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Improved Root Penetration of Soil Hard Layers by a Selected Genotype

W. J. Busscher,[a] J. Lipiec,[b] P. J. Bauer,[a] and T. E. Carter, Jr.[c]

[a]*Coastal Plain Soil, Water, and Plant Research Center, USDA-ARS, 2611 West Lucas Street, Florence, SC 29501-1242*
[b]*Polish Academy of Sciences, Institute of Agrophysics, Doswiadczalna 4, P.O. Box 201, 20-290 Lublin 27, Poland*
[c]*Soybean and Nitrogen Fixation Research, USDA-ARS, 312 7 Ligon Street, Raleigh, NC 27695-7631*

ABSTRACT

Crops can be effectively grown on hardpan soils and water effectively used from deep in the profile if hard layers in soils can be penetrated or if they are broken up by tillage. Addition of gypsum to the soil or exploitation of genetic differences in root penetrability may help improve root penetration through hard layers with less need to depend on the energy requirements of deep tillage. To test this theory, a single-grained Ap horizon of Norfolk loamy sand soil was compacted into soil columns to compare root penetrability of soybean [*Glycine max* (L.) Merr.] genotypes Essex and PI 416937 in the presence and absence of gypsum and at two soil compaction levels (columns with uniform compaction at 1.4 g cm^{-1} and columns with increasing compaction with depth from 1.4 to 1.75 g cm^{-1}). Compaction treatments were imposed by constructing soil columns composed of 2.5-cm-deep, 7.5-cm-diameter cylindrical cores compacted to predetermined bulk densities (1.40, 1.55, 1.65, and 1.75 g cm^{-3}). Soil penetration resistances were measured on duplicate cores using a 3-mm-diameter cone-tipped penetrometer. Columns were not watered during the

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study; soybean genotypes were grown in the columns until they died. Both genotypes lived one day longer in columns with lower bulk density and penetration resistance. Although root growth was more abundant for Essex than for PI 416937, root growth of PI 416937 was not decreased by compaction as much as it was for Essex. These results suggest that PI 416937 may possess the genetic capability to produce more root growth in soils with high penetration resistance. This study suggests that genetic improvement for root growth in soils with hard or acidic layers may potentially reduce our dependence on tillage. Gypsum did not affect root growth in this study.

INTRODUCTION

High resistance to root penetration is common in many hardpan soils and decreases the effectiveness of the soil as a plant growth medium. It has been shown to decrease seedling growth, leaf size (Arvidsson and Hakansson, 1996; Beemster and Masle, 1996; Young et al., 1997) root development, and yield (Arvidsson and Hakansson, 1996; Beemster and Masle, 1996; Young et al., 1997; Costantini, et al., 1996; Lipiec et al., 1993; Misra and Gibbons, 1996). Because high penetration resistance limits roots to smaller volumes, uptake of water is also decreased. In areas with subsoil hardpans, the problem of penetration resistance can be reduced and plant growth increased by deep tillage (Sojka et al., 1991). However, deep tillage can be expensive in terms of time (0.3 to 0.7 h ha^{-1}), energy (20 to 25 L fuel ha^{-1}), and equipment power requirements (14 to 20 kw per shank) (Karlen et al., 1991). Tillage effects are also temporary because soils tend to recompact over time (Busscher et al., 1995; Carter et al., 1996). Because of theses problems, alternative management strategies are needed.

One alternative to deep tillage is to amend the soil. Although most beneficial effects of gypsum are attributed to the elimination of subsoil aluminum toxicity or enhanced calcium nutrition (Sumner et al., 1986), gypsum can decrease soil penetration resistance, maintain low levels of penetration resistance, or improve root ability to penetrate a hard soil layer (Abusharar, 1996; Hall et al., 1994; Radcliffe et al., 1986; Wallace, 1994). The ability of gypsum addition to help ameliorate high strength and improve root growth in compacted southeastern Coastal Plain soil needs to be further examined.

A second, and because it leaves the soil untreated, a potentially more economical alternative to tillage, is the development of varieties with enhanced ability of roots to penetrate hard soils. However, few examples of genetic differences in rooting behavior are available. Kasperbauer and Busscher (1991) found that two cotton (*Gossypium hirsutum*) genotypes differed in their ability to penetrate compacted soil columns and speculated that the rooting of the superior genotype might impart drought tolerance through greater water extraction from lower, harder regions of the soil profile. For soybean, a plant introduction from Japan (PI 416937) wilted

several days later than normal southern U.S. cultivars during drought; this slow wilting was associated with a prolific root system (Sloane et al., 1990; Hudak and Patterson, 1995, 1996; Pantalone et al., 1996a, 1996b). The root system of the PI 416937 was also more tolerant of soil Al toxicity than typical southern U.S. cultivars (Goldman et al., 1989; Campbell et al., 1990; Ritchey and Carter, 1993; Bianchi-Hall et al., 1998). The ability of this prolific rooting system to penetrate a hard soil is not known.

Our overall objective was to test the theory that soybean root penetration in compacted soil could be improved by gypsum addition or genotype selection. Our specific objectives were to 1) evaluate gypsum as an amendment to improve root penetrability for soybean and 2) determine whether prolific rooting type PI 416937 was better able to penetrate hard soil layers than control variety Essex.

MATERIALS AND METHODS

Treatments and Experimental Design

Experimental treatments were the two soybean genotypes (Essex and PI 416937), two gypsum additions (0 and 1 g kg^{-1}), and two compaction levels of soil (columns uniformly compacted at 1.4 g cm^{-1} and columns with increasing compaction with depth from 1.4 to 1.75 g cm^{-3}). Essex, a maturity group V cultivar, was chosen as a standard for comparison with PI 416937 because it had been widely grown in the southeastern U.S. for many years (Smith and Camper, 1973). The experimental design was a randomized complete block that was replicated 4 times. The experiment was repeated in a second run to verify the results.

Preparation of Soil Columns

Soil for the columns was taken from a field that had been in row-crop production for at least 10 years. Soil was taken from the Ap horizon of a Norfolk sandy loam, a Typic Kandiudult (fine loamy Acrisol), located near Florence, SC. Soil was sieved through a 2-mm screen to filter out debris and then mixed to improve uniformity. For the appropriate treatments, gypsum was added by mixing it with the soil in a twin shell dry blender[1] (Patterson-Kelley Co., Inc., East Stroudsburg, PA) for 10 min. The blender was also used to add water to amended and unamended soils, equilibrating it to 6% on a dry weight basis.

Cores (i.e., short sections of a soil column) were produced by using a hydraulic press to compact a known weight of gypsum-amended and non-gypsum-amended

[1]Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or the Institute of Agrophysics and does not imply its approval to the exclusion of other products or vendors that may also be suitable.

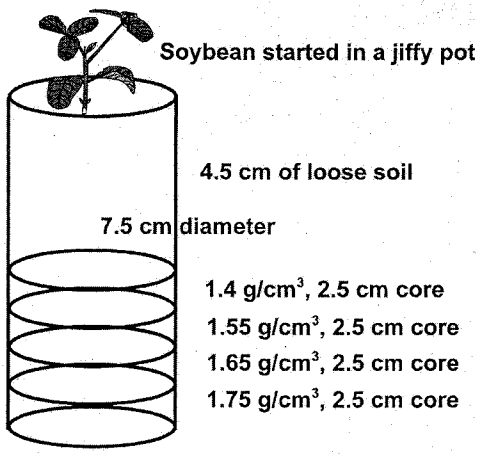

FIGURE 1. The experimental setup showing a variable column. In uniform columns, the bottom four layers were compacted to 1.4 g cm^{-3}.

soil into 7.5-cm-diameter, 2.5-cm-deep cylinders. A column was constructed by stacking four compacted cores (2.5-cm-deep) and overlaying the compacted cores with a 4.5-cm-deep cylinder containing loose soil (approximately 1 g cm^{-1}). A first set of columns with increasing resistance with depth (variable compaction) had four successive cores compacted to 1.4, 1.55, 1.65, and 1.75 g cm^{-1} (Figure 1). In a second set (uniform compaction), all four cores were compacted to a bulk density of 1.4 g cm^{-1}. Cores were fastened together with 4-cm wide masking tape. Bulk density, penetration resistance, and soil water content were measured on a duplicate set of cores not used in the main study, but constructed at the same time. Bulk densities measured on the duplicate set of cores coincided with targeted values within 0.01 g cm^{-3} (Table 1). Initial soil water contents were the same (0.06 g water per g soil with a standard error of 0.0002) for all treatments and both runs of the experiment.

Soil samples measured at the end of the experiment showed that pH was 5.4 for the gypsum-amended soil and 5.6 for the non-amended soil. Aluminum concentrations were 146 mg kg^{-1} for the gypsum-amended soil and 143 for the non-amended soil. Base saturations were 3.48 cmol kg^{-1} Ca, 0.59 cmol kg^{-1} Mg, 0.15 cmol kg^{-1} K, 0.05 cmol kg^{-1} Na, and 1.79 cmol kg^{-1} Ca, 0.54 cmol kg^{-1} Mg, 0.16 cmol kg^{-1} K, 0.03 cmol kg^{-1} Na, for the gypsum-amended and non-amended soils, respectively. Except for Ca, these differences were small. None of these appeared to influence the results.

TABLE 1. Measured bulk densities (g cm^{-3}) for the duplicate set of cores as they varied with column depth for the two runs of the experiment. Readings were means over four replicates. Numbers in parentheses were standard errors.

	Bulk density	
Depth[a]	First run	Second run
1	1.40 (0.002)	1.40 (0.002)
2	1.55 (0.003)	1.55 (0.0003)
3	1.65 (0.001)	1.65 (0.003)
4	1.74 (0.002)	1.74 (0.001)

[a]Depths were successive 2.5-cm deep rings below 4.5 cm of loose soil at the top of the column.

Controlled Environment Chamber

The experiment was conducted in a controlled environment chamber where temperature was maintained between 28° and 29°C. The chamber photoperiod was 12 h and light intensity was 75 μE^{-2} s^{-1} at the top of the soil columns. Illumination was supplied by four 40-watt GroLux bulbs (Osram Sylvania, Danvers, MS).

Seeds were germinated on moist filter paper and, subsequently, three were transplanted into moist peat pots atop each column. After plants emerged from peat pots, they were thinned to one healthy plant per column. Columns were covered with Parafilm to prevent surface evaporation. When plants were tall enough, leaves were pulled above the Parafilm and the Parafilm was wrapped around the plant stem. Since adding water would have softened the soil and since we were testing root penetration of hard layers, columns were not watered during the experiment. As a result, plant roots had to penetrate the hard layers to reach available water. After water was exploited, plants wilted; ultimately all plants dried; and we terminated the experiment.

Soil Penetration Resistance

Penetration resistance (PR) was measured in the duplicate cores with a 3-mm-diameter, stainless-steel flat-tipped probe. The probe was attached to a strain gauge and a motor geared to penetrate the soil at a constant rate of 0.28 mm s^{-1}. Strain gauge output was expressed as millivoltage read on a Metrabyte DAS-8 interface (Keithley Metrabyte Corp, Taunton, MA) between the gauge and a desktop computer. Output was captured in the computer using Pascal software (Borland International, Inc., Scotts Valley, CA) and recorded at a rate of 1 khz while the probe penetrated the top 5 mm of the core. After probing to 3- to 4-mm depth,

TABLE 2. Penetration resistances (MPa) for the duplicate set of cores as they varied with column depth for the two runs of the experiment. Readings were means over both gypsum treatments and four replicates.

	Penetration resistance	
Bulk density[a]	First run	Second run
1.40	0.78a[b]	0.79a
1.55	1.06b	1.07b
1.65	1.42c	1.49c
1.74	2.11d	2.17d

[a]Bulk densities were associated with successive 2.5 cm depths below 4.5 cm of loose soil at the top of the column.

[b]Means within rows with the same letter were not different by the LSD test at P=0.05.

output as a function of depth reached a plateau. This 'plateau' reading was used for analysis. Three probings were taken at equally spaced positions on each core, averaged, and treated as a single data point for that core.

The probe was calibrated to relate strain gauge millivolt output to PR. Calibration was developed by applying a known force to the probe (using a lever and weight) and measuring the output voltage. The force and millivolt data were regressed (SAS Institute, 1990) to construct a calibration curve of PR=0.512V-0.021 where PR was measured in MPa and V was strain gauge millivoltage. The regression was determined on data taken over a range of 0 to 10 V and 0 to 5.1 MPa (r^2=0.99). The PR increased with depth and/or bulk density from less than 1 MPa to greater than 2 MPa (Table 2), where 2 MPa is considered to be a root limiting value (Blanchar et al., 1978; Taylor and Gardner, 1963).

Plant Traits Measured

Plant height was measured daily; leaf area was measured between 1 and 2 weeks after emergence, and root growth was measured at the end of the experiment. Leaf area was estimated by tracing leaves on pieces of paper, cutting out the traces, and determining their area with an area meter (Licor, Inc., Lincoln, NE). After separating the cores manually, each soil core was subjected to hydropneumatic elutriation which separated roots from soil with water and air pressure and then deposited roots on a fine screen (Smucker et al., 1982). After washing, roots were stained methyl violet blue, floated on water in a transparent tray, and counted with an automated digitizer (Delta-T Devices, Ltd., Burwell, Cambridge, England). All roots, primary and laterals, were counted together. Root data were not lengths, but

associated root counts based on digitization of the root image on the digitizer (Harris and Campbell, 1989). Each count correlated to approximately 0.4 to 0.5 cm of root length.

Data Analysis

Data were analyzed using analysis of variance (SAS Institute, 1990). Data were tested for significant differences at the 0.05 level unless otherwise specified. Treatment means for the root data were regressed against PR. Since data between the two runs were not significantly different, they were averaged for analysis and presentation.

RESULTS AND DISCUSSION

We feel that genetic capabilities can potentially improve the plant rootability within a soil, increase deep soil water uptake, and reduce tillage frequency thus saving energy. Current tillage recommendations list a tillage frequency of every year or two (Busscher et al., 1995). Other recommendations include every growing season for double-cropped management (Frederick et al., 1998). PI 416937 is one candidate that can aid in improved rooting, improved use of deep soil water, and less tillage. Other candidates will develop from time to time during screening programs. Establishing genetic candidates for improvement is just one step in improved resistance to hard soils and reduction of tillage. Past and current studies are also considering levels of recompaction from different tillage tools or different management systems that may be able to maintain beneficial conditions for root growth for more than one growing season (Frederick et al., 1998) or more than one year (Karlen et al., 1991).

Effect of Gypsum on Penetration Resistance and Root Growth

Neither PR nor root growth differed with gypsum treatment. Plots treated with gypsum had a mean PR of 1.37 MPa while those without gypsum had a mean of 1.35 MPa (LSD=0.09 at P=0.05). Root count, a trait associated with total root lengths, averaged 44 with gypsum and 43 without (LSD=12 at P=0.05). However, the ineffectiveness of gypsum in this experiment could be a result of the high degree of compaction of these soils and their high initial PR. If gypsum's potential effectiveness against a hard layer could result from increased cementation and improved aggregation as suggested by Chan (1995) and Radcliffe et al. (1986), it would be more effective in softer soils where it could maintain initial soil looseness, perhaps through increased root growth. Artificially compacting the soil at the beginning of this experiment or soil that is already compacted *in situ* may circumvent the beneficial physical effect of the gypsum by not allowing it to maintain softer soil.

TABLE 3. Digitized root counts as they varied by depth and column type for both runs of the experiment. For the variable columns, bulk densities were 1.40, 1.55, 1.65, and 1.74 g cm^{-3} for depths 1, 2, 3, and 4, respectively. For the uniform columns, bulk densities were 1.40 g cm^{-3} for all depths. "Difference" was uniform minus variable root counts.

	Essex			PI 416937		
Depth	Uniform	Variable	Difference	Uniform	Variable	Difference
1	103a[a]	86a	18a	54a	77a	-22a
2	70b	35b	35a	24b	29b	-5b
3	52b	25bc	27a	21b	20b	1b
4	53b	7c	46a	26b	13b	13b
Uniform means [b]	70a	--	--	31b	--	--
Variable means	--	39a	--	--	35b	--
Difference means	--	--	32a	--	--	-3b

[a] Means within columns for depth with the same letter are not different by the LSD test at P=0.05.

[b]Means are comparisons between Essex and PI 416937. Values with the same letter are not different by the LSD test at P=0.05. Uniform means compare the two uniform columns; variable means compare the variable columns; and difference means compare the difference of those two.

Effect of Genotype on Penetration Resistance and Root Growth

Root count for Essex was greater than that for PI 416937 (Table 3). However, root count for Essex decreased more with increased depth in the columns, i.e. increased PR or bulk density, than root count for PI 416937. Root count of Essex decreased significantly between bulk densities 1.55 and 1.74 g cm^{-3}, which were the second and fourth depths in the variable columns. It did not decrease significantly between these depths in the uniform columns. Essex's total root count also was significantly lower in the higher strength, variable columns than in the lower strength, uniform columns; counts were 39 for the variable columns and 70 for the uniform columns (LSD=17 at P=0.05). On the other hand, root count of PI 416937 did not decrease as much with increased PR; it did not decrease significantly between bulk densities 1.55 and 1.75 g cm^{-3} in variable columns (nor for the equivalent depths in the uniform columns). Also, PI 416937's root count was about the same for variable and uniform columns (root counts of 35 for the variable column and 31 for the uniform column with an LSD=17 at P=0.05).

Subtracting uniform minus variable root counts at each depth highlighted the differential responses of Essex and PI 416937. Comparing the difference between uniform and variable columns was important because it corrected for the expected reduction of root growth with depth. If root count differences within the uniform column were taken as variability with depth, then the difference between uniform

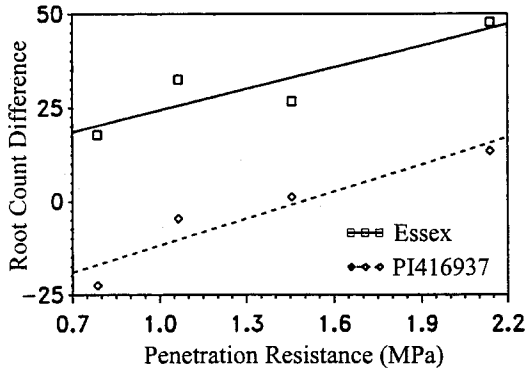

FIGURE 2. Regression of digitized root count differences (CTD, counts of uniform minus variable columns) with penetration resistance (PR). For genotype Essex, CTD=19 PR+5 (r^2=0.80). For genotype PI 416937, CTD=24 PR-36(r^2=0.89).

and variable columns could be interpreted as a result of increased PR. Differences between columns for Essex were greater than those for PI 416937 (Table 3). Essex was more affected by increases in soil penetration resistance than PI 416937.

Differences between uniform and variable columns were regressed against PR (Figure 2). The greater effect of PR on Essex was seen by its greater count differences when compared to PI 416937. Slopes for the two curves were greater than zero, but not significantly different from one another.

Leaf Area, Plant Height, and Plant Longevity

As with root growth, the properties of leaf area, plant height, and plant longevity were not affected by gypsum treatment. Mean leaf areas were 31.9 cm^2 for treatments with gypsum and 33.5 cm^2 for treatments without gypsum (LSD=2.9 cm^2 at P=0.05). Mean plant heights were 25.6 cm for treatments with gypsum and 26.2 cm for treatments without gypsum (LSD=1.5 cm at P=0.05). Plant longevity was 32 days for both treatments with and without gypsum.

Averaged across uniform and variable columns, genotypes did not differ in leaf areas; but Essex had taller plants that dried later than PI 416937. Essex had a leaf area of 32.5 cm^2 and PI 416937 had a leaf area of 32.8 cm^2 (LSD=2.9 cm^2 at P=0.05). Mean heights of Essex were 30 cm vs 22 cm for PI 416937 (LSD=1.5 for P=0.05). Essex dried at 33.5 days while PI 416937 dried at 31.1 days (LSD=1.1 days at P=0.05). Taller, longer growing shoots of Essex agreed with the root data.

When data from uniform columns were subtracted from variable columns, neither leaf area nor plant height differences were statistically significant between cultivars.

Reduction in leaf area between uniform and variable columns for Essex was 4.9 cm^2 while for PI 416937, it was 4.4 cm^2 (LSD=6.9 at P=0.05). Plants were 6 mm taller in variable columns for Essex and 7 mm shorter in variable columns for PI 416937 (LSD=2.3 cm for P=0.05). While significance was seen for root growth in the differences between uniform and variable columns, it was not seen for above-ground characteristics. This may be a result of data variability because differences were similar to root data, but not significant.

When comparing uniform with variable columns that were averaged over cultivars, plant heights were not different; but leaf area and longevity were greater in uniform columns. Plant heights were 25.9 cm for uniform columns and 25.8 cm for variable columns (LSD=1.5 cm for P=0.05). Leaf areas were 34.9 cm^2 in uniform and 30.3 cm^2 in variable columns (LSD=2.9 cm^2 for P=0.05). Smaller leaf area in variable columns resulted from higher PR in those columns. A similar reduction in leaf elongation rate was seen by Young et al. (1997) when root impedance was increased. Longevity was 33 days in columns with uniform bulk density and 32 days in columns with variable bulk density (LSD=1 day at P=0.05). These differences are consistent with better root growth in uniform columns.

CONCLUSIONS

Under the conditions of this test, gypsum treatment did not affect soil or plant characteristics. This may be because the soil started out with a high degree of compaction. Gypsum might help in a soil with lower penetration resistance that is softened by tillage or root growth by maintaining lower penetration resistance (Chan, 1995; Radcliffe et al., 1986). It is not unusual for tillage to reduce soil strengths lower than those used in the uniform columns in this study (Threadgill, 1982).

Essex had more root growth, leaf area, and lived longer than PI 416937. Yet, root growth for Essex was more sensitive to compaction than for PI 416937. As a result of this sensitivity of Essex to compaction, rooting of PI 416937 was actually greater than for Essex at the highest compaction level. PI 416937 may possess the genetic capability to produce better root growth than Essex in soils of high penetration resistance.

Carter and Rufty's (1993) observation that PI 416937 was a more prolific rooting variety in hard layer soils might explain why it wilted later than other cultivars. Since root growth of PI 416937 was found to be more tolerant of high soil penetration resistance in this study, it could explore more, harder soil for water in times of drought. A combination of soil and plant effects will be needed to further explain the difference of penetration resistances of Essex, PI 416937, and other cultivars. Cooperation of soil and plant scientists will be needed to identify and incorporate germplasm with improved root penetration that can produce cultivar improvement for improved growth and drought resistance in soils with compacted layers.

Kasperbauer and Busscher (1991) noted a difference between two cotton varieties in a similar test using a single hardlayer. The advantage of the method used here was that it incorporated the effects of several hard layers and a weakly compacted column, giving several PR levels to separate rooting effects and giving the opportunity to separate depth effects from strength effects.

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