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Soil-profile distribution of primary and secondary plant-available nutrients under conventional and no tillage

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Abstract

Nutrient distributions under no tillage (NT) compared with conventional disk-and-bed tillage (CT) management in the warm, humid region of the southeastern USA need to be assessed so that future placement, quantity, and type of fertilizers can be altered, if necessary, to efficiently match crop demands. We determined soil-profile distributions of pH, N, P, S, K, Ca, Mg, Na, Zn, Fe, Mn, and Cu to a depth of 0.9 m at the end of 8.5 years of continuous CT and NT management on a Weswood silty clay loam (fine, mixed, thermic Fluventic Ustochrept) in southcentral Texas. Most dramatic changes occurred within the 0–0.05 m depth, where soil under NT had lower pH, Fe, and Cu than under CT, but greater P, K, Zn, and Mn. Greater P and K under NT than under CT also occurred below the till-zone (0.15–0.3 m). At a depth of 0–0.3 m, soil under NT contained greater amounts of extractable P, K, Zn, Fe, Mn, and Cu than under CT. Nitrogen fertilization had little effect on nutrient distributions, except resulting in greater extractable K at 0–0.05 m and greater nitrate at 0–0.15 m. Few changes in soil-profile distributions were observed for extractable S, Ca, Mg, and Na. Long-term continuous use of NT on this fine-textured, high-fertility (except for N) soil had no apparent adverse effects on nutrient distributions relative to CT, but enhanced conservation and availability of P, K, Zn, Fe, Mn, and Cu near the soil surface where crop roots proliferate.

Keywords: Calcium; Copper; Iron; Magnesium; Manganese; Nitrate; pH; Phosphate; Potassium; Sodium; Sulfate; Tillage; Zinc

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1. Introduction

Changes in soil quality with adoption of NT management is a concern when searching for sustainable agroecosystems (Doran et al., 1994). Changes in soil-profile nutrient distributions could have a significant impact on the productivity and ecology of land management systems by altering (i) the quantity and timing of nutrient availability, (ii) competition between crops, weeds, pests, and soil microorganisms and fauna, and (iii) the potential for environmental degradation due to excessive nutrients entering surface and ground waters.

Adoption of continuous NT for several years has led to reduced soil pH, although the depth to which this reduction occurs has varied from 0.01 m (Unger, 1991) to 0.3 m (Dick, 1983) and appears also to be related to the level of N fertilization (Blevins et al., 1977; Ismail et al., 1994). Changes in soil pH are important for determining P and micronutrient availability, root growth, herbicide persistence, and microbial activity.

Nutrient availability may be altered under NT compared with CT due to surface-placement of residues rather than mixing of residues within the till-zone (Blevins et al., 1977; Unger, 1991; Ismail et al., 1994). Slower decomposition of surface-placed residues may prevent rapid leaching of nutrients through the soil profile, which is more likely when residues are incorporated into the soil. However, possible development of more continuous pores between the surface and the subsurface under NT (Kay, 1990) may lead to more rapid passage of soluble nutrients deeper into the soil profile than when soil is tilled.

Eck and Jones (1992) found that nitrate-N increased under both stubble-mulch and NT below ≈ 1.5 m, suggesting that this was the depth of rooting. Most previous studies on the distribution of nutrients under CT and NT have concentrated on a few primary nutrients within the near-surface condition (≈ 0–0.3 m) (Blevins et al., 1977; Weil et al., 1988; Unger, 1991) or on soil organic C, N, and P within the near-surface (Dick, 1983; Dalal, 1989; Unger, 1991). Few data are available to evaluate the effect of tillage regime and level of N fertilization on a wide range of plant-available nutrients (both primary and secondary) distributed throughout the entire rooting depth (≈ 0–1 m). We determined plant-available nutrient distributions to a depth of 0.9 m under CT and NT management of crops receiving no N fertilizer and N fertilizer to attain optimum yield.

2. Materials and methods

A long-term field experiment was initiated in 1982 in the Brazos River floodplain of southcentral Texas (30°32′N, 94°26′W). Crops of sorghum (*Sorghum bicolor* (L.) Moench) and wheat (*Triticum aestivum* L.) were grown in monoculture, in a sorghum-wheat/soybean (*Glycine max* (L.) Merr.) rotation, and in a wheat/soybean continuous double-crop under CT and NT.

Conventional tillage operations in sorghum and soybean consisted of disking (0.1–0.15 m depth) after harvest, followed by chisel-plowing (0.2–0.25 m depth), a second disking (0.1–0.15 m depth), ridging prior to winter, and cultivating two or three times during early crop growth. Conventional tillage operations in wheat consisted of disking

(0.1–0.15 m depth) two to three times following harvest. No soil disturbance occurred under NT, except for banded fertilizer application in sorghum and planting of all crops. Sorghum stalks were shredded following harvest under both tillage regimes.

Nitrogen fertilizer (NH_4NO_3) was banded preplant at 0 and 9 g N m^{-2} in sorghum, broadcasted during early spring at 0 and 6.8 g N m^{-2} in wheat, and not applied to soybean. The high N fertilizer rate in sorghum and wheat systems is referred to in the text as 'optimum' based on yield response curves in Franzluebbers et al. (1995c). The only other fertilizer applied was P topdressed shortly after planting wheat and banded prior to planting of sorghum at 1.3 g P m^{-2}. Sorghum was planted in 1-m-wide rows in mid-March and harvested in early August. Wheat was planted in 0.2-m-wide rows in early November and harvested in late May. Soybean was planted in 1-m-wide rows in early June following wheat harvest and harvested in late October. Plots measured 4 m × 12.2 m. Treatments were arranged as a randomized complete block with four replications.

The soil was classified as a Weswood silty clay loam (fine, mixed, thermic Fluventic Ustochrept) and contained an average of 13% sand, 52% silt, and 35% clay. The soil is calcareous with a pH of 8.2 (1:2, soil:water) and 9.4% $CaCO_3$ equivalent. Quartz, feldspars (K and Na), chlorite, and mica are present in the sand and silt fractions and mica, kaolinite, chorite, and smectite are present in the clay fraction. Long-term annual temperature averages 20°C and rainfall averages 978 mm.

Six soil cores (0.05-m diameter) were collected between the middle rows from each of four replicates of 20 tillage–crop sequence–fertilizer combinations on 28–31 May 1991 (Table 1). Soil cores were divided into depth increments of 0–0.05, 0.05–0.15, 0.15–0.3, 0.3–0.6, and 0.6–0.9 m; oven-dried (55°C, 3 days); and ground to pass a 2-mm screen. Soil pH, NO_3-N, and SO_4-S were determined in water (1:2, soil:water) using a glass electrode, automated Cd-reduction procedure (Bundy and Meisinger, 1994), and inductively coupled plasma spectroscopy (ICPS), respectively. Extractable P, K, Ca, Mg, and Na were determined on a Perkin Elmer Model P2000 ICPS from the filtered extracts of 2 g soil shaken for 1 h in 40 ml of 1.4 M NH_4OAc–0.025 M ethylenediaminetetraacetic acid (EDTA) (pH 4.2) (Texas Agricultural Extension Service, 1980; Hons et al., 1990). Zinc, Fe, Mn, and Cu were extracted from 10 g soil shaken for

Table 1
Tillage–crop sequence–fertilizer combinations sampled in May 1991 at the end of 8.5 years from initiation

Block [a]	No N fertilizer			Optimum N fertilizer [b]	
1	CT [c]	NT	Sorghum [d]	CT	NT
2	CT	NT	Wheat	CT	NT
3	CT	NT	Sorghum–wheat/soybean	CT	NT
4	CT	NT	Sorghum–wheat/soybean	CT	NT
5	CT	NT	Wheat/soybean	CT	NT

[a] Blocks characterized for analysis of variance.
[b] Optimum N fertilizer was 9 g N fertilizer m^{-2} in sorghum, 6.8 g N fertilizer m^{-2} in wheat, and no N fertilizer in soybean.
[c] CT is conventional disk and bed tillage and NT is no tillage.
[d] Crop underlined was present in the field at the time of sampling.

2 h with 20 ml of 0.005 M diethylenetriaminepentaacetic acid–0.1 M EDTA (pH 7.3) and determined by ICPS.

Soil pH and mineral nutrients of each soil depth were analyzed as a randomized, complete block design (Table 1) using the general linear model procedure of SAS (SAS Institute Inc., 1990). Sources of variation within each depth were block (crop sequences as random variable, Table 1), tillage, N fertilization, and the interaction between tillage and N. Means at 0–0.3 m and 0–0.9 m depths were calculated assuming bulk densities of 1.1, 1.5, 1.6, 1.5, and 1.5 Mg m^{-3} under CT and 1.3, 1.6, 1.6, 1.5, and 1.5 Mg m^{-3} under NT at depths of 0–0.05, 0.05–0.15, 0.15–0.3, 0.3–0.6, and 0.6–0.9 m, respectively, to reflect observed changes with soil depth and tillage regime (McFarland et al., 1990; Franzluebbers et al., 1995b). Mean separations were declared significant at $P \leq 0.1$.

3. Results and discussion

3.1. Soil pH

Soil pH under NT was 0.1–0.2 units lower than under CT at a depth of 0–0.05 m, but was not different between tillage regimes at other depths (Fig. 1). Increasing pH with depth is common in western US soils, which tend to experience moisture stress during summer (Unger, 1991). Soil pH at the end of 8 years of NT in a clay loam from Texas was 6.0 at 0–0.01 m depth compared with 6.1 in stubble mulch, but not different at any other depth (Unger, 1991). In contrast, a silty clay loam from Ohio under NT for 18 years was 0.2–0.5 pH units lower than under CT throughout the 0–0.3 m depth (Dick, 1983).

Soil pH was not different between zero and optimum N fertilization at any depth (Fig. 1). This is in contrast with the results from a silt loam in Kentucky, in which soil pH at the end of 5 years of continuous maize decreased 0.02–0.03 units for every g m^{-2} $year^{-1}$ of N fertilizer under both CT and NT at depths of 0–0.05 and 0.05–0.15 m, but had no effect at 0.15–0.3 m depth (Blevins et al., 1977). At the same location at the end of 20 years, soil pH decreased 0.02–0.03 units for every g m^{-2} $year^{-1}$ of N fertilizer (Ismail et al., 1994). At the end of 5 years of continuous maize on a poorly buffered sandy loam from Nigeria, soil pH was 5.8 without N fertilization, but 5.2 with 15 g N m^{-2} (Juo et al., 1995). Our results, however, suggest that moderate N fertilization to achieve optimum yield on this high-pH, calcareous soil does not negatively impact soil acidity.

3.2. Primary anions

Nitrate-N concentration in the soil was low and decreased with soil depth from 2.5–5 mg kg^{-1} at the 0–0.05 m depth to 1–1.4 mg kg^{-1} at depths below 0.15 m (Fig. 1). Nitrate-N under NT was more concentrated in the upper part of the plow layer (0–0.05 m) than under CT, but less concentrated in the lower part (0.05–0.15 m) especially with N fertilization. To a depth of 0.9 m, NO_3-N was similar between tillage regimes, but

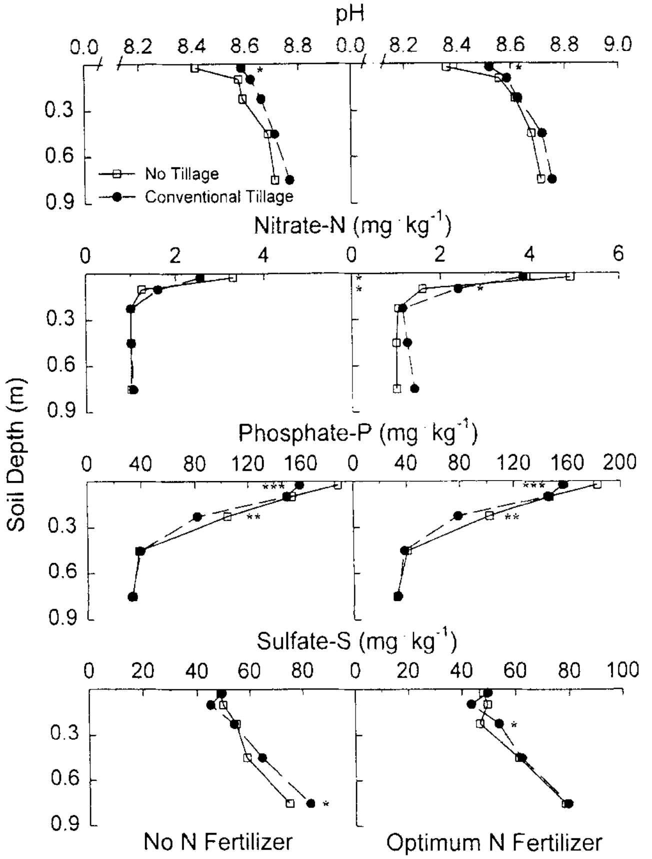

Fig. 1. Soil-profile distributions of pH and primary anions (NO_3-N, PO_4-P, and SO_4-S) as affected by tillage and N fertilization. (Optimum N fertilizer was 9 g m^{-2} in sorghum, 6.8 g m^{-2} in wheat, and none in soybean. *, **, and *** indicate significance at $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively, between tillage means within N fertilization regime when placed next to symbols and between N fertilization regimes when placed along *y*-axis.)

was 32% greater with N fertilization than without N fertilization under CT (Table 2), primarily due to differences at 0–0.15 m depth (Fig. 1).

Large amounts of nitrate movement through the soil profile does not appear to have occurred, despite more than 600 mm of precipitation during the 6 months prior to sampling. Other information collected from this location supports this conclusion. Residual soil nitrate in May 1990 following 2 years of wheat indicated carryover of N only within 0–0.3 m depth, but none in the 0.3–0.9 m depth (Alcoz et al., 1993). In continuous sorghum, NO_3-N averaged 3.8 g m^{-2} to a depth of 0.9 m when sampled in December 1990, whether unfertilized or fertilized (Hons et al., 1993). The aforementioned study also reported no difference in NO_3-N at a depth of 0.45–1.2 m between unfertilized soil and soil that received 900 g sorghum methane-generator sludge m^{-2}, but four times more nitrate in sludge-amended compared with unfertilized soil at a depth of 0–0.45 m. Losses of N in this soil, therefore, may be more likely due to denitrifica-

Table 2
Mean soil pH and extractable nutrient contents at 0–0.3 m and 0–0.9 m as influenced by tillage and N fertilization

Tillage [a]	N fertilizer [b]	pH ($-\log[H^+]$)	NO_3-N ($g\ m^{-2}$)	PO_4-P ($g\ m^{-2}$)	SO_4-S ($g\ m^{-2}$)	K ($kg\ m^{-2}$)	Ca ($kg\ m^{-2}$)	Mg ($kg\ m^{-2}$)	Na ($g\ m^{-2}$)	Zn ($g\ m^{-2}$)	Fe ($g\ m^{-2}$)	Mn ($g\ m^{-2}$)	Cu ($g\ m^{-2}$)
0–0.3 m depth													
CT	None	8.64	0.62	50.7	22.4	0.16	10.2	0.30	18.2	0.10	5.7	3.4	0.45
NT	None	8.56	0.65	61.8	22.1	0.19	10.5	0.31	19.2	0.15	6.4	4.6	0.49
CT	Optimum	8.60	0.85	49.3	24.3	0.16	10.2	0.30	18.7	0.10	5.6	3.2	0.42
NT	Optimum	8.56	0.83	59.8	22.2	0.20	10.5	0.32	19.8	0.19	7.0	4.8	0.52
$LSD_{(P \leq 0.05)}$		0.11	0.24	5.7	2.9	0.03	0.4	0.03	6.5	0.05	0.4	0.9	0.05
0–0.9 m depth													
CT	None	8.71	1.54	83.0	88.5	0.28	31.0	0.91	76.2	0.15	16.5	8.1	0.97
NT	None	8.65	1.55	93.9	84.3	0.31	30.8	0.90	63.2	0.21	17.1	9.2	0.99
CT	Optimum	8.69	2.04	81.3	85.6	0.27	30.8	0.92	73.7	0.15	16.1	8.0	0.91
NT	Optimum	8.65	1.73	92.5	84.9	0.34	30.7	0.94	68.1	0.28	18.7	9.6	1.10
$LSD_{(P \leq 0.05)}$		0.10	0.40	9.2	6.9	0.05	1.2	0.08	20.1	0.09	1.2	0.8	0.14

[a] Tillage regime: CT, conventional tillage; NT, no tillage.
[b] Nitrogen fertilizer regime: none, no N fertilizer to any crop; optimum, 9 g N m^{-2} in sorghum, 6.8 g N m^{-2} in wheat, and no N fertilizer in soybean.

tion as a result of the high clay content and high water-filled pore space during much of the year (Franzluebbers et al., 1995b) and due to volatilization as a result of the high pH rather than nitrate leaching.

Extractable P was greatest at the soil surface and decreased rapidly with depth (Fig. 1). Soil under NT contained greater concentration of P at depths of 0–0.05 m and 0.15–0.3 m. Nitrogen fertilization regime had no effect on extractable P. Greater P concentration near the soil surface was likely due to long-term P fertilization of this soil prior to initiation of this experiment. Greater available P at 0–0.05 m depth with NT compared with ridge tillage was observed in a silt loam from Iowa (Robbins and Voss, 1991). In a silt loam from Kentucky, Mehlich-extractable P at the end of 20 years of NT compared with CT was 42% greater at 0–0.05 m, but 8–18% lower at 0.05–0.3 m depth (Ismail et al., 1994). Redistribution of extractable P with NT compared with CT is probably a direct result of surface-placement of crop residues that leads to accumulation of soil organic matter and microbial biomass near the surface (Franzluebbers et al., 1994, 1995a). In a clay loam from Texas, extractable P was 22–52% greater under NT compared with stubble mulch within the 0–0.02 m depth, but not different below this near-surface zone (Unger, 1991). To a depth of 0.9 m, extractable P was 13% greater under NT than under CT (Table 2). Our results indicate that more extractable P with NT compared with CT is also present below the till-zone, rather than only near the soil surface as reported in other studies (Unger, 1991), and may be due to accumulation of P in senescent roots.

Sulfate-S increased with soil depth under both tillage regimes and both N fertilization regimes (Fig. 1). Only small changes in SO_4-S occurred with respect to tillage regime and no changes due to N fertilization. The increase in sulfate concentration with depth was likely due to leaching from the surface. Evidence of leaching of sulfate, but not of nitrate, reflects the excessive precipitation that preceded sampling and the lack of mineral transformations that were specific to N (i.e. denitrification and volatilization).

3.3. Primary cations

Extractable K exhibited a similar soil-profile distribution as that observed for extractable P (Figs. 1 and 2). Extractable K with NT was greater than with CT only at 0–0.05 m depth without N fertilization, but at 0–0.6 m depth with N fertilization (Fig. 2). A silt loam in Kentucky contained 29% greater extractable K under NT compared with CT at 0–0.05 m depth, but was 13–16% lower at 0.05–0.3 m depth, regardless of N fertilization regime (Ismail et al., 1994). Nitrogen fertilization resulted in greater extractable K at 0–0.05 m depth than without N fertilizer. Greater return of plant residues to the soil with N fertilization (Franzluebbers et al., 1995c) likely resulted in greater extractable K near the soil surface, especially with NT. To a depth of 0.9 m, extractable K was 26% greater under NT than under CT with N fertilization (Table 2).

Extractable Ca was very high at all soil depths and was unaffected by tillage and N fertilization regimes (Fig. 2). Extractable Mg was also unaffected by tillage and N fertilization regime. Within the 0–0.3 m depth, extractable Mg was evenly distributed with depth, but at 0.3–0.6 m depth a large decrease occurred, followed by a large increase at 0.6–0.9 m (Fig. 2). This variation with depth may have been due to crop

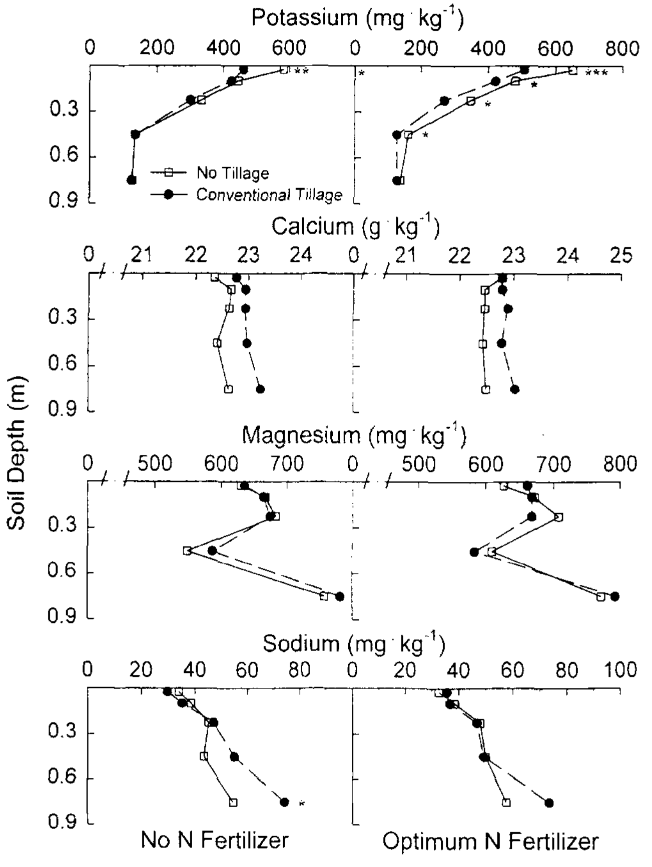

Fig. 2. Soil-profile distributions of primary cations (K, Ca, Mg, and Na) as affected by tillage and N fertilization. (*, **, and *** indicate significance at $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively, between tillage means within N fertilization regime when placed next to symbols and between N fertilization regimes when placed along y-axis.)

uptake or the presence of a soil layer that contained less Mg. This soil was developed from river sediments with stratification of soil sediments during deposition. In contrast to our results, a silt loam from Kentucky under NT contained 28–36% greater extractable Ca and Mg than under CT at 0–0.05 m depth, but 11–42% less extractable Ca and Mg at 0.05–0.3 m depth (Ismail et al., 1994). The supply of extractable Ca in the Weswood silty clay loam was 18–25 times higher than in the Maury silt loam from Kentucky and Mg was 3–7 times higher, which may have been one of the reasons for differential response to tillage between these studies.

Extractable Na increased with depth under both tillage and N fertilizer regimes, but was otherwise little affected, except for greater concentration under CT than under NT at a depth of 0.6–0.9 m (Fig. 2). Sodium absorption ratio was less than 1 at all depths, and therefore, Na concentrations presented little potential for harm due to salinity or sodicity.

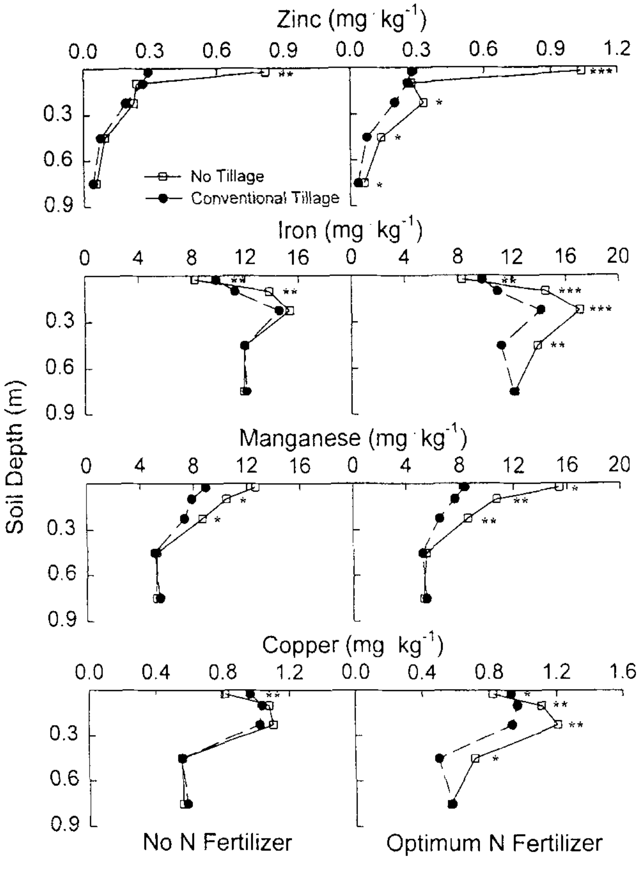

Fig. 3. Soil-profile distributions of micronutrient cations (Zn, Fe, Mn, and Cu) as affected by tillage and N fertilization. (*, **, and *** indicate significance at $P \leq 0.1$, $P \leq 0.01$, and $P \leq 0.001$, respectively, between tillage means within N fertilization regime when placed next to symbols and between N fertilization regimes when placed along y-axis.)

3.4. Micronutrient cations

Extractable Zn and Mn were greatest near the soil surface and decreased with depth (Fig. 3). However, extractable Zn was 2.8–3.7 times greater and extractable Mn was 42–84% greater under NT than under CT at 0–0.05 m depth. Extractable Zn was greater under NT than under CT down to 0.9 m with N fertilization, but was similar between tillage regimes when unfertilized. The effect of greater extractable Mn under NT compared with CT near the soil surface decreased slowly with depth until no difference occurred below 0.3 m (Fig. 3). To a depth of 0.9 m, extractable Zn was 40–87% greater and extractable Mn was 14–20% greater under NT than under CT (Table 2).

Extractable Fe and Cu exhibited similar soil-profile distributions, with levels increasing with depth to 0.3 m and decreasing sharply below 0.3 m (Fig. 3). Extractable Fe and Cu were lower under NT compared with CT at 0–0.05 m depth, but greater under NT at 0.05–0.6 m with N fertilization. Lower extractable Fe and Cu under NT than under CT at 0–0.05 m may have been due to the high extractable P present at the surface under NT and increased complexation of Cu with the higher organic matter content under NT, respectively. Fewer differences between tillage regimes occurred when soil was unfertilized. To a depth of 0.9 m, extractable Fe was 16% greater and extractable Cu was 21% greater under NT than under CT with N fertilization, but were unaffected by tillage regime when unfertilized (Table 2).

Greater water-filled pore space under NT compared with CT (Franzluebbers et al., 1995b) may have contributed to the higher levels of extractable Fe, Mn, and Cu under NT by providing a more reduced soil condition. Greater levels of these nutrients under NT compared with CT primarily with N fertilization rather than without may have also been due to greater availability of C from crop roots and residues, which may have further enhanced reducing conditions by providing C substrates for microbial activity leading to O_2 consumption. Mean yearly crop residue production under NT was 98% of that under CT with N fertilization, but only 89% without N fertilization (Franzluebbers et al., 1995c). Soil maintained at 0.9 water-filled pore space (v/v) resulted in large increases in DTPA-extractable Fe, Mn, and Cu with incorporation of hairy-vetch (*Vicia villosa* Roth.) residues, but no change in these nutrients with residue addition at 0.6 water-filled pore space or at either water content without residue addition (Walters et al., 1992).

4. Summary and conclusions

Soil-profile distributions of extractable P, K, Zn, Fe, Mn, and Cu were significantly altered with continuous implementation of NT for 8 years on this Fluventic Ustochrept. These nutrients under NT tended to be present in higher levels than under CT, especially near the soil surface for extractable P, K, Zn, and Mn due to surface-placement of crop residues. Micronutrient cations (Zn, Fe, Mn, and Cu) were generally greater under NT than under CT throughout the 0–0.3 m depth probably due to reducing conditions, which appeared to be exacerbated with N fertilization. Few differences in soil-profile distributions between tillage regimes occurred with (i) soil pH, except at 0–0.05 m depth due to greater soil organic matter accumulation leading to acidity from decomposition, (ii) nitrate due to high demand for N in this soil with low organic matter and poor aeration status, which may have led to significant denitrification, (iii) sulfate due to its high mobility in soil solution regardless of tillage, and (iv) extractable Ca, Mg, and Na due to their very high native levels, except for Na. Continuous NT did not appear to have any detrimental effect on soil-profile nutrient distributions, and in the case of extractable P and K especially, was beneficial from a soil fertility aspect by allowing accumulation near the soil surface where plant roots tend to be most active.

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