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Tillage effect on nutrient stratification in narrow- and wide-row cropping systems

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Abstract

Recent research has indicated that conservation systems with narrow-rows have potential for higher crop productivity on southeastern USA Coastal Plains Soil. The objective of this study was to determine how surface tillage and subsoiling affect nutrient distribution in the soil profile in narrow- and wide-row systems. A secondary objective was to determine the effect of row position on soil pH and nutrient concentrations in the wide-row system. Soil samples were collected in 1996 from plots that had been growing soybean (*Glycine max* (L.) Merr.) double cropped with wheat (*Tritiucum aestivum* L.) for 3 years and then again in 1999 after 3 years of continuous corn (*Zea mays* L.). Narrow-row spacing was 19 cm for soybean and 38 cm for corn. Wide-row spacing was 76 cm for both soybean and corn. Wheat was grown in 19 cm wide-rows. Soil samples were randomly collected from throughout the plots in the narrow-row culture. In the wide-row culture, separate samples were collected from the row and from between rows. Treatments were surface tillage (disc tillage (DT) and no surface tillage (NT)), with different frequencies of subsoiling. The soil type was Goldsboro loamy sand (fine-loamy, siliceous, thermic, Aquic Kandiudult). Soil samples from four depths (the surface 5 cm of the A horizon, the remainder of the A horizon, the E horizon, and the top 7.5 cm of the B horizon) were analyzed for pH, P, K, Ca, and Mg. Nutrient concentrations and pH differed little between row spacings at any depth after either 3 or 6 years. Differences due to subsoiling appeared mainly due to nutrient removal as the treatments with more intense subsoiling had higher yield and lower concentrations of nutrients (except K). Concentrations of P, Mg, and Ca at the soil surface tended to be higher in NT than in DT, especially in the mid-rows of the 76 cm wide-row systems. The data suggest only small differences in soil nutrient stratification can be expected as growers adopt narrow-row crop production systems with intensive subsoiling. Published by Elsevier Science B.V.

Keywords: Wheat; Soybean; Corn; Subsoiling; Conservation tillage; Phosphorous; Potassium; Calcium; Magnesium

1. Introduction

Narrow-row crop production systems may become more popular for soybean and corn as planting equipment and weed control methods improve. Frederick et al. (1998) demonstrated a substantial potential to increase double cropped soybean yields in the southeast USA by combining narrow-rows (19 cm) with conservation tillage and intense subsoiling, and there is widespread interest for developing narrow-row corn production systems.

Conservation tillage, especially no-tillage, results in vertical stratification of plant nutrients in the soil profile. Studies have shown that P, Ca, Mg, and K accumulate near the surface in no-tillage culture

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(Triplett and van Doren, 1969; Lal, 1976; Dick, 1983). Rhoton et al. (1993) compared tillage systems for nutrient distribution in four long-term experiments in different areas of the southeastern USA. Though differences between tillage systems for chemical properties were often not significant, they found a trend for higher amounts of exchangeable basic cations near the surface in conservation tillage compared to conventional tillage. Edwards et al. (1992) found P, Ca, and Mg at the soil surface at higher concentrations in conservation tillage than in conventional tillage after 10 years on a fine sandy loam soil. In that study, differences between tillage systems for K at the soil surface were dependant on the crop rotation. Similarly, Karlen et al. (1989) found P, Ca, and Mg concentrations were stratified in the upper 20 cm of a loamy sand soil after 8 years of conservation tillage, but K concentrations were not.

Conservation tillage systems developed for the Coastal Plain of the southeastern USA usually include some form of deep tillage because many of these soils are easily compacted and often have naturally occurring hardpans (Naderman, 1985). The in-row subsoiler is a common implement used in wide-row crop production systems (76 cm and wider) to reduce soil compaction. This implement loosens an area approximately 8 cm wide and 40 cm deep directly under the row. For narrow-row systems (such as wheat), bent-legged subsoilers (paratill and similar implements) spaced close together to disrupt most of the surface horizon are gaining wider acceptance by growers for crops grown in narrow-row culture. Yield increases due to subsoiling are attributed to these implements disrupting the hardpan so that roots have a greater volume of soil from which to extract water (Doty et al., 1975; Kamprath et al., 1979). Busscher et al. (2000, 2001) found that yield of both narrow-row soybeans (19 cm wide-rows) and corn (38 cm wide-rows) decreased linearly with increasing mean profile cone index. Information is lacking; however, on how loosening these soils with subsoiling implements affects the distribution of plant nutrients in the soil.

From 1993 to 1999, we conducted two experiments using the same experimental plots to investigate crop productivity as affected by surface tillage and subsoiling in wide- and narrow-row width spacings. Winter wheat double cropped with soybean was grown the first 3 years (Frederick and Bauer, 1996; Frederick et al., 1998) and corn was grown during the last 3 years. Surface tillage treatments were kept intact throughout the 6 years. We collected soil samples from selected plots after the wheat–soybean experiment in 1996 and after the corn experiment in 1999. The objective of this study was to determine how surface tillage and subsoiling affect nutrient distribution in the soil profile in narrow- and wide-row systems. A secondary objective was to determine the effect of row position on soil pH and nutrient concentrations in the wide-row system.

2. Materials and methods

The experiment was conducted at the Clemson University, Pee Dee Research and Education Center at Florence, SC. Soil type was structureless Goldsboro loamy sand, which is a siliceous fine-loamy Aquic Paleudult (fine-loamy Acrisol). From the fall of 1993 through 1996, a wheat–soybean double crop rotation was grown. During the growing seasons of 1997–1999, corn was grown on the same plots. Experimental design was a randomized complete block with four replicates. Plots were 3 m wide and 15 m long.

The treatments in the study were row width for soybeans and corn (wide and narrow), surface tillage (disc tillage (DT) and no surface tillage (NT)), and subsoiling management schemes. Soybean was planted in 19 cm wide-rows (narrow) and 76 cm rows (wide). Corn was planted in 38 cm wide-rows (narrow) and 76 cm wide-rows (wide). DT was with double discing followed by smoothing with a field cultivator. All tillage was done either the day before or on the day of planting. Three subsoiling management schemes during the first 3 years of the study were: (1) none; (2) subsoiling before planting the soybean in the spring; (3) subsoiling before planting wheat in the fall and subsoiling again in the spring before planting soybean. During the second 3 years, no subsoiling was done in plots assigned to treatment 1 (the non-subsoiled treatment); subsoiling was discontinued in plots assigned to treatment (2); and subsoiling was before corn planting for plots assigned to treatment (3). For the narrow-row systems (19 cm wide-row soybean, 38 cm wide-row corn, and before planting wheat in the first 3 years of the study), plots were subsoiled to a depth of approximately 35 cm with a paratill (Tye[1] Brand, AGCO Equipment, Duluth, GA) in a separate pass. The wheat and soybean planted in 19 cm wide-rows were seeded with a John Deere 750 grain drill. This same drill was used to plant the 38 cm wide-row corn in 1997 by closing every other seed opener. In 1998 and 1999, a Monosem NG Plus planter equipped with Yetter wavy coulters and planter units spaced 38 cm apart was used to plant the corn. For the wide-row treatments, plots were subsoiled to a depth of approximately 30 cm in the same pass as planting with an in-row subsoiler (Kelley Manufacturing, Tifton, GA) that was mounted in front of the planter (John Deere 7200).

Wheat and soybean yields were determined by hand harvesting six 1 m row lengths from the middle rows of each plot each year. For corn, the center 18.2 m^2 areas of each plot were hand harvested (two 12 m long rows for the 76 cm wide spacing and four 12 m long rows for the 38 cm wide spacing). Following the hand harvest, remaining grain in the plots was harvested with a commercial scale combine. Crop management details have been reported previously for the wheat–soybean part of the rotation (Frederick and Bauer, 1996; Frederick et al., 1998).

Each year, approximately 30 randomly selected soil cores were collected from the surface 20 cm of the soil profile and combined for lime and fertilizer recommendations for the entire experimental area. Lime, P_2O_5 and K_2O were broadcast applied each year based on the analysis of those samples and recommendations of the Clemson University Cooperative Extension Service (Anonymous, 1988). By coincidence, equal amounts of P_2O_5 and K_2O were recommended each year. In the first 3 years of the experiment (the wheat–soybean double crop rotation), fertilizer was applied before wheat planting. Fertilizer amounts and dates of application were 90 kg ha^{-1} of P_2O_5 and K_2O on 17 November 1993; 84 kg ha^{-1} of P_2O_5 and K_2O on 15 November 1994; and 84 kg ha^{-1} of P_2O_5 and K_2O on 16 November 1995. In the second 3 years, the fertilizer was applied prior to corn planting. Amounts and dates of application were 84 kg ha^{-1} of P_2O_5 and K_2O on 12 March 1997; 56 kg ha^{-1} of P_2O_5 and K_2O on 24 March 1998; and 56 kg ha^{-1} of P_2O_5 and K_2O on 4 March 1999. Dolomitic limestone was used as the source of the Ca and Mg. Throughout the duration of the study, soil testing indicated the need for only two applications of lime, which were made on 9 November 1994 (1120 kg ha^{-1}) and on 4 March 1999 (2240 kg ha^{-1}).

After soybean harvest in 1996 and after corn harvest in 1999, soil cores were collected from each plot for nutrient analysis. In plots where crops were grown in 76 cm wide-rows, separate composite samples were collected throughout the entire length of the plots from the mid-row areas around the two center rows and directly from within the two center rows. Row position was ignored while collecting one composite sample in each narrow-row plot. Composite samples consisted of ten 2.5 cm diameter cores in 1996 and five 5 cm diameter cores in 1999. Nutrient analysis was done separately for four depths of the profile. These depths were the surface 5 cm, the remainder of the A horizon, the entire E horizon, and the top 7.5 cm of the B horizon. Although there is variability in depths of horizons in Coastal Plain fields, these four sampling depths roughly correspond to 0–5 cm for the surface, 5–25 cm for the remainder of the A horizon, 25–35 cm for the entire E horizon, and 35–42.5 cm for the top of the B horizon.

After collection, samples were air-dried, ground, and passed through a 2 mm screen. Soil samples were analyzed for nutrients at the Clemson University Soil and Plant Analysis Laboratory (Clemson, SC). Plant available P and exchangeable cations (K, Ca, and Mg) were extracted with Mehlich 1 reagents (0.05 N HCl and 0.025 N H_2SO_4) and quantified.

All soil pH and nutrient data were subjected to analysis of variance. For each year, two separate analyses of the data were performed. First, using all data, data were analyzed as a split-plot with main plots being width, tillage, and subsoil treatments and subplots being depth. For this analysis, data from the two row widths in the 76 cm wide-row treatments were averaged at each depth in each plot. Then, data from only the 76 cm row widths were analyzed as a split–split-plot with tillage and subsoiling, as main plots, row position as subplots, and depth as sub–subplots. When sources of variation involving more than two means were significant, these means were separated with an LSD, using a probability level of 0.05.

[1] Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA or Clemson University and does not imply approval of a product to the exclusion of others that may be suitable.

3. Results and discussion

3.1. Grain yield

Grain yields for each of the treatment combinations are shown in Table 1. For wheat (which was always grown in 19 cm rows), highest yield was generally for those treatments that included subsoiling both in the spring and in the fall. The highest total yield for soybean and corn was for the treatment that included NT, narrow-rows, and paratilling twice in the first 3 years of the study and each year before planting corn in the last 3 years. Lowest grain yield generally occurred with those treatment combinations that did not include subsoiling. Yield and nutrient removal differences between the highest and lowest yielding treatments were greater when crops were grown in narrow-row system than when grown in wide-rows. Using average feed grain composition values (Anonymous, 1988) to estimate the amount of these nutrients in the harvested grain, differences in nutrient removal between the highest and lowest yielding treatments over the 6 years for the narrow-rows were 73 kg ha^{-1} P, 157 kg ha^{-1} K, 22 kg ha^{-1} Ca, and 26 kg ha^{-1} Mg. When crops were grown in wide-rows, the differences between the highest and lowest yielding treatments for nutrient removal were 34 kg ha^{-1} P, 52 kg ha^{-1} K, 7 kg ha^{-1} Ca, and 12 kg ha^{-1} Mg.

Earlier studies looking at how the individual factors that we investigated (surface tillage, deep tillage, and row spacing) affected grain yield have often provided mixed results for both corn and soybeans. Camp et al. (1984) compared subsoiling and surface tillage treatments for 3 years under rainfed conditions and found subsoiling resulted in higher corn yield but not soybean yield with both DT and NT when grown in rows spaced 98 cm apart. Previous studies have sometimes reported higher soybean seed yield with subsoiling (Kamprath et al., 1979) or narrow-row culture (Board et al., 1990). Farnham (2001) conducted two experiments in his study on row spacing of corn in the Midwest US and found that 76 cm wide-rows had higher yield than 38 cm wide-rows in one experiment while the yield response of corn to row spacing was hybrid specific in the other experiment. Although further research is needed, our study expands on these findings as we found that yield levels were dependent on the combination of treatment levels rather than

Table 1
Total crop yield after 3 years of wheat–soybean followed by 3 years of corn

Row Width	Tillage	Subsoil	Total crop yield		
			Wheat (Mg ha^{-1})	Soybean (Mg ha^{-1})	Corn (Mg ha^{-1})
Wide	DT[a]	None[b]	8.6	7.0	19.9
		Spring only	9.0	7.5	19.1
		Fall and spring	10.9	7.2	21.3
	NT[c]	None	8.2	6.9	18.1
		Spring only	9.0	7.9	20.5
		Fall and spring	11.5	8.2	23.0
Narrow	DT	None	8.6	9.4	17.6
		Spring only	10.0	11.4	22.2
		Fall and spring	10.7	12.1	22.8
	NT	None	8.2	10.1	19.1
		Spring only	9.3	13.6	23.1
		Fall and spring	11.0	16.4	25.2
$LSD_{(0.05)}$			0.9	1.0	3.3

[a] Disc tillage.
[b] Subsoiling treatments are for the wheat–soybean rotation in 1993–1996. For the corn experiment in 1997–1999, the treatments were not subsoiling for that listed as none, no subsoiling since the 1996 bean experiment for treatments listed as spring only, and annual subsoiling for that listed as fall and spring.
[c] No-tillage.

Table 2
Effect of surface tillage on nutrient distribution in the soil after 3 years of wheat–soybean double crop (data are averaged over row width and deep tillage treatments)

Horizon	P (mg kg^{-1})		K (mg kg^{-1})		Ca (mg kg^{-1})		Mg (mg kg^{-1})		pH	
	DT[a]	NT[b]	DT	NT	DT	NT	DT	NT	DT	NT
A (0–5 cm)	21	28	67	60	312	331	67	73	6.2	6.1
A (remainder)	15	21	45	49	234	206	39	34	6.0*	5.7
E	5	6	38	37	170	163	33	26	5.7	5.7
B (top 7.5 cm)	1	0	66	68	310	302	78	71	5.3	5.3

[a] Disc tillage.
[b] No-tillage.
* Indicates significant difference ($P < 0.05$) between tillage means at that soil horizon.

individual treatments. In this study, highest yields for both crops were a result of combining NT with intensive deep tillage and narrow-row spacing.

3.2. Nutrient distribution after 3 years of wheat–soybean double crop

The narrow- and wide-row spacings had similar soil test results for K, Ca, Mg, and pH after 3 years of a wheat–soybean double crop rotation (data not shown). Neither the main effect of row width nor any interaction with row width was significant for these variables. For P, the row width *X* tillage *X* depth interaction was significant because of differences in the surface 5 cm of the A horizon. At that horizon, P concentrations in the soil were approximately 23 mg kg^{-1} for both DT and NT when soybeans were grown 7.5 cm wide-rows and when soybeans were grown with DT in 76 cm wide-rows, but concentrations of P averaged 34 mg kg^{-1} when soybeans were grown with NT in 76 cm wide-rows ($LSD_{(0.05)} = 7.4$ mg kg^{-1}). Higher concentrations of P with NT over DT have been found previously in sandy southeastern USA soils (e.g. Karlen et al., 1989; Edwards et al., 1992), but it is not apparent why higher P concentration in the surface soil occurred in the 76 cm wide-row culture and not in the narrow-row culture.

Besides the interaction described above for P, tillage did not have a large effect on nutrients or pH after only 3 years (Table 2). A significant tillage *X* depth interaction occurred for pH because NT averaged 0.3 pH units lower than DT at only one depth (in the A horizon below the surface 5 cm). No differences between tillage systems at the surface were found for the other nutrients.

Averaged over both row spacings, both tillage systems, and all four depths, the trend was for lower concentrations of P, Ca, and Mg in the soil as the frequency of deep tillage increased (Table 3). Similarly, pH was higher for the soil that was not subsoiled

Table 3
Effect of subsoiling frequency on soil nutrient concentration and pH after 3 years of wheat–soybean double cropping (1996) and after 3 years of corn (1999)[a]

Subsoil frequency	P (mg kg^{-1})		K (mg kg^{-1})		Ca (mg kg^{-1})		Mg (mg kg^{-1})		pH	
	1996	1999	1996	1999	1996	1999	1996	1999	1996	1999
None[b]	14	15	54	54	272	238	57	49	5.8	5.4
Spring only	13	14	54	51	253	213	51	44	5.7	5.3
Fall and spring	10	14	54	52	236	211	49	43	5.7	5.3
$LSD_{(0.05)}$	3	NS	NS	NS	25	23	7	5	0.1	NS

[a] Data are averaged over the tillage and row spacings treatments and the four soil depths measured.
[b] Subsoiling treatments are for the wheat–soybean rotation in 1993–1996. For the corn experiment in 1997–1999, the treatments were not subsoiling for that listed as none, no subsoiling since the 1996 bean experiment for treatments listed as spring only, and annual subsoiling for that listed as fall and spring.

than for both treatments that included subsoiling. Subsoiling increased yield (Table 1), therefore lower nutrient levels with increasing frequency of tillage may have been due to greater nutrient removal by the crop plants.

3.3. Nutrient distribution after 3 years of corn

Row spacing affected soil test levels of K after 3 years of continuous corn. A significant row spacing X depth interaction occurred as K concentrations were 25 mg kg^{-1} higher in the 76 cm wide-row spacing than in the 38 cm wide spacing only at the surface 0–5 cm of the A horizon. At the other soil depths, concentrations between the row spacing treatments were similar. This higher concentration of K in the wide-row spacing at the soil surface may partially have been due to our sampling procedure. In the wide-row system, we collected one-half of the samples from the in-row and one-half of the samples from the mid-row position, while in the narrow-row system we ignored row placement (because of the narrow distance between rows, especially following soybeans). Average K concentrations in the narrow-row system were 56 mg kg^{-1} while K concentrations were 80 mg kg^{-1} in soil collected from the wide-row plots. In the wide-row plots in 1999, K in the row averaged 118 mg kg^{-1} while mid-row levels of K at the soil

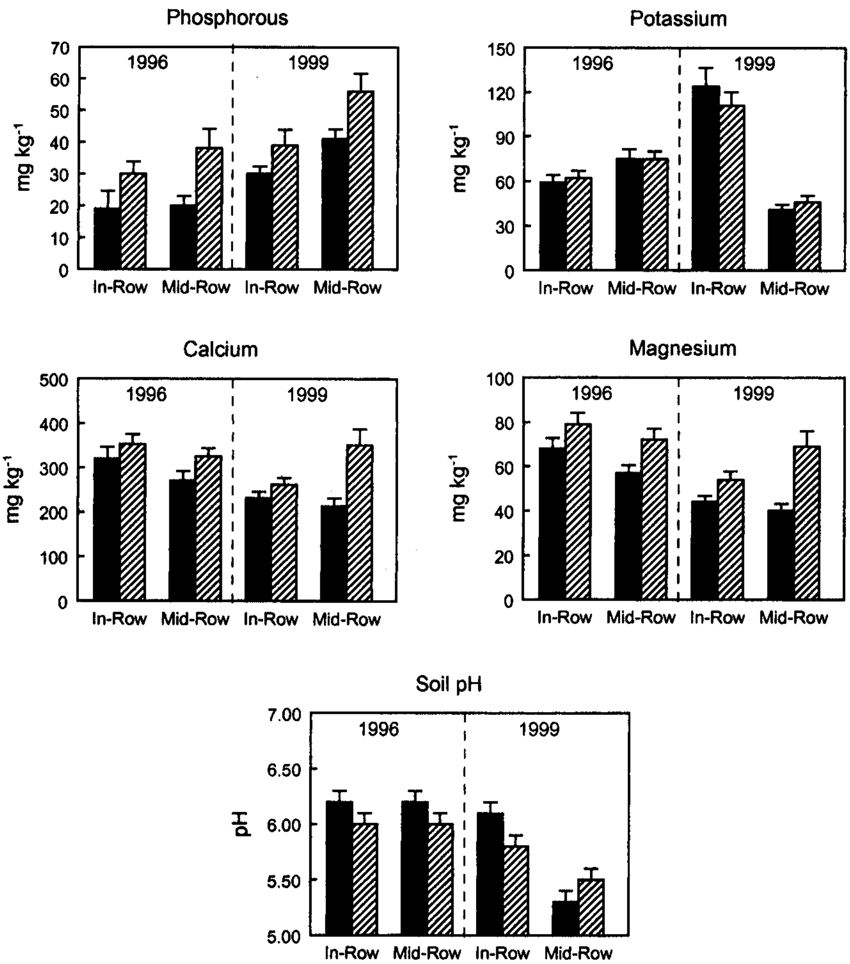

Fig. 1. Nutrient concentrations and pH of the surface 0–5 cm of the A horizon as affected by tillage and row position after 3 years of wheat–soybean double crop (1996) and 3 years of corn (1999). Solid bars indicated DT while hatched bars are NT. Error bars indicate standard deviation of means.

Table 4
Effect of surface tillage on nutrient distribution in the soil after 3 years of corn (data are averaged over row width and deep tillage treatments)

Subsoil frequency	P (mg kg^{-1})		K (mg kg^{-1})		Ca (mg kg^{-1})		Mg (mg kg^{-1})		pH	
	DT[a]	NT[b]	DT	NT	DT	NT	DT	NT	DT	NT
A (0–5 cm)	35*	48	69	67	243*	302	47	59	5.7	5.6
A (remainder)	12	16	35	35	147	143	22	21	5.3	5.2
E	2	2	40	39	157	156	33	31	5.4	5.4
B (top 7.5 cm)	0	0	69	66	303	315	76	73	5.0	5.0

[a] Disc tillage.
[b] No-tillage.
* Indicates significant difference ($P < 0.05$) between tillage means at that soil horizon.

surface were numerically closer to concentrations in the narrow-row system (mean of 44 mg kg^{-1}) (Fig. 1).

A significant tillage *X* depth interaction occurred for concentrations of P and Ca in 1999 (Table 4). The response was similar to previous findings on sandy soils with these relatively immobile nutrients (Edwards et al., 1992; Rhoton et al., 1993) as NT had higher concentrations of P and Ca than DT in the surface 0–5 cm of the A horizon, but there were no differences between tillage treatments at any other depth. A similar trend occurred for Mg, with NT having 25% higher concentrations of this nutrient than DT in the surface 0–5 cm of the A horizon (Table 4). No differences between NT and DT for concentrations of K and pH levels occurred at any depth (Table 4).

As occurred after the 3 years of the wheat–soybean rotation, plots that were subsoiled had higher concentrations of Ca and Mg than those that were not in 1999 (Table 3). However, after the 3 years of the continuous corn, there were no differences in P among subsoil treatments. Also significant for both Ca and Mg in 1999 was the row width *X* tillage *X* subsoiling. Though significant, inspection of the means revealed no apparent pattern to explain the interaction (data not shown). Averaged over all sampling depths, the highest concentrations of these nutrients occurred in the NT plots that were not subsoiled in both the 38 and 76 cm row spacings while lowest concentrations were for treatments that included subsoiling.

3.4. Comparison of sampling positions in the wide-row system

Most of the differences between in-row and mid-row sampling sites occurred at the soil surface. In 1996, the P concentration difference between DT and NT was greater in the mid-row position than in the in-row (Fig. 1). Concentrations of P with NT and concentrations of K with both tillage systems were greater in the mid-row sampling position than in the in-row position of the surface 5 cm of the A horizon. On the other hand, Ca and Mg concentrations were higher in the in-row position than in the mid-row position regardless of tillage (Fig. 1). There was no difference in soil pH between row positions.

In 1999, P concentrations in the surface 5 cm of the A horizon were greater for NT than for DT (Fig. 1). As occurred in 1996 for this nutrient, the magnitude of difference between tillage treatments was greater in the mid-row sampling position than in the row. For Ca and Mg, NT had higher concentrations of these nutrients than DT only in the mid-row sampling position. For K, there was no difference between NT and DT, but concentrations were much higher in the in-row position than in the mid-row position. These row position differences probably reflect nutrient uptake and redistribution in the soil by the plants. For soil pH, although no differences were found between row positions in 1996, the mid-row position had significantly lower pH than the in-row position (Fig. 1) for both DT and NT. Row position effects were either not statistically significant or were small and of little apparent practical significance in the rest of the A horizon, the E horizon, and the top of the B horizon. Also, subsoiling had little affect on the horizontal distribution of nutrients and soil pH.

Crozier et al. (1999) studied nutrient stratification in the surface 20 cm of conventional and conservation tillage fields. They concluded that when soil sampling for lime and fertilizer application needs, more attention to sampling depth is required in conservation tillage fields than in fields managed with conventional tillage and recommendations for soil sampling in conservation tillage include taking the samples only from the surface 7.5 to 10 cm of soil (Kovar, 1994). Our results expand the findings of Crozier et al. (1999) in that they indicate that consideration of where the samples are collected in relation to the row may also be important for wide-row systems. This may especially be important if rows are planted into the same area over several years in a controlled traffic scheme to reduce compaction. However, Tyler and Howard (1991) found that a random sampling procedure, disregarding row position, was better than sampling only in the row, sampling only in the mid-row, or collecting equal sample volumes from the row and mid-row when fertilizers are banded or broadcast. Further research on appropriate areas to sample appears to be warranted, especially in fields with a long-term history of conservation tillage.

4. Conclusions

Combining narrow-row widths with NT and intensive deep tillage resulted in higher yield potential for both corn and soybean in this study. However, row spacing did not have much influence on nutrient stratification after either 3 or 6 years. Subsoiling increased crop yield (Table 1), which may have increased nutrient removal by the crop resulting in reduced nutrient concentrations. Our findings that DT and NT differed for concentrations of P, Ca, and Mg but not K, in the surface 5 cm in the wide-row system support previous findings on coarse-textured soils in the southeastern USA (Karlen et al., 1989; Edwards et al., 1992; Rhoton et al., 1993). More and more growers are considering narrow-row systems in efforts to improve profitability. Our results suggest only small differences in soil nutrient stratification can be expected as growers adopt narrow-row crop production systems with intensive subsoiling.

References

Anonymous, 1988. Nutrient Requirements of Swine, 9th Revised Edition. National Academy Press, Washington, DC.

Board, J.E., Harville, B.G., Saxton, A.M., 1990. Narrow-row seed-yield enhancement in determinate soybean. Agron. J. 82, 64–68.

Busscher, W.J., Frederick, J.R., Bauer, P.J., 2000. Timing effects of deep tillage on penetration resistance and wheat and soybean yield. Soil Sci. Soc. Am. J. 64, 999–1003.

Busscher, W.J., Frederick, J.R., Bauer, P.J., 2001. Effect of penetration resistance and timing of rain on grain yield of narrow-row corn in a Coastal Plain loamy sand. Soil Till. Res. 63, 15–24.

Camp, C.R., Christenbury, G.D., Doty, C.W., 1984. Tillage effects on crop yield in Coastal Plains Soil. Trans. ASAE 27 (6), 1729–1733.

Crozier, C.R., Naderman, G.C., Tucker, M.R., Sugg, R.E., 1999. Nutrient and pH stratification with conventional and no-till management. Commun. Soil Sci. Plant Anal. 30, 65–74.

Dick, W.A., 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47, 102–107.

Doty, C.W., Campbell, R.B., Reicosky, D.C., 1975. Crop response to chiseling and irrigation in soils with a compact A2 horizon. Trans. ASAE 18, 668–672.

Edwards, J.H., Wood, C.W., Thurlow, D.L., Ruf, M.E., 1992. Tillage and crop rotation effects on fertility status of a Hapludult soil. Soil Sci. Soc. Am. J. 56, 1577–1582.

Farnham, D.E., 2001. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. Agron. J. 93, 1049–1053.

Frederick, J.R., Bauer, P.J., 1996. Winter wheat responses to surface and deep tillage on the southeastern Coastal Plain. Agron. J. 88, 829–833.

Frederick, J.R., Bauer, P.J., Busscher, W.J., McCutcheon, G.S., 1998. Tillage management for double cropped soybean grown in narrow and wide row width culture. Crop Sci. 38, 755–762.

Kamprath, E.J., Cassel, D.K., Gross, H.D., Dibb, D.W., 1979. Tillage effects on biomass production and moisture utilization by soybeans on Coastal Plains Soil. Agron. J. 71, 1001–1005.

Karlen, D.L., Berti, W.R., Hunt, P.G., Matheny, T.A., 1989. Soil-test values after eight years of tillage research on a Norfolk loamy sand. Commun. Soil Sci. Plant Anal. 20, 1413–1426.

Kovar, J.L., 1994. Sampling soils under reduced row crop tillage. In: Thom, W.O., Sabbe, W. (Eds.), Soil Sampling Procedures for the Southern Region of the United States. Southern Cooperative Series Bulletin No. 377, University of Kentucky, Lexington, KY, pp. 19–23.

Lal, R., 1976. No-tillage effects on soil properties under different crops in western Nigeria. Soil Sci. Soc. Am. J. 40, 762–768.

Naderman Jr., G.C., 1985. Subsurface compaction and subsoiling in North Carolina. North Carolina Agric. Ext. Serv. Publ. AG-353, Raleigh, NC.

Rhoton, F.E., Bruce, R.R., Buehring, N.W., Elkins, G.B., Langdale, C.W., Tyler, D.D., 1993. Chemical and physical characteristics of four soil types under conventional and no-tillage systems. Soil Till. Res. 28, 51–61.

Triplett Jr., G.B., van Doren Jr., D.M., 1969. Nitrogen, phosphorous, and potassium fertilization of non-tilled maize. Agron. J. 61, 637–639.

Tyler, D.D., Howard, D.D., 1991. Soil sampling patterns for assessing no-tillage fertilization techniques. J. Fertilizer Issues 8, 52–56.