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# TILLAGE INTENSITY EFFECTS ON CHEMICAL INDICATORS OF SOIL QUALITY IN TWO COASTAL PLAIN SOILS

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## ABSTRACT

Few experiments in the coastal plain region of the southeastern United States have reported the effect of long-term tillage and tillage intensity on chemical soil quality indicators. The purpose of this study was to determine the 17-year influence of four tillage systems on chemical soil quality indicators in a Benndale fine sandy loam (coarse-loamy, siliceous, semiactive, thermic, Typic Paleudults) and a Lucedale very fine sandy loam (fine-loamy, siliceous, subactive, thermic, Rhodic Paleudults) in the coastal plain region of Alabama. Tillage systems were no-tillage, disk, moldboard plow, and chisel plow under varied double-cropping in a randomized complete block design with four replications. Soil pH, sum of extractable bases, soil organic carbon (SOC), and soil nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), zinc (Zn), manganese (Mn), copper (Cu), and iron (Fe) were determined on soil samples collected at depths of 0–2.5, 2.5–7.5, 7.5–15.0, 15.0–22.5, and 22.5–30 cm. Soil carbon (C) accumulation occurred primarily in the top 2.5 cm, varied by soil type, and was inversely proportional to tillage intensity. The coarse textured Benndale soil averaged 27.6, 13.1, 12.7, and 10.4 g C $kg^{-1}$ soil with no-tillage, disk, chisel, and moldboard plow management, respectively, in the top 2.5 cm. The finer textured Lucedale soil averaged 16.7, 10.0, 9.8, and 6.9 g C $kg^{-1}$ soil, for the same treatments and depth, respectively. Surface applications of lime maintained soil pH at an acceptable level within the plow layer on both soil types and all tillage systems. Extractable P was higher with no-tillage than moldboard plowing to the 22.5 cm depth on the Lucedale soil. On the Benndale soil, P tended to accumulate at the 15 to 22.5 cm depth with tillage systems other than moldboard plowing, and no-tillage had the most extractable P at these depths. Soil C and pH combined proved effective as continuous pedotransfer functions, predicting 73% and 86% of the variation in sum of extractable bases for the Benndale and Lucedale soils, respectively. As determined from chemical indicators of soil quality, adoption of conservation tillage with doublecropping is a sustainable practice for these soils.

## INTRODUCTION

Assessing soil quality has become a serious challenge in soil management. Since soil properties vary greatly across soil types and management systems, use of a Minimum Data Set (MDS) consisting of common indicators is recommended to evaluate soil quality (1). Doran and Parkin (2) included SOC, total organic N, pH, and extractable N, P, and K as chemical soil quality indicators. Many soil attributes can be estimated from other soil attributes using mathematical functions, pedotransfer functions (PTF), due to the close relationship among them. For example, Bell and van Keulen (3) found that SOC, clay content, and pH predicted soil CEC values for four agroecological environments in Mexico. Although these pedotransfer functions may only apply for one region, they can be used to determine soil improvement or degradation as a result of management practices (1).

Soil quality can be strongly affected by soil management, and maintaining or improving soil quality can be accomplished using long term conservation tillage systems (4,5). A key to enhancing soil quality is increasing soil organic carbon (SOC) which greatly influences soil physical, chemical, and biological properties (5). Increasing SOC with no-tillage is generally associated with an accumulation near the soil surface (6,7). Therefore, SOC with no-tillage is characterized by stratification while SOC in conventional tillage systems is more evenly distributed within the plow layer (8,7). Long-term studies comparing tillage system effects on soil quality indicators have largely been conducted in temperate climates (5). A prime example of the lack of research for thermic regimes is the coastal plain region of the southeastern USA. Although the region occupies over 300,000 square miles, only one long-term tillage study has been reported from the Southeastern Coastal Plain, with results being reported after eight (9) and 14 years (6). In that study, SOC in the top 5-cm after 14 years was nearly twice as great with no-tillage compared to disk tillage. However, the study consisted of only two tillage systems; conservation tillage (no-tillage plus in-row subsoiling) and multiple diskings with in-row subsoiling. No long term studies have evaluated changes in soil properties in coastal plain soils using a comprehensive set of tillage systems that included commonly used more intensive practices like moldboard plowing and chisel plowing.

Another important soil quality indicator affected by tillage systems is soil pH. Surface lime application in no-tillage often does not ameliorate soil acidity deep within the profile due to limits in lime mobility (10,11). However, results from the only long-term study conducted in the coastal plain region that reported soil chemical properties demonstrated maintenance of soil pH at an acceptable level for crop production after eight years with no-tillage using surface application of lime (9).

In general, no-tillage results in increased nutrient concentrations near the surface soil, but such concentrations rapidly decrease with depth, while conventional tillage results in a more homogeneous distribution of nutrients with depth (8,12). The higher level of $Ca^{++}$ and $Mg^{++}$ in surface soil with no-tillage compared to conventional tillage has been attributed to increased cation exchange capacity due to increased SOC as well as surface application of lime (8). But soil acidification from using high levels of N fertilizer may cause $Ca^{++}$ and $Mg^{++}$ to be substituted by $Al^{+++}$ and $H^{+}$ and thereby leached. Such results have been reported for soil managed with no-tillage when lime was not applied (13). Karlen et al. (9) described higher concentrations of extractable $Ca^{++}$ and $Mg^{++}$ with no-tillage than conventional tillage (disking) in the 0 to 5-cm depth of a coastal plain soil, but no difference was observed in the 5 to 20-cm layer.

Variable results have been reported for extractable K in relation to tillage systems. Greater (13) and lower (8,11) extractable K for no-tillage versus other tillage systems have been reported in surface horizons. Results of a three-year study on a coastal plain soil in Mississippi showed no K accumulation in the 0 to 5-cm depth with no-tillage compared to disking (14) and downward movement of K was also reported with this system. No difference in extractable K between no-tillage and disk tillage was reported by Karlen et al. (9) for an eight-year experiment conducted in South Carolina on a coastal plain soil. On the other hand, P will accumulate more at the surface with no-tillage compared to conventional tillage (8,11). However, considerable P movement, in the organic form, can be obtained by enhancing soil microbial activity (15). Increased P mobility as organic P with no-tillage was reported by Ismail et al. (16) on a Maury silt loam in Kentucky. The only study conducted in the coastal plain region reported no difference between disking and no tillage for extractable P when compared at the same depth (9).

Changes in micronutrient distribution within the soil profile have also been reported for different tillage systems. No-tillage enhances concentration of Zn in the first few cm of soil compared to conventional tillage (8,11). Likewise, extractable Mn tends to be greater in the surface soil layers with no-tillage (8,13). However, no differences have been reported for extractable Cu, regardless of tillage system (8,11). We found no reference describing micronutrient distribution as affected by tillage in long-term studies for coastal plain soils.

The objective of our research was to determine the effect of tillage systems, over a range of tillage intensities, on chemical indicators of soil quality for a long-term (17 year) study on two coastal plain soils in Alabama. In addition, we wished to determine the relationship between commonly measured indicators such as SOC and pH to other soil chemical properties, for use as pedotransfer functions to estimate other chemical indicators of soil quality.

## MATERIALS AND METHODS

Two tillage experiments were conducted for 17 years in the coastal plain region of southwestern Alabama; at Monroeville and Brewton (Table 1). The experimental locations are characterized by high average rainfall intensities (1516 mm/year for Monroeville and 1584 mm/year for Brewton). Since 1981, wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.), triticale (*Triticum aestivum* L. × *Secale cereale* L.), and white lupin (*Lupinus albus* L.) were cropped during the winter and soybean [*Glycine max* (L.) Merr.], grain sorghum [*Sorghum bicolor* (L.) Moench], cotton (*Gossypium hirsutum* L.), tropical corn (*Zea mays* L.), and pearl millet [*Pennisetum americanum* (L.) Leeke] were cropped during the summer (Table 2). The experimental design at both locations was a randomized complete block with four replications. Treatments consisted of four tillage systems (no tillage, disk, chisel plow, and moldboard plow) applied prior to the winter crop each year. The no-tillage treatment consisted of planting into killed summer crop residue using a double disk-opener planter. The disk treatment consisted of one pass with an offset tandem disk. For the chisel plow, shanks on the front and rear tool bars were offset so that actual distance between chisel points was 19 cm. The moldboard plow was used as a total soil inversion treatment. Chisel plow and moldboard plow treatments had a secondary tillage with a disking and leveling with a disk harrow and drag board. The disk, chisel plow, and moldboard plow reached an average depth of 7.5–12.5, 15–20, and

***Table 1.*** Location and Soil Type for Long-Term Tillage Systems Experiment in the Coastal Plain Region of Alabama

| Location | Series | Family | Subgroup | Order | Clay Mineralogy (%) | Clay ($g\,kg^{-1}$) |
|---|---|---|---|---|---|---|
| Brewton | Benndale | Coarse-loamy, siliceous, semiactive, thermic | Typic Paleudults | Ultisols | 30 kaolinite | 87 (0–7 cm) |
| | | | | | 34 HIV[a] | 122 (7–24 cm) |
| | | | | | 13 gibbsite | 170 (24–17 cm) |
| Monroeville | Lucedale | Fine-loamy, siliceous, subactive, thermic | Rhodic Paleudults | Ultisols | 48 kaolinite | 168 (0–8 cm) |
| | | | | | 34 HIV | 249 (8–13 cm) |
| | | | | | 7 mica | 343 (13–74 cm) |

[a] Hydroxy-interlayered vermiculite. From Hajek and Steers (17).

***Table 2.*** Winter and Summer Crops Used During 17-Year Tillage Experiment on a Benndale and Lucedale Soil in the Coastal Plain of Alabama

| Season | Year | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 |
| Winter | Wheat | Wheat | Wheat | Wheat | Wheat | Wheat | Rye | Rye | Rye |
| Summer | Soybean | Soybean | Soybean | Sorghum | Sorghum | Sorghum | Cotton | Cotton | Cotton |
| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | |
| Winter | Wheat | Wheat | Wheat | Triticale | Triticale | White lupin | White lupin[a] | Rye | |
| Summer | Tropical corn | Tropical corn | Tropical corn | Tropical corn | Fallow | Pearl millet | Pearl millet | Fallow | |

[a]Crop failure for winter crop this year.

20.0–25.0 cm, respectively. Summer crops were no-tilled into winter crop residue. A more detailed description of the location, experiment establishment, weed control, and other cultural practices utilized in the experiment was given by Touchton et al. (18). Lime, P, and K fertilizers were applied according to Auburn University soil test recommendations (19), based on fertility levels for the top 15-cm soil collected during the fall prior to planting the winter crop. The fertilization plan was to maintain extractable P between 52 and 66 kg $ha^{-1}$ and extractable K between 120 and 160 kg $ha^{-1}$. These values are considered in the 'high' rating. The Benndale soil received 4.5 and 3.4 Mg $ha^{-1}$ lime in 1986 and 1993, respectively. The Lucedale soil received 4.5 $ha^{-1}$ of lime in 1984 and 1992. In the fall of 1997, twenty soil cores were collected (hand probe, 2-cm diameter) per plot and composited by depth (0–2.5, 2.5–7.5, 7.5–15.0, 15.0–22.5, and 22.5–30 cm). Samples were air-dried and sieved (2-mm). Soil Ca, Mg, K, sodium (Na), P, Fe, Mn, Zn, and Cu were extracted using Mehlich-1 (double acid) solution (20) and determined by Inductively Coupled Air Plasma Emission Spectrometry [ICAP] (21). The sum of extractable bases ($Ca^{++} + Mg^{++} + K^{+} + Na^{+}$) was calculated. Soil pH was determined on 1:1 soil/water suspension with a glass electrode pH meter. Approximately 5 g of dried soil was finely ground prior to determining total C and N using a Nitrogen/Carbon analyzer (Fisons Instruments, Beverly, MA 01915). Total C is equivalent to SOC for these soils, which have no carbonate C.

Analyses of variance were conducted prior to determination of protected least significant difference (LSD) values at the 95% level of confidence (22). Sampling depths were analyzed as a split in the design. The soil type or location was initially also included in the analysis model as suggested by McIntosh (23). Results indicated that, with few exceptions, soil type had interactive effects with tillage and/or depth on dependent variables, therefore, results are presented by soil type. Correlation and stepwise regression were used to analyze relationships among chemical soil quality variables for determination of usefulness as estimators of other indicators, i.e., pedotransfer functions.

## RESULTS AND DISCUSSION

Soil organic carbon, a key indicator of soil quality, was affected by the interaction of soil type, tillage, and depth. Soil carbon accumulation occurred within the first 2.5 cm of soil at both locations and was inversely related to soil disturbance at this depth (Fig. 1). Soil C under no-tillage was more than doubled compared to the moldboard plow treatment for both soil types. Only a slight effect of tillage was observed in the second depth layer (2.5 to 7.5 cm), where moldboard plow had the smallest value among tillage systems for the Lucedale soil. The accumulation of SOC, even though restricted to the first 2.5 cm or so of

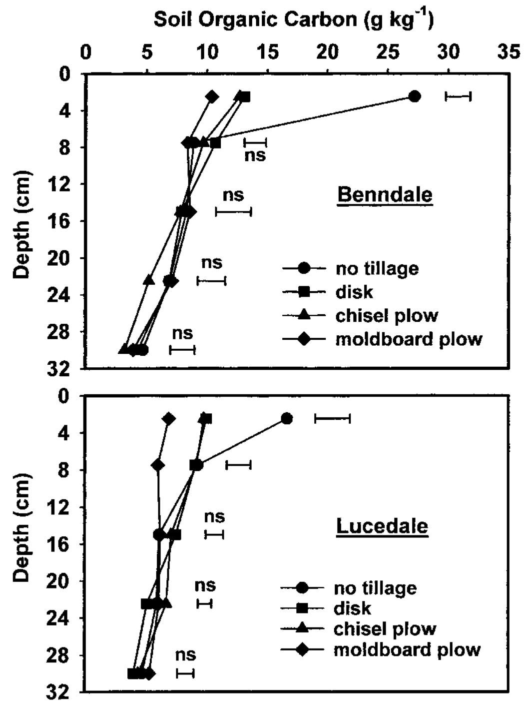


***Figure 1.*** Effect of tillage system after 17 years on soil organic carbon in a Benndale and a Lucedale soil in the coastal plain of Alabama. Horizontal bars indicate $LSD_{0.05}$ and ns = nonsignificant at $P \leq 0.05$.

the soil surface, is meaningful for these highly weathered soils. According to Hargrove et al. (11) and Hunt et al. (6), climatic conditions in the southern USA cause rapid and extensive residue decomposition. They suggested that such conditions limit surface build up of SOC even with no-tillage. Another factor that hinders SOC accumulation under our experimental conditions is low clay content in these soils. Havlin et al. (4) and Campbell et al. (24) reported that SOC and N content were directly proportional to clay content. The Lucedale soil, higher in clay content, exhibited increased SOC to the 7.5-cm depth with no-tillage, while the increase in SOC with no-tillage was limited to the top 3 cm or so in the Benndale soil. It is interesting, however, that at the shallowest depth, the increase in SOC with no-tillage was greater for the coarse-textured Benndale soil. We speculate that variations in root distribution and soil properties, such as water availability, may be responsible for the difference in SOC distribution between soils. Although the amount of SOC accumulated within the first few cm may not represent substantive values quantitatively when compared to total C in the soil profile, it plays an important role in soil quality. Bruce et al. (25) found that maintenance of SOC within the first few cm of soil is essential for improving infiltration and crop-available soil water on degraded Ultisols. An increase in SOC with no-tillage compared to other systems has been associated with greater return of crop residues (8), and/or lower soil organic matter decomposition (13). Given the climatic and edaphic constraints for increasing SOC on these soils, the increase in SOC under conservation tillage systems was associated with the use of doublecropping systems and high residue producing crops like corn, sorghum, wheat, rye, and triticale. This confirms that cropping intensity and high production of crop residues combined with conservation systems can enhance or sustain SOC under thermic regimes (5,6,26).

Like SOC, total soil N was affected by tillage, depth, and soil type (Fig. 2). Soil N distribution mirrored the variation in SOC among treatments for both soils.

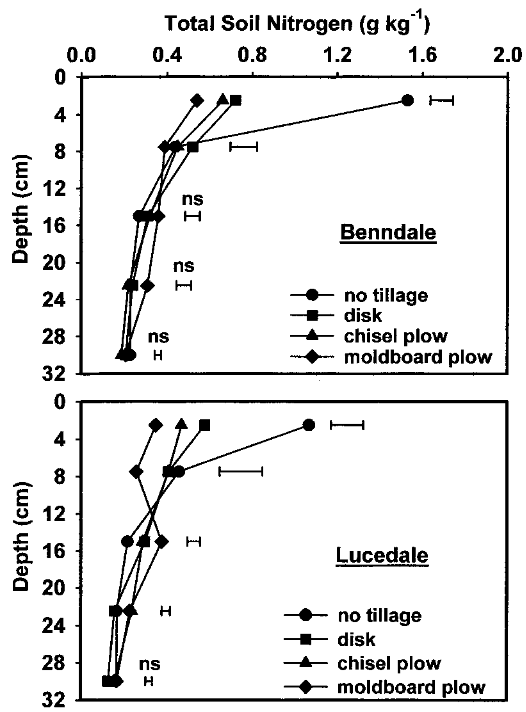


***Figure 2.*** Effect of tillage system after 17 years on soil nitrogen in a Benndale and a Lucedale soil in the coastal plain of Alabama. Horizontal bars indicate $LSD_{0.05}$ and ns = nonsignificant at $P \leq 0.05$.

Combined over all treatments and depths, soil N was highly correlated with SOC for the Benndale ($R^2 = 0.93$) and Lucedale ($R^2 = 0.95$) soils. Increasing the N pool by approximately 450 kg ha$^{-1}$ for the Benndale and 300 kg ha$^{-1}$ for the Lucedale soils, respectively, within the first 2.5 cm depth with no-tillage compared to moldboard plow could positively affect plant N supply. Torbert et al. (27) reported higher N mineralization with no-tillage compared to chisel plow on a Houston clay soil in Texas. Wienhold and Halvorson (28) reported that soils with a large N pool as a result of more intensive cropping combined with conservation tillage were able to ameliorate a decline in N fertility on a Temvik–Wilton silt loam soil association in North Dakota.

Another key indicator of soil quality, soil pH, was not affected by tillage, regardless of depth, on the Benndale soil (Fig. 3). There was, however, a trend ($P \leq 0.17$) for chiseling to result in increased pH compared to moldboard plowing or no-tillage at depths below 7.5 cm. Disking tended to maintain pH at a level intermediate to chiseling and moldboard or no-tillage. We have no

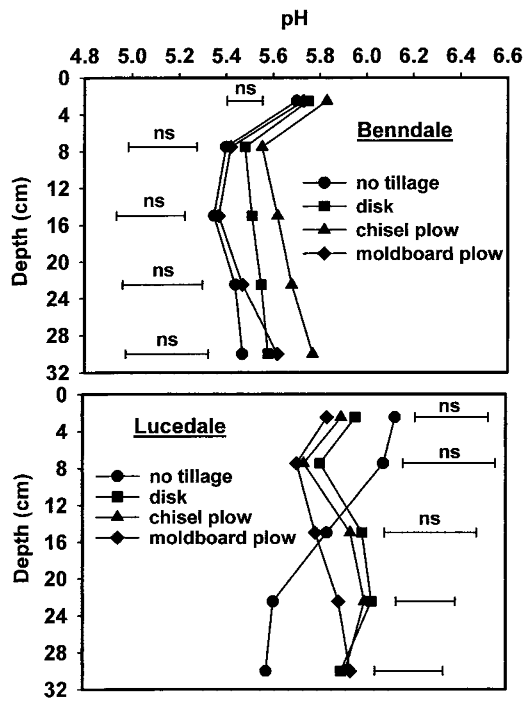


*Figure 3.* Effect of tillage system after 17 years on soil pH in a Benndale and a Lucedale soil in the coastal plain of Alabama. Horizontal bars indicate $LSD_{0.05}$ and ns = nonsignificant at $P \leq 0.05$.

explanation for the tendency for higher pH maintenance with chisel plowing, but it is interesting to note that no-tillage and moldboard plowing maintained similar pH levels to the 30-cm depth. This suggests that surface lime under no-tillage is as effective as lime incorporation by moldboard plow in controlling soil acidification. Similar results were obtained by Blevins et al. (13), Edwards et al. (8), and Ismail et al. (16). Blevins et al. (13) reported a slight decrease in soil pH down to 30 cm with no-tillage compared to moldboard plow on a silt loam in Kentucky. However, the same experiment was evaluated after 10 years by Ismail et al. (16), who found that soil acidity was effectively controlled by surface liming. Working with a sandy soil in northeastern Alabama, Edwards et al. (8) found no difference in soil pH within the 10- to 45-cm depth between no-tillage and moldboard plow. Edwards and Beegle (10) suggested that earthworm channels in conjunction with mass flow of rainwater through soil macropores could incorporate lime, thereby increasing pH slightly at depths below 5 cm. This could explain the results observed at the Benndale soil site (Fig. 3). Also, lime movement could have occurred via root channels and other pathways common under conservation tillage (29).

In contrast to the Benndale soil, pH of the Lucedale soil at the 15- to 30-cm depth was lower with no-tillage compared to other tillage systems. Hargrove et al. (11) reported lower pH with no-tillage than moldboard plow at depths between 7.5 and 30 cm after 5 years on a sandy loam soil in Georgia. However, in our study, there was a trend for no-tillage to maintain a higher pH than other tillage systems at the soil surface for the Lucedale soil ($P \leq 0.23$ for a 2.5 cm depth and $P \leq 0.18$ for 2.5–7.5 cm depth). The reason for differences in results between soils for pH is not known. Differences between soils could be related to buffer capacity, since lower SOC and sum of extractable bases (discussed below) were observed for the Lucedale soil. Others factors, such as differences in infiltration capacity, mobility of ammonium, and nitrification could be responsible for the variation observed.

As observed for SOC, $Ca^{++}$ and $Mg^{++}$ accumulation occurred within the top 2.5-cm depth for the Benndale soil and to the 7.5-cm depth for the Lucedale soil (Tables 3 and 4). It is well established that SOC and pH are major factors that influence cation exchange capacity in sandy soils, especially with low activity clays. This statement also holds true for $Ca^{++}$ and $Mg^{++}$, the major components of summed extractable bases. In our study, the influence of SOC and pH on the sum of extractable bases was demonstrated using multiple regression techniques for both soil types (Table 5). Results indicated that maintenance of SOC through intensive cropping coupled with conservation tillage and lime application may inhibit cation loss.

In contrast to other studies (8,11), extractable P did not accumulate in the uppermost soil layer with no-tillage compared to other tillage systems for the Benndale soil (Fig. 4). However, there was an accumulation of P within the 7.5 to

***Table 3.*** Chemical Soil Quality Indicators Affected by Long-Term (17 Years) Use of No Tillage (NT), Chisel Plow (CP), Disk, and Moldboard Plow (MP) for a Lucedale Soil in the Coastal Plain of Alabama

| | $Ca^{++}$ ($mg\,kg^{-1}$) | | | | | $Mg^{++}$ ($mg\,kg^{-1}$) | | | | | $K^{+}$ ($mg\,kg^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | NT | CP | Disk | MP | $LSD_{0.05}$[a] | NT | CP | Disk | MP | $LSD_{0.05}$ | NT | CP | Disk | MP | $LSD_{0.05}$ |
| 0–2.5 | 744 | 368 | 310 | 230 | 110 | 193 | 98 | 84 | 59 | 28 | 109 | 139 | 106 | 82 | 32 |
| 2.5–7.5 | 451 | 327 | 285 | 200 | 126 | 104 | 62 | 62 | 39 | 23 | 43 | 61 | 57 | 49 | 12 |
| 7.5–15.0 | 241 | 336 | 351 | 262 | 110 (ns) | 56 | 67 | 63 | 44 | 22 (ns) | 37 | 47 | 40 | 40 | 7 |
| 15.0–22.5 | 205 | 319 | 274 | 272 | 78 | 44 | 65 | 57 | 55 | 20 (ns) | 33 | 41 | 32 | 30 | 10 (ns) |
| 22.5–30.0 | 210 | 250 | 225 | 255 | 48 (ns) | 49 | 71 | 61 | 56 | 17 (ns) | 43 | 41 | 38 | 31 | 8 (ns) |

| | SEB[b] ($cmol_c\,kg^{-1}$) | | | | | Zn ($mg\,kg^{-1}$) | | | | | Mn ($mg\,kg^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NT | CP | Disk | MP | $LSD_{0.05}$ | NT | CP | Disk | MP | $LSD_{0.05}$ | NT | CP | Disk | MP | $LSD_{0.05}$ |
| 0–2.5 | 5.12 | 3.25 | 2.64 | 1.98 | 0.80 | 8.3 | 2.5 | 3.0 | 1.6 | 0.9 | 39 | 31 | 28 | 25 | 3 |
| 2.5–7.5 | 2.88 | 2.30 | 2.05 | 1.50 | 0.69 | 2.2 | 2.6 | 2.6 | 1.5 | 0.7 | 23 | 26 | 23 | 20 | 3 |
| 7.5–15.0 | 1.65 | 2.24 | 2.25 | 1.76 | 0.58 (ns) | 1.0 | 1.4 | 2.4 | 1.8 | 0.7 | 16 | 19 | 20 | 20 | 4 (ns) |
| 15.0–22.5 | 1.41 | 2.10 | 1.78 | 1.75 | 0.44 | 0.9 | 1.5 | 0.9 | 1.5 | 0.6 (ns) | 15 | 17 | 13 | 16 | 4 (ns) |
| 22.5–30.0 | 1.53 | 1.77 | 1.60 | 1.68 | 0.26 (ns) | 0.7 | 1.0 | 0.9 | 1.2 | 0.3 (ns) | 16 | 13 | 14 | 15 | 2 |

[a] Values of $LSD_{0.05}$ for comparing tillage means within a depth; ns = nonsignificant at $P \leq 0.05$.
[b] SEB = sum of extractable bases ($Ca^{++}$, $Mg^{++}$, $K^{+}$, $Na^{+}$).

***Table 4.*** Chemical Soil Quality Indicators Affected by Long-Term (17 Years) Use of No Tillage (NT), Chisel Plow (CP), Disk, and Moldboard Plow (MP) for a Benndale Soil in the Coastal Plain of Alabama

| | $Ca^{++}$ ($mg\,kg^{-1}$) | | | | | $Mg^{++}$ ($mg\,kg^{-1}$) | | | | | $K^{+}$ ($mg\,kg^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | NT | CP | Disk | MP | $LSD_{0.05}$[a] | NT | CP | Disk | MP | $LSD_{0.05}$ | NT | CP | Disk | MP | $LSD_{0.05}$ |
| 0–2.5 | 613 | 339 | 358 | 317 | 114 | 158 | 93 | 99 | 93 | 29 | 189 | 219 | 217 | 208 | 31 (ns) |
| 2.5–7.5 | 310 | 318 | 330 | 261 | 100 (ns) | 82 | 58 | 64 | 56 | 24 (ns) | 87 | 115 | 111 | 138 | 26 |
| 7.5–15.0 | 264 | 354 | 319 | 298 | 86 (ns) | 51 | 63 | 63 | 56 | 13 (ns) | 89 | 100 | 90 | 108 | 23 (ns) |
| 15.0–22.5 | 320 | 359 | 352 | 335 | 96 (ns) | 62 | 83 | 71 | 71 | 17 (ns) | 98 | 88 | 87 | 88 | 23 (ns) |
| 22.5–30.0 | 323 | 358 | 314 | 329 | 50 (ns) | 90 | 102 | 90 | 88 | 25 (ns) | 88 | 77 | 72 | 72 | 21 (ns) |

| | SEB[b] ($cmol_c\,kg^{-1}$) | | | | | Zn ($mg\,kg^{-1}$) | | | | | Mn ($mg\,kg^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NT | CP | Disk | MP | $LSD_{0.05}$[a] | NT | CP | Disk | MP | $LSD_{0.05}$ | NT | CP | Disk | MP | $LSD_{0.05}$ |
| 0–2.5 | 4.87 | 3.03 | 3.18 | 2.89 | 0.81 | 3.34 | 2.16 | 2.15 | 1.96 | 0.37 | 96 | 74 | 73 | 75 | 11 |
| 2.5–7.5 | 2.45 | 2.37 | 2.47 | 2.12 | 0.70 (ns) | 1.55 | 1.87 | 1.74 | 1.63 | 0.42 (ns) | 60 | 64 | 66 | 62 | 7 (ns) |
| 7.5–15.0 | 1.97 | 2.55 | 2.35 | 2.23 | 0.55 (ns) | 1.75 | 1.67 | 1.52 | 1.64 | 0.31 (ns) | 48 | 50 | 44 | 63 | 9 |
| 15.0–22.5 | 2.36 | 2.71 | 2.57 | 2.49 | 0.62 (ns) | 1.79 | 1.36 | 1.43 | 1.45 | 0.33 (ns) | 47 | 40 | 42 | 57 | 11 |
| 22.5–30.0 | 2.59 | 2.84 | 2.51 | 2.56 | 0.48 (ns) | 0.75 | 0.48 | 0.69 | 0.61 | 0.35 (ns) | 39 | 33 | 33 | 29 | 7 (ns) |

[a] Values of $LSD_{0.05}$ for comparing tillage means within a depth; ns = nonsignificant at $P \leq 0.05$.
[b] SEB = sum of extractable bases ($Ca^{++}$, $Mg^{++}$, $K^{+}$, $Na^{+}$).

***Table 5.*** Relationships Among Soil Chemical Properties from a Long-Term Experiment with Different Tillage Systems for Two Coastal Plain Soils in Alabama

| | Benndale | | Lucedale | |
|---|---|---|---|---|
| Dependent Variable | Independent Variable(s) | $R^2$ | Independent Variable(s) | $R^2$ |
| N ($g\,kg^{-1}$) | $-0.007 + 0.055$ SOC | 0.93 | $-0.020 + 0.072$ SOC | 0.95 |
| SEB[a] ($cmol_c\,kg^{-1}$) | $-7.7 + 0.74$ SOC $+ 1.75$ pH | 0.73 | $-9.3 + 2.4$ SOC $+ 1.6$ pH | 0.86 |
| Mn ($mg\,kg^{-1}$) | $29.9 + 27.9$ SOC | 0.62 | $5.4 + 20.5$ SOC | 0.81 |
| Zn ($mg\,kg^{-1}$) | $0.6 + 1.07$ SOC | 0.73 | $6.2 + 1.1$ SEB $+ 2.1$ SOC $- 1.4$ pH | 0.86 |

[a] SEB = sum of extractable bases ($Ca^{++} + Mg^{++} + K^{+} + Na^{+}$).

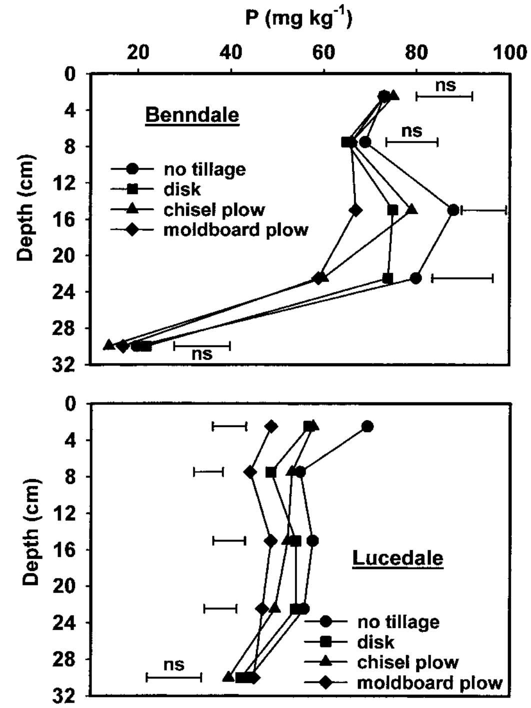


***Figure 4.*** Effect of tillage system after 17 years on soil extractable P in a Benndale and a Lucedale soil in the coastal plain of Alabama. Horizontal bars indicate $LSD_{0.05}$ and ns = nonsignificant at $P \leq 0.05$.

22.5-cm depths for all tillage systems other than moldboard plowing; with no-tillage resulting in the greatest P accumulation at this depth (Fig. 4). It is likely that P accumulation at the 7.5 to 22.5-cm depth is related to hardpan formation and restricted water movement and root growth that typically occurs at this depth in the Benndale soil. In contrast to the Benndale soil, there was a difference in P accumulation among tillage systems at the soil surface (0–2.5 cm) in the Lucedale soil. The accumulation was inversely related to the intensity of tillage disturbance. Also, tillage impacts on extractable P were not limited to the soil surface on the Lucedale soil, and the pattern of increased P corresponding to reductions in soil disturbance or tillage intensity occurred to the 22.5-cm depth. Movement of P within the soil profile due to leaching processes is usually considered insignificant. However, P movement by leaching or other processes needs to be considered in our study due to several factors. Combined low P adsorption capacity and high levels of extractable P can contribute to P mobility.

Surface SOC accumulation can decrease P adsorption capacity in no-tillage (30) as well as contribute to maintenance of soil pH between 5.5 to 7.0, which is generally the soil pH range with the least soil P adsorption capacity. Long-term addition of plant residues under favorable conditions for decomposition and abundant rainfall could result in ideal conditions leading to leaching of organic P (7,31,32). Finally, preferential pathways for movement of water and nutrients are common under conservation tillage due to earthworm activity (10) and root channels (29).

Potassium accumulated in the surface of both soils, regardless of tillage system, similar to results reported by Holanda et al. (12) (Tables 3 and 4). In our study, extractable K was not stratified more with no-tillage than the other systems. For the Benndale soil, there tended to be less K with no-tillage at the 0–2.50 cm depth compared to the disk, moldboard plow, and chisel plow treatments ($P \leq 0.20$); at the second depth (2.5–7.5 cm) these differences were significant (Table 3). Lower levels of extractable K under no-tillage have been reported by others (8,11). These finding were also different from that observed for the Lucedale soil (Table 4), where the lowest K level was found with the moldboard plow treatment. Differences in residue accumulation, nutrient removal by grain harvest, fertilizer applications, and leaching patterns could contribute to differences in tillage system effects on K distribution between soils.

Extractable Zn was affected by tillage systems at both locations (Tables 3 and 4). Our results are similar to those reported by others (8,11). Like SOC, $Ca^{++}$, and sum of extractable bases, extractable Zn accumulation in the first few cm of soil was generally inversely proportional to soil disturbance by tillage systems. With no tillage, stratification of extractable Zn occurred in both soils, with the highest level being noted at the 0–2.5 cm depth. Residue accumulation and broadcast fertilizer application in conjunction with lack of tillage and low Zn mobility could explain this pattern. Greater soil incorporation with moldboard plow and disking increased extractable Zn compared to no-tillage for the Lucedale soil within the 7.5 to 15-cm depth. Regression results indicated variation in extractable Zn was strongly related to SOC, pH, and sum of extractable bases (Table 5) for the Lucedale soil. For the Benndale soil, only SOC affected extractable Zn. Relationships between Zn and SOC (8), and Zn and pH (8,33) have been reported. Davis-Carter and Shuman (34) reported that CEC was the best parameter for predicting exchangeable Zn on four coastal plain soils. Our results also showed that sum of extractable bases can be used as a co-predictor of extractable Zn.

Extractable Mn was directly related to SOC on both soils (Table 5). This may explain the accumulation of extractable Mn for both soils within the surface layer under no-tillage (Tables 3 and 4) compared to other tillage systems. Similar accumulation of extractable Mn with no-tillage has been reported by others (8,11,13). In contrast to other reports (8,33), pH had no affect on Mn distribution in our study.

Tillage had no effect on extractable Cu and Fe (data not shown). No differences have been observed for extractable Cu among different tillage systems in several studies (8,11). No correlation was observed between SOC or pH and extractable Fe and Cu.

## CONCLUSIONS

Tillage system affected chemical indicators of soil quality interacting with soil type. Although reduced clay content and climatic patterns in this region can adversely affect SOC accumulation, increases in SOC occurred when soil disturbance was limited. No-tillage resulted in more than twice as much SOC compared to the moldboard plow treatment within the first 2.5 cm for both soils. The Lucedale soil, higher in clay content, had increased SOC to the 7.5-cm depth with no-tillage, chisel plow, and disk systems, compared to moldboard plowing. In contrast to SOC, pH was slightly affected by tillage systems for one of the soils studied, with lower pH occurring at depths below the plow layer ($\geq$22.5 cm) with no-tillage relative to other tillage systems. However, broadcast application of lime maintained pH at an acceptable level within the plow layer for both soils with no-tillage. The expected accumulation of extractable P in the surface soil layer under no-tillage was not observed and may have been caused by downward movement of P due to macroorganism activity, physical movement, and leaching of organic P. Significant changes in $Ca^{++}$, $Mg^{++}$, sum of extractable bases, total N, Zn, and Mn accumulation in surface soil were observed, mirroring the distribution pattern of SOC; but no differences were noted for Cu and Fe. In general, $Ca^{++}$, $Mg^{++}$, sum of extractable bases, total N, Zn and Mn accumulation in surface soils was inversely related to the amount of soil disturbance (no-tillage $>$ disk $>$ chisel plower $>$ moldboard plow). Extractable K for the Benndale soil was least with no-tillage compared to other systems. The opposite result was observed for the Lucedale soil where moldboard plow resulted in the least extractable K. Soil organic C and pH served as co-predictors of extractable bases; alone or in combination, these two soil quality indicators were also highly correlated to Mn and Zn. Our results show that, as determined from chemical indicators of soil quality, adoption of conservation tillage with doublecropping offers long-term sustainability for managing coastal plain soils.

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