of heavy rainfall and reduces runoff and evaporation, thus enabling increased moisture for use by summer cash crops.

Controlled traffic has shown potential as a method of reducing soil compaction in problematic soils (Cooper et al., 1969; Reicosky et al., 1977; Williford, 1980; Cooper et al., 1983; Reeves et al., 1989; Clark, 1991; McPhee and Braunack, 1992; Beard et al., 1995). Restricting wheel traffic to certain areas within a field allows plant roots to grow into soil not compacted by random wheel traffic. Crops usually respond with greater productivity when these systems are established.

However, the ability to absolutely control traffic in a field situation over a broad area is difficult, as most field operations require different implement widths. Year-to-year variations in traffic location are also common due to the increased use of conservation tillage and the presence of cover crop residues, which can mask previous years' rows. At the USDA-

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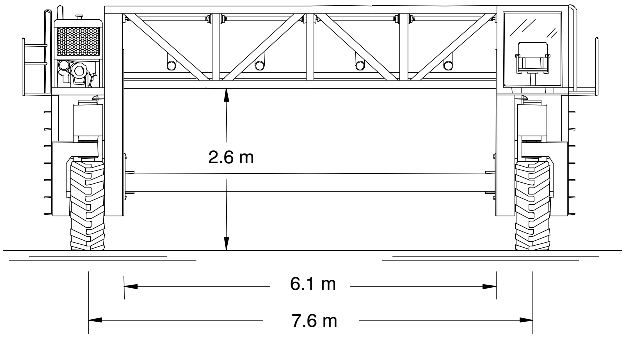

Figure 1. WFTV used for soil compaction research studies at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama.

ARS National Soil Dynamics Laboratory (NSDL), a WFTV (Monroe and Burt, 1989) was created that allowed a 6.1 m wide growing zone that was kept completely free of traffic (fig. 1). Targeted research was then carried out to determine if controlled traffic could reduce soil compaction managed using conservation tillage technologies or if it would reduce recompaction of soils disrupted by a subsoiler.

Cotton response from studies carried out with the WFTV failed to show clear advantages of controlled traffic even though the soil had reduced soil compaction (Torbert and Reeves, 1991; Raper et al., 1994). Another study was conducted to investigate other crops' abilities to make maximum use of decreased soil compaction from controlled traffic in a Coastal Plain soil (Reeves et al., 1992). Results from this study were similar in that crop yield did not indicate a clear advantage to the controlled traffic system. At the conclusion of the 5-year experiment, a complete set of soil strength data was taken to investigate why soils benefited from controlled traffic systems but crop yields did not.

Objectives:

- Determine effects of surface tillage, subsoiling, and traffic on: soil moisture, soil bulk density, and cone index.
- Determine why the effects of controlled traffic did not result in improved crop yields.

Materials and Methods

A long-term corn-soybean [*Zea mays* L.-*Glycine max* (L.) Merr.] rotation experiment was conducted from 1988 to 1993 to analyze the effects of traffic and its interaction with surface and deep tillage practices on a Compass loamy sand (coarse-loamy, siliceous, subactive, thermic, Plintic Paleudults) at Alabama Agricultural Experiment Station's E.V. Smith Research Center near Shorter, Alabama. This soil is highly compactable and has a well developed hardpan at the 18 to 30 cm depth. Row spacing was 76 cm. Plot size was 8 rows by 21.3 m.

The experimental design was a strip-split plot design with four replications. Vertical factors were deep tillage: (1) no subsoiling, (2) annual in-row subsoiling, and (3) initial complete subsoiling. Annual subsoiling treatments were conducted to a depth of 40 to 44 cm with a KMC in-row subsoiler (Kelly Manufacturing Co., Tifton, Ga.) at a spacing of 76 cm. The implement consisted of rippled coulters in front of the subsoiler shanks. The shanks had an angle of 45° with the horizontal and were 25 mm wide. The closing system behind the shanks was composed of smooth concave disks, which moved surface soil back into the subsoiled zone. The initial complete subsoiling treatment was conducted only once at the beginning of the experiment in 1988 and was accomplished by subsoiling three times offset with the same implement to result in the area being subsoiled on 25 cm centers. This resulted in complete disruption of the soil to a 40 to 44 cm depth. Horizontal factors were traffic: (1) no traffic, and (2) trafficked. Intersection or subplot treatments were surface tillage: (1) no surface tillage, and (2) disk field cultivation.

All field operations were done with the WFTV and consisted of primary tillage, secondary tillage, planting, harvesting, and cover crop planting. Pest management was conducted with a sprayer that was operated from nearby access lanes. A 4.6 t two-wheel drive tractor with 18.4 R38 tires inflated to 125 kPa was driven through the trafficked plots immediately after operations were conducted with the WFTV or sprayer. This process simulated traffic that would have been applied had the WFTV or boom sprayer not been used. The number of passes varied depending on the tillage operation: chisel plowing (1 pass), disking (2 passes), field cultivating (1 pass), and subsoiling and planting (1 pass). The number of passes also varied depending on the cropping system: conventional (5 passes including chisel plowing, disking, field cultivating, subsoiling and planting) or conservation (1 pass including subsoiling and planting). After planting, traffic would normally have been 1 pass for herbicide application, 1 pass for side dress fertilizer, 2 additional passes for post-plant weed control, and any additional passes needed for pest control. Soybean normally required 0 to 2 sprays. Corn would normally have required 1 spray. In the spring and summer, traffic was kept on appropriate row middles to simulate planting operations with 4-row equipment. In the fall, traffic was randomly applied to the whole plots that received traffic to simulate the land preparation and planting operations necessary for establishing a winter cover crop of crimson clover (*Trifolium incarnatum* L.). No-traffic plots did not receive any traffic.

Extensive soil sampling was conducted in the spring after five years to determine whether significant changes in soil condition were induced by management practices. Corn was grown in the previous year on the portion of the plots sampled. Soil bulk density samples were taken in each plot at two different locations using the core method (Raper and Erbach, 1987). The diameter of the core was 3.8 cm and the length was 60 cm. Three positions across the third row were sampled: (1) in the non-trafficked row middle, (2) in the row, and (3) in the trafficked row middle. Samples were also taken at three depths: (1) near the surface at a depth of 3 to 8 cm, (2) in the hardpan at a depth of 20 to 25 cm, and (3) below the hardpan at a depth of 45 to 50 cm. Gravimetric water content and dry bulk density were determined from these samples (Baver, 1956).

Cone index measurements (*ASAE Standards*, 2004a, 2004b) were taken during the same period in a fashion similar to the bulk density samples. Five sets of force-depth measurements were made about the third row: (1) in the non-trafficked row middle (2) midway between the non-trafficked row middle and the row, (3) in the row, (4) midway between the row and midway between the trafficked row middle, and (5) in the trafficked row middle. To simplify data analysis, only positions (1), (3), and (5) were analyzed and presented.

These sets of measurements were taken at five locations within each plot with a cone penetrometer with a base area of 130 mm^2 that was mounted on the WFTV. Cone index forces were recorded approximately every 3 mm of depth and were reduced by averaging the data in 0.05 m increments. Depth was automatically measured by a rotary position potentiometer (Celesco Transducer Products, Inc., Chatsworth, Cal.)

Data were subjected to analysis of variance, and Fisher's protected least significant difference was used for mean separation of preplanned comparisons using SAS (SAS Institute, Cary, N.C.). A predetermined significance level of $p \leq 0.05$ was chosen to separate treatment effects. Discussions will focus on significant main effects and significant two-way interactions with trends mentioned where appropriate.

Results and Discussion

Non-Trafficked Row Middle Position

Moisture Content

Soil moisture did not vary appreciably due to treatments in the non-trafficked row middle position, but the main effect of subsoiling on soil moisture at the middle depth of 22.5 cm was significant ($p \leq 0.042$), and a trend was noted at the deep depth of 47.5 cm ($p \leq 0.085$; fig. 2a). Annual subsoiling had reduced soil moisture at these depths, which was probably caused by reduced soil compaction and consequent greater crop rooting and water extraction and perhaps increased drainage. The main effect of surface tillage was found to cause slightly decreased soil moisture at the deepest depth of 47.5 cm in the non-trafficked row middle (8.8 %; $p \leq 0.049$) as compared to the no-tillage treatment (9.8%; data not shown). Increased residue coverage in the no-tillage treatment probably resulted in reduced evaporation and increased infiltration. In the trafficked row position (fig. 2c), traffic caused higher soil moisture levels at the 22.5 cm depth, but not at the shallower or deeper depth.

Bulk Density

In the non-trafficked row middle position, any traffic effect would only be due to the random presence of fall traffic (fig. 3a). A main effect of traffic was noted at the shallow depth of 5.5 cm ($p \leq 0.014$) with the traffic treatment having a greater bulk density (1.41 Mg/m^3) compared to the no-traffic treatment (1.31 Mg/m^3). No significant effects were found at the two deeper measurement depths.

Also in the non-trafficked row middle position, the main effect of subsoiling was significant at the middle depth of 22.5 cm ($p \leq 0.002$; fig. 4a). At this depth, no-subsoiling had the highest bulk density (1.65 Mg/m^3), which was significantly greater than the initial complete subsoiling treatment (1.61 Mg/m^3) or the annual subsoiling treatment (1.53 Mg/m^3). The initial complete subsoiling treatment also differed significantly from the annual subsoiling treatment.

The main effect of surface tillage was significant near the surface at the 5.5 cm depth, with no-tillage causing higher bulk density (1.40 Mg/m^3; $p \leq 0.001$) compared to the surface tillage treatment (1.32 Mg/m^3; fig. 5a) in the non-trafficked row middle position. At the medium depth of 22.5 cm, an opposite trend was found, with no-tillage having decreased

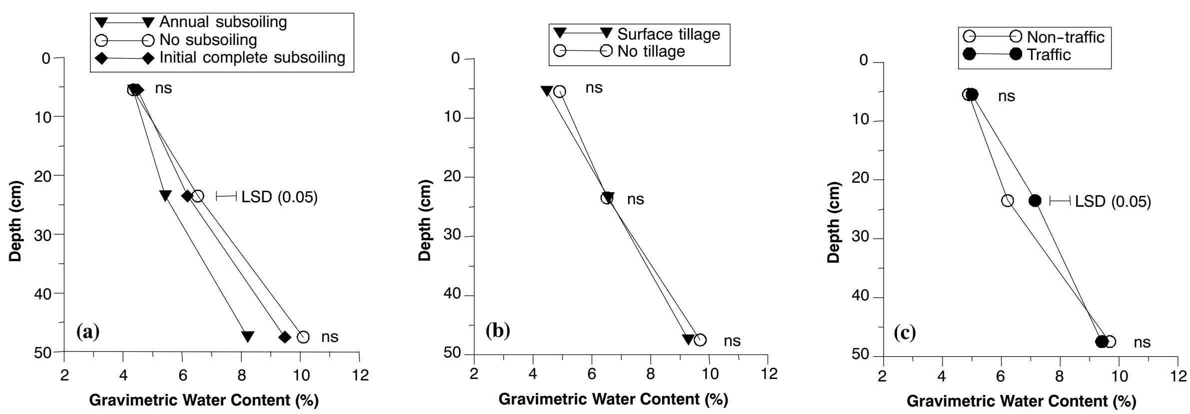

Figure 2. Gravimetric soil moisture measurements in three row positions: (a) subsoiling main effect in non-trafficked row middle, (b) surface tillage main effect in in-row position, and (c) traffic main effect in trafficked row middle.

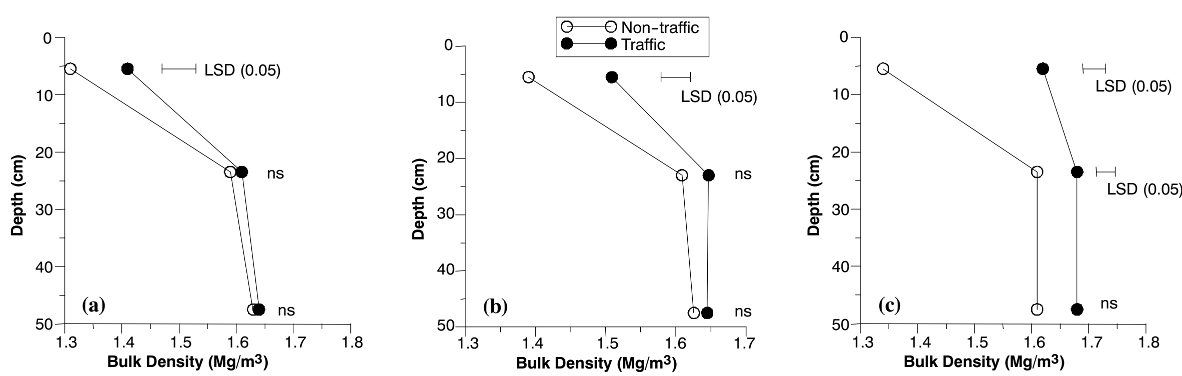

Figure 3. Traffic main effects on bulk density measurements in three row positions: (a) non-trafficked row middle, (b) in-row position, and (c) trafficked row middle.

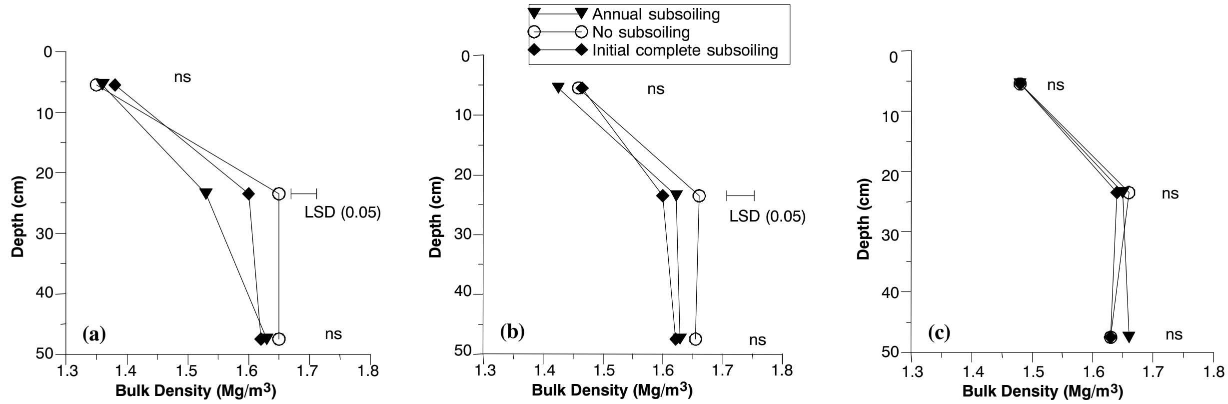

Figure 4. Subsoiling main effects on bulk density measurements in three row positions: (a) non-trafficked row middle, (b) in-row position, and (c) trafficked row middle.

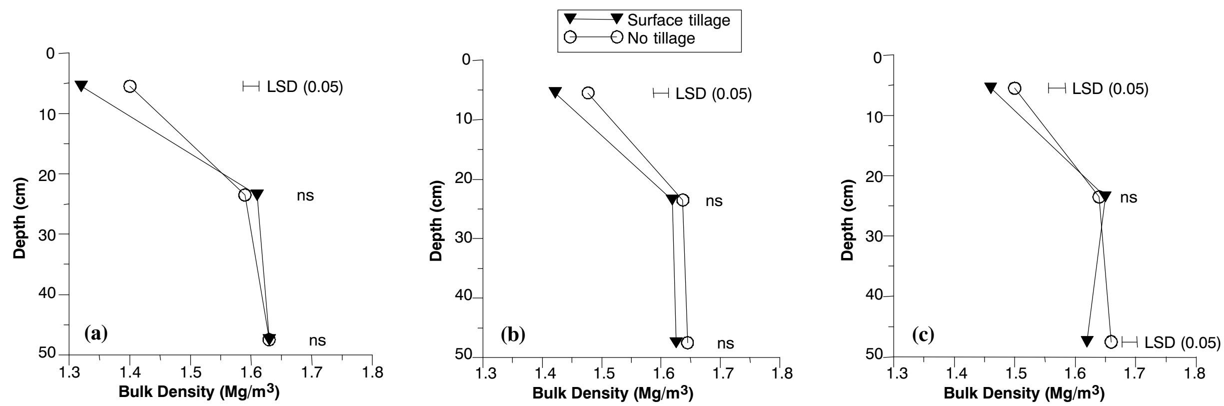

Figure 5. Surface tillage main effects on bulk density measurements in three row positions: (a) non-trafficked row middle, (b) in-row position, and (c) trafficked row middle.

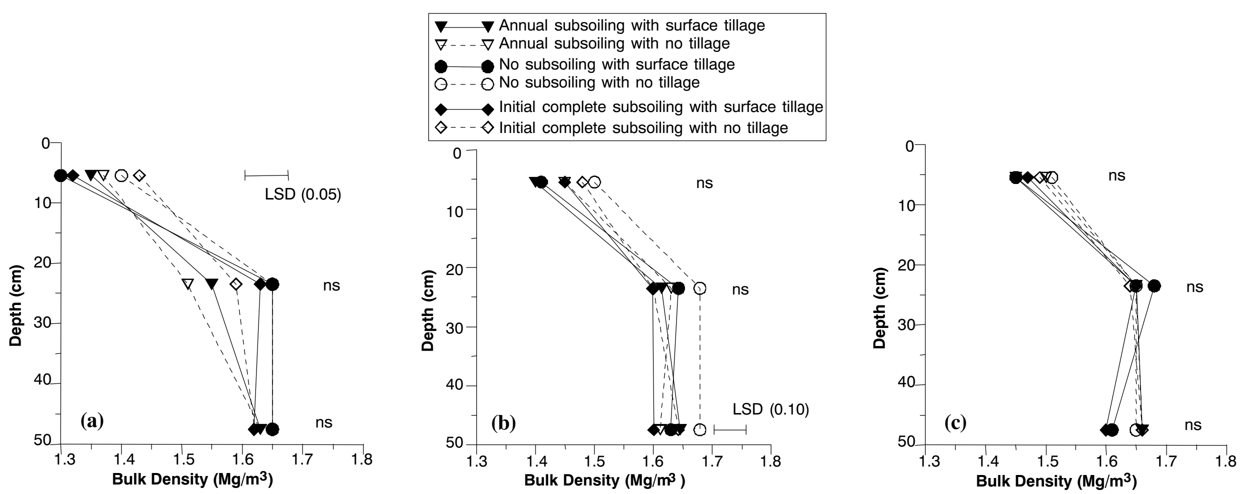

Figure 6. Interactions of subsoiling and surface tillage on bulk density measurements in three row positions: (a) non-trafficked row middle, (b) in-row position, and (c) trafficked row middle.

bulk density (1.59 Mg/m^3; P $\leq$ 0.051) compared to surface tillage (1.61 Mg/m^3). No effect was found at the deepest depth of 47.5 cm. Surface tillage was found to interact with subsoiling (p $\leq$ 0.017). There was also a trend between surface tillage and traffic (p $\leq$ 0.063) at the shallow depth of 5.5 cm, with increased bulk densities at this depth being attributed to no-till treatments (fig. 6a).

Cone Index

As stated earlier, the effect of traffic in the non-trafficked row middle position was from random vehicle traffic and not the majority of vehicle traffic, which would have been on the other side of the row, more than 0.7 m away. Cone index measurements obtained in the non-trafficked row position showed an effect of traffic from the surface down to a depth of 0.20 m, with a trend extending down to 0.25 m (table 1). A surface tillage effect was also found on cone index in this

Table 1. Main effects and interaction effects for cone index measurements.[a]

Depth (m)	Row Position: Non-Traffic	In-Row	Traffic
0.00-0.05	Tr, *Ti*	*Tr*	*Tr*
0.05-0.10	*Tr*, **Ti**, Su	*Tr*	**Tr**, *Ti*, Su **Tr*Ti**
0.10-0.15	**Tr**, *Su*	*Tr*	**Tr**, *Ti*, **Su** **Tr*Ti**
0.15-0.20	**Tr**, **Su** *Su*Ti*	*Tr*, **Su**	**Tr**, **Su**
0.20-0.25	Tr, **Su** Tr*Ti, **Su*Ti**	Tr, **Ti**, **Su** *Su*Tr*	*Tr*, **Su** *Su*Tr*
0.25-0.30	**Su** Su*Ti, *Tr*Ti*	Tr, *Ti*, **Su** **Su*Tr**	**Su** *Su*Tr*
0.30-0.35	**Su** *Su*Tr*	**Su** *Su*Tr*, *Ti*Tr*	**Su** *Su*Tr*
0.35-0.40	**Su**	**Su** *Su*Tr*, Ti*Tr	*Su*Tr*
0.40-0.45	*Su*	**Su** *Su*Tr*	
0.45-0.50		Ti, **Su** Su*Tr	*Tr* Su*Ti
0.50-0.55		Ti, *Su* Su*Ti, Su*Tr	*Su* *Su*Ti*

[a] Tr = traffic effect, Ti = surface tillage effect, Su = subsoiling effect, Tr*Ti = traffic by surface tillage interaction, Su*Ti = subsoiling by surface tillage interaction, Su*Tr = subsoiling by traffic interaction (plain text = $LSD_{0.1}$, *italics* = $LSD_{0.05}$, and **bold** = $LSD_{0.01}$).

row position, although it was restricted to shallow depths and did not extend downward past 0.1 m. A strong subsoiling effect was also found to reduce cone index measurements from the 0.05 m depth down to 0.40 m, with a trend extending downward to 0.45 m.

Traffic increased cone index at all depths in plots that were annually subsoiled (fig. 7a). Treatments that received no-subsoiling had maximum values of cone index, with traffic causing largest values near the soil surface down to 0.18 m and no-traffic values being greatest below this depth. Plots that were initially completely disrupted also exhibited greater values of cone index down to depths of 0.3 m as a result of traffic.

In-Row Position

Moisture Content

At the shallow depth of 5.5 cm, the main effect of surface tillage caused a trend in the no-tillage treatment to have higher soil moisture (4.9%) than the no-tillage treatment (4.5%; $p \leq 0.079$), probably due to increased infiltration and decreased evaporation resulting from increased residue coverage (fig. 2b).

Bulk Density

The main effect of traffic increased bulk density at the shallow depth of 5.5 cm (1.51 Mg/m^3; $p \leq 0.003$) compared to the no-traffic treatment (1.39 Mg/m^3; fig. 3b). This same effect was also found to cause a trend at the medium depth of 22.5 cm ($p \leq 0.060$), with traffic causing increased bulk density (1.65 Mg/m^3) compared to no-traffic (1.61 Mg/m^3). No effects of traffic were found on bulk density at the deepest depth of 47.5 cm.

Not surprisingly, significant effects of soil loosening were attributed to subsoiling treatments at the upper two depths in the tillage depth range (fig. 4b). At the shallowest depth of 5.5 cm, annual subsoiling was found to have a strong trend to cause reduced bulk density (1.42 Mg/m^3; $p \leq 0.052$) compared to no subsoiling (1.46 Mg/m^3) or initial complete subsoiling (1.46 Mg/m^3). At the depth of 22.5 cm, initial complete subsoiling had similar bulk density (1.60 Mg/m^3; $p \leq 0.046$) compared to annual subsoiling (1.62 Mg/m^3), which were both reduced from no subsoiling (1.66 Mg/m^3).

The main effect of surface tillage was also found to be significant on bulk density, but only adjacent to the soil surface. No-tillage had greater bulk density (1.47 Mg/m^3; $p \leq 0.001$) compared to surface tillage (1.42 Mg/m^3) at the shallow depth of 5.5 cm (fig. 5b). Surface tillage was also found to interact with subsoiling ($p \leq 0.028$) and to a lesser degree with traffic ($p \leq 0.064$; fig. 6b) at the deepest depth of 47.5 cm.

Cone Index

Cone index measurements in the in-row position were affected by the occurrence of traffic in the trafficked-row middle position to a 0.3 m depth (table 1). Cone index was

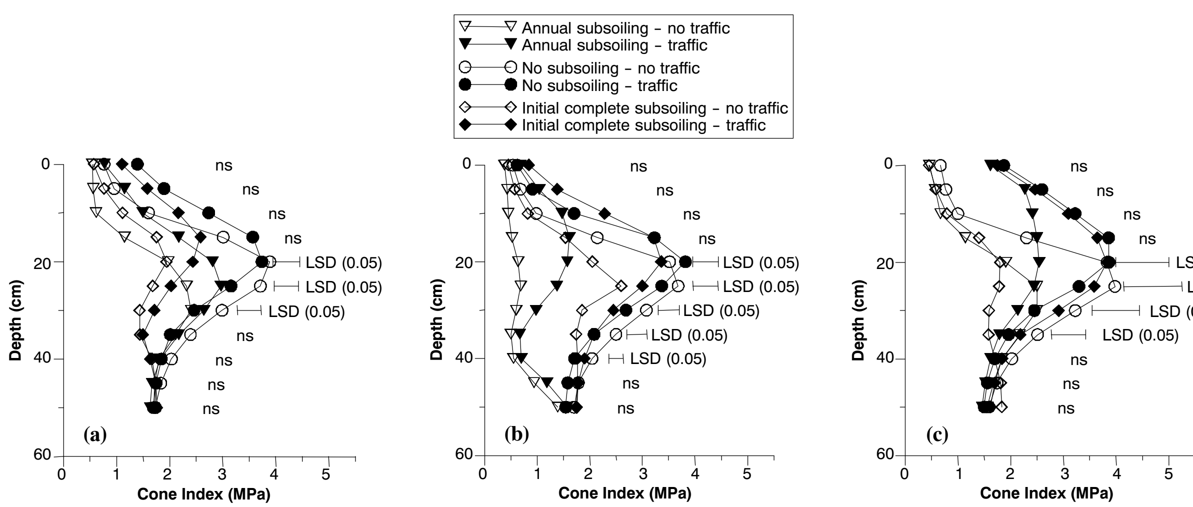

Figure 7. Interactions of subsoiling and traffic on cone index measurements in three row positions: (a) non-trafficked row middle, (b) in-row position, and (c) trafficked row middle.

also strongly affected by the presence of subsoiling, beginning at a depth of 0.15 m and progressing down through the remainder of the profile to a depth of 0.50 m. Surface tillage also had a significant effect on cone index measurements in this position at a depth of 0.20 to 0.30 m, but the results were most likely due to differences in soil moisture because surface tillage did not penetrate past a depth of 0.2 m.

The compacting effect of vehicle traffic was easily found by examining measurements of cone index obtained in the in-row position (fig. 7b). Differences in cone index due to the main effects of traffic were found down to depths of 0.3 m. These differences were particularly obvious in the annual deep tillage plots, which had the loosest soil profile and created the soil condition most susceptible to soil compaction. Significant differences in cone index were also found in the initially disrupted plots as a result of vehicle traffic. The no-subsoiling treatment was least affected by vehicle traffic, with small differences occurring at all depths in cone index.

Similar cone index profiles were found for the initially complete subsoiled treatments as for the no-subsoiled treatments. The annual deep subsoiling treatments had greatly reduced values of cone index, but caution should be observed because the presence of traffic caused this soil condition to return to cone index values similar to no-subsoiling or initially completely subsoiled. The initially completely subsoiled cone index profile at some depths was greater than that of the no-subsoiling treatment, indicating the sensitivity of completely disturbed soil to traffic impacts.

Trafficked-Row Middle Position

Moisture Content

Traffic was found to increase soil moisture at the middle depth of 22.5 cm (7.1%) compared to the no-traffic treatment (6.2%; $p \leq 0.025$). Increased compaction caused by the traffic treatment decreased evaporation and drainage, resulting in increased soil moisture at this depth (fig. 2c).

Bulk Density

Traffic increased soil compaction compared to plots where traffic was not present (fig. 3c). At a depth of 5.5 cm, traffic was found to be statistically significant (1.62 Mg/m^3; $p \leq 0.002$) compared to those plots where no traffic was present (1.34 Mg/m^3). At the depth of 22.5 cm, traffic contributed to higher bulk densities (1.68 Mg/m^3) than no-traffic (1.61 Mg/m^3; $p \leq 0.006$). At the depth of 47.5 cm, traffic also tended to cause higher bulk densities (1.67 Mg/m^3) than no-traffic (1.61 Mg/m^3; $p \leq 0.080$).

No effect of subsoiling was found (fig. 4c) except at the deepest depth of 47.5 cm, where a trend existed ($p \leq 0.094$). At this depth, which was below the depth of subsoiling, annual subsoiling may have contributed to cause the highest bulk density (1.66 Mg/m^3) compared to no subsoiling (1.63 Mg/m^3) or initial complete subsoiling (1.63 Mg/m^3). This result may indicate that repeated subsoiling (annual) may be responsible for creating a zone of increased soil compaction slightly below the zone of tillage.

Near the soil surface at the 5.5 cm depth, no-till had significantly higher bulk density (1.50 Mg/m^3; $p \leq 0.004$) than surface tillage (1.46 Mg/m^3; fig. 5c). A similar effect was found at the deepest depth of 47.5 cm, where higher bulk density was found for no-till (1.66 Mg/m^3; $p \leq 0.011$) compared to surface tillage (1.62 Mg/m^3).

A trend existed that caused surface tillage to interact with traffic ($p \leq 0.068$; data not shown), causing increased levels of bulk density near the surface at 5.5 cm when traffic was present. Traffic caused a 19% increase in bulk density in the surface tillage plots and a 16% increase in bulk density in the no-tillage plots at this depth.

Cone Index

Vehicle traffic, surface tillage, and subsoiling all significantly affected cone index in the trafficked row middle. Traffic had a significant effect on cone index in the trafficked row position down to a 0.25 m depth (table 1). Surface tillage was also found to reduce cone index measurements near the soil surface down to the 0.15 m depth, the depth of chisel plowing. The effect of subsoiling was found deeper in the soil, with cone index being reduced by subsoiling down to 0.35 m.

Near the soil surface, the effect of traffic was easily seen on cone index measurements (fig. 7c). For those plots that did not receive traffic, significant reductions in cone index were found from the surface down to a 0.2 m depth for the no-subsoiling treatment, down to a 0.25 m depth for the annual deep subsoiling treatment, and down to a depth of 0.4 m for the initial complete subsoiled treatment. For those plots with traffic, the only significant reduction in cone index was due to the effect of annual subsoiling. Virtually no difference was found between those plots that were initially completely subsoiled and those plots that were never subsoiled when traffic was placed over this area.

Results from Reeves et al. (1992) in these same plots showed that traffic had no effect on crop yields but that subsoiling increased crop yields. They hypothesized that corn compensated for reduced rooting in the trafficked row middles by increasing rooting in the non-trafficked row middles. Our results would concur that the presence of traffic greatly increased bulk density and cone index in the trafficked row middle across the in-row position and upwards to the soil surface of the non-trafficked row middle. Traffic did not, however, increase the bulk density of the soil at the medium and deep depths in the non-trafficked row middle. Our data also showed that significant reductions in bulk density and cone index were found in the in-row position and the non-trafficked row middle due to annual in-row subsoiling. The ability of the plant roots to explore the subsoiled profiles in the non-trafficked row middles and the inability of the traffic treatment to compact these same areas may explain why traffic did not affect crop yields, but in-row subsoiling did.

Conclusions

Vehicle traffic was found to increase soil bulk density at all depths and in all row positions. The greatest increase occurred in the trafficked row position where vehicle traffic was directly applied. However, vehicle traffic applied in the trafficked row position also increased bulk density and cone index in the in-row position and the non-trafficked row position.

The no-subsoiling treatment had higher bulk density and cone index values compared to initial one-time complete subsoiling or annual in-row subsoiling. Annual in-row subsoiling reduced bulk density and cone index values mostly in the in-row position, but also showed reduced values in the non-trafficked row middle.

Significantly increased bulk density values were found near the soil surface in all three row positions resulting from no-tillage.

Annual in-row subsoiling partially loosened the non-trafficked row middle. This loosened zone may have allowed crop roots to proliferate, thereby withstanding the negative effects of vehicle traffic, which were mostly confined to the trafficked row middle, explaining previously reported increased crop yields from annual in-row subsoiling, regardless of vehicle traffic.

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