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One-Time Tillage of No-Till: Effects on Nutrients, Mycorrhizae, and Phosphorus Uptake

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ABSTRACT

Stratification of nutrient availability, especially of P, that develops with continuous no-till (NT) can affect runoff nutrient concentration and possibly nutrient uptake. The effects of composted manure application and one-time tillage of NT on the distribution of soil chemical properties, root colonization by arbuscular mycorrhizae (AM), and plant P uptake were determined. Research was conducted on Typic Argiudoll and Mollic Hapludalf soils under rainfed corn (*Zea mays* L.) or sorghum [*Sorghum bicolor* (L.) Moench.] rotated with soybean [*Glycine max* (L.) Merr.] in eastern Nebraska. Tillage treatments included NT, disk, chisel, moldboard plow (MP), and mini-moldboard plow (MMP). Subplots had either 0 or 87.4 kg P ha^{-1} applied in compost before tillage. Bray-P1 was five to 21 times as high for the 0- to 5-cm as compared with the 10- to 20-cm soil depth. Greater redistribution of nutrients and incorporation of compost P resulted from MP tillage than from other tillage treatments. One-time chisel or disk tillage did not effectively redistribute nutrients while MMP tillage had an intermediate effect. Compost application reduced AM colonization of roots at R6 for all crops. Tillage reduced AM colonization with reductions at R6 due to MP tillage of 58 to 87%. The tillage effect on colonization persisted through the second year with no indication of AM recovery. Root P concentration was increased by MP and was negatively correlated to colonization. Decreased colonization did not result in decreased plant P uptake. Infrequent MP tillage can reduce surface soil P and the potential for P loss in runoff, but may reduce AM colonization of the roots, possibly reducing P uptake with some low P soils. The results do not indicate any advantage to one-time tillage of NT if runoff P loss is not a concern.

Soil nutrient stratification with NT is common with relatively high nutrient concentrations in the 0- to 5-cm soil depth (Morrison and Chichester, 1994; Pezzarossa et al., 1995). Nutrients derived from crop residues and applied fertilizer and manure, especially P and other relatively immobile nutrients, accumulate at or near the soil surface in long-term no-till systems because of limited soil mixing (Karathanasis and Wells, 1990).

Stratification of P, K, and pH with no-till may not affect crop performance unless the surface soil is often dry during the growing season and there is low nutrient availability in subsurface soil (Mallarino et al., 1999). Bordoli and Mallarino (1998 and 2000) did not find increased soybean yield response to deep placement compared with surface placement of P for stratified no-till soils. Schwab et al. (2006) did not find a tillage × P placement interaction for several crops, but sorghum grain yield was more with deep placement than with broadcast application for all tillage treatments. McGonigle et al. (1999) compared no-till, ridge-till, and conventional tillage and found that soybean P uptake was unchanged while maize P uptake was more with no-till.

Phosphorus stratification may result in excessively high P concentration in runoff water as runoff P concentration is related to surface soil P concentration (Daverede et al., 2003). Stratification of soil pH and K may be of less environmental concern. Runoff P loss is often more sensitive to changes in rates of erosion and runoff than to soil P concentration (Wortmann and Walters, 2006). The potential for increased P runoff due to P stratification may be offset by reduced erosion with no-till because of good ground cover and improved soil aggregation in the 0- to 5-cm depth (Doran, 1987; West and Post, 2002).

One-time tillage of NT, conducted once in 10 or more years, to mix high-nutrient surface soil with deeper soil may be practiced to redistribute nutrients and reduce the potential for nutrient loss in runoff. Quincke et al. (2007a, 2007b) found that such tillage can be done without loss of soil organic C, soil aggregate stability, or grain yield during the 2 or 3 yr following the one-time tillage. Sharpley (2003) found that in P-stratified soils, the P sorption maxima were 2 to 4.5 times higher at the 5- to 20-cm depth as compared with the surface 5 cm of soil. Guertal et al. (1991) also found less P sorption capacity for soil at the 0- to 2-cm depth as compared with the 2- to 20-cm depth for P-stratified, manure applied soils. Tillage may reduce the potential for P loss in runoff by redistributing nutrients in the soil as well as increasing the P sorption capacity of the surface soil. The effect of one-time MP on the distribution of P and K, but not of soil pH, was still significant 5 yr after tillage (Pierce et al., 1994).

One-time tillage of NT may, however, reduce AM colonization of crop roots and the potential for P uptake. The extent of AM hyphal networks can be several meters per cubic centimeter of soil, providing the major nutrient-absorbing interface between plant and soil (Jakobsen et al., 1992). Damage to the hyphal network by tillage can reduce AM growth and root colonization due to death or reduced infectivity of the hyphal frag-

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Abbreviations: AM, arbuscular mycorrhizae; ARDC, Agricultural Research and Development Center of the University of Nebraska-Lincoln; CH20 and CH30, chisel tillage at the 20- and 30-cm depths; FAME, ester-linked fatty acid methyl ester; MMP, mini-moldboard plow; MP, moldboard plow; NT, continuous no-till; R6, stage of physiological maturity for corn and sorghum or full enlargement of soybean seed; RMF, Rogers Memorial Farm of the University of Nebraska-Lincoln; TP, total phosphorus; V6, six-leaf growth stage.

ments compared with intact networks (Evans and Miller, 1990; Johnson et al., 2001; Goss and de Varennes, 2002). Tillage can reduce AM colonization and P, Zn, and Cu uptake by plants (Evans and Miller, 1988; Evans and Miller, 1990; McGonigle et al., 1990; McGonigle and Miller, 1996; Mozafar et al., 2000; Goss and de Varennes, 2002). In undisturbed soil, roots follow preformed channels, making close contact with the AM-infected root system of the previous crop, resulting in enhanced AM colonization of the roots (Evans and Miller, 1990). Root exudation, which may be higher in undisturbed soil, stimulates AM hyphal growth and possibly root colonization (Kabir et al., 1999).

Manure application may either increase or decrease root colonization by AM fungi. Tarkalson et al. (1998) found that manure application resulted in increased AM colonization, P and Zn uptake, and crop yield. Muthukumar and Udaiyan (2002) reported that manure application increased spore populations and root colonization by AM fungi. The benefit of organic amendments on AM fungi has been attributed to increased porosity, enlarged mean weight diameter of aggregates, improved water retention capacity, greater activity of beneficial soil microbes, increased crop rooting, and a better distribution of nutrients in the soil profile (Celik et al., 2004). However, Ellis et al. (1992) and Allen et al. (2001) found that AM colonization was inconsistently affected by manure applications.

Mycorrhizal colonization tends to decrease with increasing soil P (Grant et al., 2005). The effect of soil P availability on AM colonization of roots appears to be indirect through its influence on root P concentration with less AM colonization as root P increases (Joner, 2000). This was demonstrated in split-root studies where colonization of roots by AM fungi occurred, even in the presence of high concentrations of soil P, as long as root P concentration was low (Mengue et al., 1978). Increased root P concentration may cause reduced AM colonization, infection, and spore production (Fairchild and Miller, 1990).

The objective of this research was to determine the effects of composted manure application and one-time tillage of NT land on (i) the distribution of soil pH and nutrients; (ii) AM colonization of plant roots; and (iii) plant P uptake.

MATERIALS AND METHODS

Site Description, Experimental Design, and Treatments

The research was conducted from 2003 to 2005 at Rogers Memorial Farm (RMF) east of Lincoln, NE (40°50′44″ N lat, 96°28′18″ W long, 380 m altitude), and at the Agricultural Research and Development Center (ARDC) of the University of Nebraska-Lincoln near Mead, NE (41°10′48″ N lat, 96°28′40″ W long, 358 m altitude). The soil at RMF was an upland Sharpsburg silty clay loam soil formed in loess (Typic Argiudolls) and the soil at ARDC was an upland Yutan silty clay loam soil formed in loess (Mollic Hapludalfs). The field at RMF was in NT since 1991, preceded by an uncertain number of years of reduced tillage. The field at ARDC was in NT since 1996, preceded by infrequent shallow tillage since 1988. The cropping systems were corn–soybean at ARDC and sorghum–soybean at RMF.

The experimental design was a split plot arrangement in a randomized complete block design with four replications. Five tillage treatments were the main plot treatments. At RMF, the tillage treatments were (i) NT, (ii) chisel with 10-cm wide twisted shanks at 30-cm depth (CH30), (iii) the chisel at the 20-cm depth (CH20), (iv) disk at the 10-cm depth, and (v) MP at the 20-cm depth. At ARDC, CH20 was replaced by MMP tillage at the 20-cm depth. The tillage treatments at RMF included spring and fall tillage, resulting in the NT plus eight tilled main plots in each block. The spring and fall tillage treatments at RMF were fully randomized within blocks. The tillage treatments were timed to have low soil temperatures following tillage to reduce soil organic C loss due to tillage-induced microbial activity and were conducted on 26 Mar. and 23 Oct. 2003 at RMF and on 26 Nov. 2003 at ARDC. The spring MP tillage at RMF was followed by disk tillage, but there was no other secondary tillage.

Subplot treatments were no compost applied and composted beef feedlot manure hand-applied at ≈87 kg P ha^{-1} just before tillage (Table 1). The compost application rates were 17.7, 27.7, and 27.6 Mg ha^{-1} of compost for the RMF spring and fall tillage, and the ARDC fall tillage, respectively, which contained 201, 302, and 341 kg ha^{-1} of K.

The main plot sizes were 149 m^2 (eight rows 24.4 m long with 0.76-m row spacing) and 112 m^2 (six rows of 24.4 m long with 0.76-m row spacing) at ARDC and RMF, respectively. The subplots were 12.2 m long. In 2004, soybean (cv. Dekalb 25-51 of Maturity Group 2 at the ARDC and cv. Asgrow 3302 of Maturity Group 3 at RMF) was sown at both sites at a rate of 494 000 seeds ha^{-1}. In 2005, corn (cv. Pioneer 33R81, 2750 growing degrees days at physiological maturity) was sown at the ARDC at a rate of 56 800 seeds ha^{-1} and grain sorghum (cv NC+7R37E, medium maturity group) was sown at RMF at a rate of 190 000 seeds ha^{-1}.

Sample Collection and Preparation

Soil samples at five depths (0–2.5, 2.5–5.0, 5.0–10.0, 10.0–20.0, and 20.0–30.0 cm) were taken from each subplot before planting in June 2003 and May 2004 for the spring- and fall-tilled plots, respectively. A sample was composed of 10 1.7-cm-diam. cores collected at random in each subplot. Samples were air-dried, sieved through 2-mm mesh sieve, and analyzed for $pH_{1:1}$ (Thomas, 1996), Bray-P1 (Bray and Kurtz,

Table 1. Application rates and properties of the compost applied at Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC) in 2003.

Application event	Rate†	Dry matter	P	K	Ca	Organic N	NH_4–N	NO_3–N
	Mg ha^{-1}	g kg^{-1}†						
Spring applied, RMF	14.8	839	6.0	11.4	16.1	7.6	0.21	1.59
Fall applied, RMF	19.4	701	4.5	10.9	15.8	7.2	0.32	1.08
Fall applied, ARDC	19.8	715	5.0	12.3	17.3	7.7	0.11	0.51

† Dry wt. basis.

1945), total phosphorus (TP) by perchloric acid digestion (Olsen and Sommers, 1982), and available K (Helmke and Sparks, 1996).

Crop roots, of the fall tillage treatments only, were sampled to quantify AM colonization of the roots at growth stages V6 (6-leaf) and R6 (the end of seed enlargement) for soybean (Fehr et al., 1971) and physiological maturity for corn and sorghum (Ritchie and Hanway, 1993) in June and September of both 2004 and 2005. The samples were composed of 10 adjacent plants from a representative plant stand in the same row. All roots were collected to ≈15 cm deep and to the side of the row, stored at 5°C for <24 h, and then retained on a 410-μm sieve while rinsed with water at constant pressure for 20 min using an elutriation system to remove soil. Secondary and tertiary roots were selected to form subsamples of ≈5 g of fresh roots, which were freeze-dried (Labconco, Kansas City, MO) for 100 h and ground for 24 h using a roller mill.

Aboveground plant samples collected from fall tillage plots and composed of 10 adjacent plants from a uniform and representative segment of the second row of the plot were cut at ground level each year at the V6 and R6 growth stages. The plant samples were weighed in the field using a portable scale (Model PT 6, sensitivity 1 g, Sartorius, Goettingen, Germany), dried in a forced-air oven at 70°C to constant weight for ≈10 d, and weighed.

Plant and root samples were ground to pass a 2-mm mesh screen and TP was extracted using a perchloric acid and nitric acid digestion (Stewart, 1987). Phosphorus concentration in the digested extract was determined by absorbance at 880 nm in a spectrophotometer (Type Genesys-5, Spectronic Instruments, Inc., Rochester, NY) following the procedure of Murphy and Riley (1962). Plant P uptake was calculated from P concentration, biomass dry weight, and plants ha^{-1}.

Arbuscular Mycorrhizae Colonization of Plant Roots

Plant root colonization by AM was quantified using the fatty acid biomarker C16:1*cis*11 which is found almost exclusively in AM (Larsen et al., 1998) and correlates well with microscopic estimates of root colonization (Olsson et al., 1997). Samples of 250 mg of ground root tissue were extracted by mild alkaline methanolysis using freshly prepared 0.2 *M* potassium hydroxide in methanol, and the resulting fatty acid methyl esters (FAMEs) were partitioned into hexane (Johnson et al., 2001). This method recovers ester-linked FAMEs from neutral lipids, glycolipids, and phospholipids. Methyl-nonadecanoate (0.05 μg μL^{-1}) was added to the extract as an internal standard. Released FAMEs were separated by gas chromatography, using helium as a carrier gas and an Ultra 2 HP (50 m, 0.2-mm i.d., 0.33-μm film thickness) capillary column. The gas chromatograph was run in split mode (44:1) with a 45-s purge time. Injector and flame ionization detectors were maintained at 280° and 300°C, respectively, and oven temperature was ramped from 50°C to 160°C at 40°C min^{-1} and held for 2 min, then ramped at 3°C min^{-1} to 300°C and held for 30 min. The FAMEs were identified by retention time and confirmed by mass spectrometry.

Data Analysis

Analysis of variance was performed for each site by depth and combined across depths to determine treatment effects on soil properties and P uptake using SAS PROC MIXED (Littel and Hills, 1997). Treatment interaction effects with tillage time at RMF were generally not significant with an ANOVA combined for spring and fall tillage, and the treatment means presented were the averages for the two tillage events. An ANOVA combined across sampling times was conducted for root P concentration, but not for C16:1*cis*11 due to heterogeneity of error for the two sampling times. Pearson correlation coefficients were determined for the relationship of C16:1*cis*11 concentration to root P concentration and plant P uptake. A probability level of $P \leq 0.05$ was considered significant.

RESULTS

Soil Properties

Stratification of the No-till Soil

Bray-P1 and the proportion of TP that was extractable as Bray-P1 were the most stratified soil properties with NT (Table 2). At RMF, nearly 10 times as much of the TP in the surface 2.5 cm was Bray-P1 extractable compared with the 20- to 30-cm depth, generally agreeing with the findings of Sharpley (2003) and Guertal et al. (1991). The magnitude of stratification was less at ARDC, where Bray-P1 in the surface soil was less than at RMF. Soil pH and total soil P were the least stratified properties. Soil pH was highest in the surface 0- to 2.5-cm depth, intermediate at 2.5 to 5 cm, and lowest at 5 to 20 cm. The higher pH at RMF of the 0- to 2.5-cm depth is due to surface lime application in preceding years. Soil pH was higher at the 20- to 30-cm depth as compared with the 10- to 20-cm depth.

Bray-P1 decreased with depth to very low availability at the 20- to 30-cm depth (Shapiro et al., 2003). Bray-P1 was 2 to 3 times more in the 0- to 2.5-cm depth compared with the 2.5- to 5-cm depth, and 5 to 20 times more than for the 10- to 20-cm depth. The depth weighted mean Bray-P1 to 20-cm depth indicated low P availability at ARDC. Available K was much higher in the 0- to 5-cm depth than at deeper depths, but was still of high availability at all depths.

Table 2. Surface soil profile characteristics for the no-till treatment with no compost applied, and Bray-P1 with compost ($Bray\text{-}P1_c$) applied, at two locations in eastern Nebraska.†

	RMF						ARDC					
Soil depth	pH	K	Bray-P1	$Bray\text{-}P1_c$	TP	BP1:TP	pH	K	Bray-P1	$Bray\text{-}P1_c$	TP	BP1:TP
cm		mg kg^{-1}						mg kg^{-1}				
0–2.5	7.1a‡	502a	74.0a	146.7a	593a	0.155a	6.5a	647a	20.5a	39.8a	414	0.047a
2.5–5	6.6b	428b	35.3b	46.0b	560a	0.080b	6.0b	405b	7.2b	10.2b	353	0.027b
5–10	5.3c	272c	12.0c	14.0c	456bc	0.029c	5.6c	241c	4.1b	5.5b	345	0.016c
10–20	5.1d	199d	7.3c	6.7c	405c	0.022d	5.8c	204c	3.7b	4.7b	449	0.011c
20–30	5.6d	186d	5.0c	7.0c	512a	0.015e	6.1c	195c	4.3b	5.7b	293	0.019c

† ARDC, Agricultural Research and Development Center; RMF, Rogers Memorial Farm; TP, total phosphorus; BP1:TP, ratio of Bray-P1 to total phosphorus with no compost applied.

‡ Different letters within a column indicate significant differences between means using the LSD 0.05 means comparison.

Table 3. Results of ANOVAs, combined for five soil depths to the 30-cm depth, on the effects of tillage and compost application on soil properties at Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC) in eastern Nebraska.

	RMF†			ARDC		
Source of variation	Bray-P1	K	pH	Bray-P1	K	pH
Tillage (T)	***	***	***	NS‡	*	0.05
Compost (C)	***	***	NS	***	**	NS
Depth (D)	***	***	***	***	***	***
T × C	***	NS	NS	*	NS	**
T × D	***	***	***	***	***	***
C × D	***	***	NS	***	NS	*
T × C × D	***	*	NS	***	NS	NS

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† Treatment × tillage time interactions at RMF were not significant and the results are from the combined analysis of spring and fall tillage.
‡ NS, not significant at $P \leq 0.05$.

Bray-P1

The three-way interaction of tillage × compost × depth was significant for Bray-P1 at both sites (Table 3; Fig. 1), primarily due to increased Bray-P1 with compost application in the surface 5 cm at RMF for all tillage treatments except for MP. Bray-P1 was increased with compost application at ARDC in the surface 2.5 cm for all tillage treatments and at the 10- to 20-cm depth for MP (Table 4).

Compost application resulted in a mean increase in Bray-P1 to the 20-cm depth, but the increase below the 5-cm depth was primarily due to MP tillage (Table 4; Fig. 1). Disk tillage incorporated compost P sufficiently to result in increased Bray-P1 at the 2- to 5-cm depth, while the effect of chisel and MMP tillage extended to the 5- to 10-cm depth. Disking was not effective for reducing Bray-P1 in the surface 2.5-cm of soil. With compost applied, disk tillage resulted in increased Bray-P1 compared with no-till at the 0- to 2.5-cm depth at RMF.

The ratio of Bray-P1 to TP concentration increased as Bray-P1 increased according to the ratio of Bray-P1 to TP = $-0.205 + 0.613$ Bray-P1$^{0.7}$, $R^2 = 0.86$. This ratio was larger in the surface 5-cm depth with compost compared with no compost applied, and the ratio was least with MP (Table 5). The ratio was relatively high with CH30 and compost applied at ARDC, more due to a nonsignificant decrease in TP than an increase in Bray-P1.

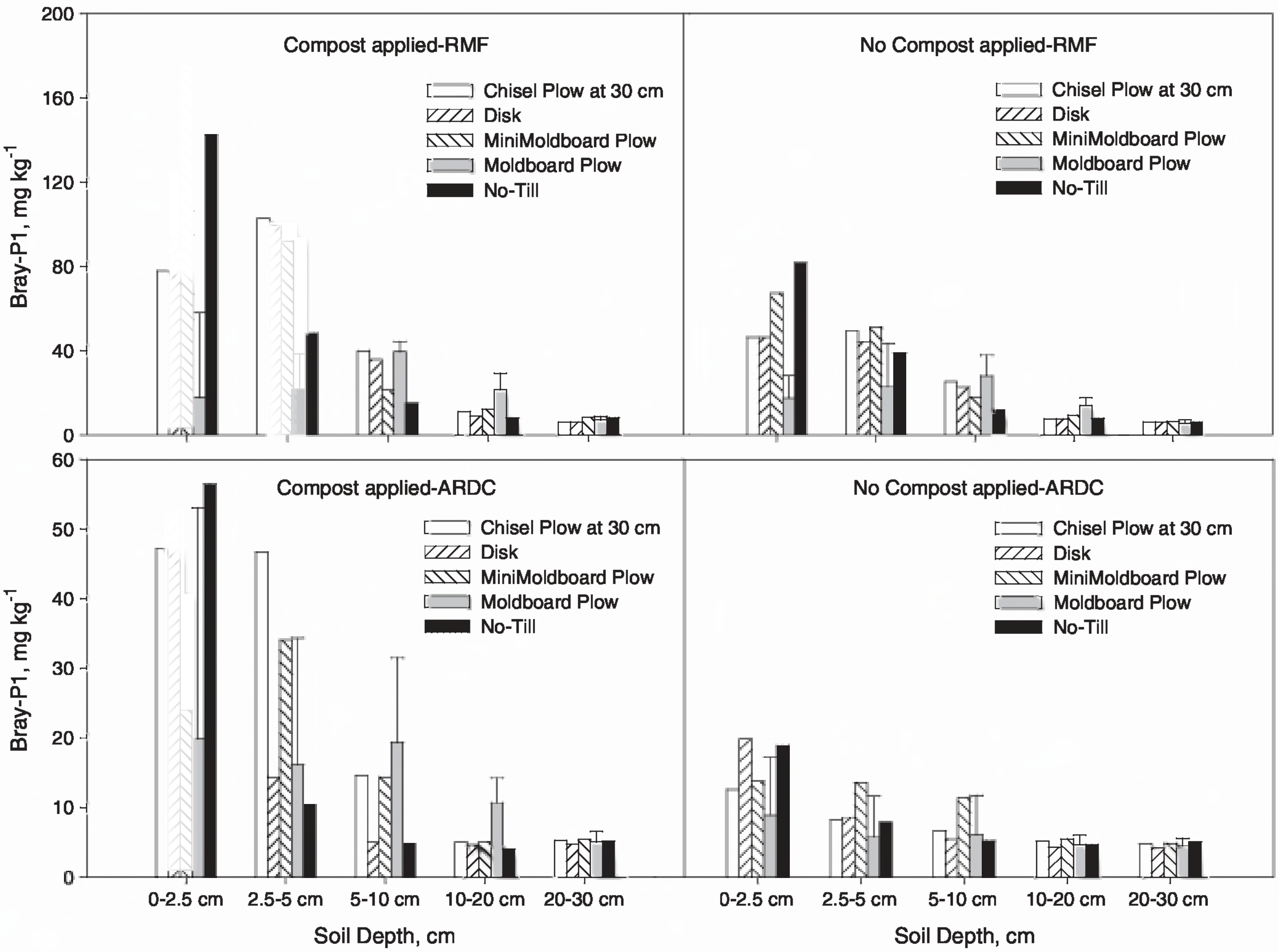

Fig. 1. Tillage effect on Bray-P1 (mg kg^{-1}) with and without compost applied at Rogers Memorial Farm (RMF) and Agricultural Research and Development Center (ARDC), respectively. The Y-bars are the LSD 0.05 values for tillage effects.

Table 4. ANOVA results for the effects of tillage (T) and compost (C) on soil properties at five depths at Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC) in eastern Nebraska.

	Depth, cm									
	RMF, spring and fall tillage combined					ARDC, fall tillage				
Source of variation	0–2.5	2.5–5	5–10	10–20	20–30	0–2.5	2.5–5	5–10	10–20	20–30
Bray-P1										
Tillage (T)	***	***	***	**	NS†	*	**	0.09	**	NS
Compost (C)	***	***	***	**	NS	***	**	*	0.09	NS
T × C	***	*	NS	0.06	NS	NS	*	0.09	*	NS
K										
T	***	***	**	*	NS	**	**	**	**	NS
C	***	***	*	NS	NS	*	0.07	NS	NS	NS
T × C	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
pH										
T	***	***	***	*	NS	***	**	**	0.09	NS
C	NS	NS	NS	NS	NS	*	*	NS	NS	NS
T × C	NS	NS	NS	NS	NS	*	NS	NS	NS	NS

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† NS, not significant at $P \leq 0.05$.

Soil Potassium

The tillage × compost × depth and the compost × depth interaction effects on soil test K were significant at RMF (Table 3). The three-way interaction was due to a greater tillage effect in the 0- to 5-cm depth with compost compared with no compost applied. The two-way interaction was due to increased K in the 0- to 10-cm depth with compost applied, but with no effect on K below the 10-cm depth (Table 4; Fig. 2). These interactions were not significant at ARDC which had a higher initial soil test K level than RMF (Table 2) and where K was increased with compost application to the 5-cm depth only.

The tillage × depth interaction was significant for soil test K at both sites (Table 3, Fig. 2). Soil test K decreased with depth to 20 cm except for an increase in the 5- or 10-cm depth at RMF with CH30, CH20, and MP tillage, and an increase at ARDC with MP in the 5- to 20-cm depth. Soil test K was increased by 79 mg kg^{-1} and by 51 mg kg^{-1} with compost applied in the 0- to 2.5-cm and 2.5- to 5-cm depths at RMF, respectively, and by 64 mg kg^{-1} in the 0- to 2.5-cm depth at ARDC (Table 4). The effect of tillage on soil K redistribution was least for disk, intermediate and similar for CH30, CH20, and MMP, and greatest for MP.

Table 5. The ratio of Bray-P1 to total soil P (mg kg^{-1}) in the 0- to 5-cm soil depth as affected by one-time tillage of no-till land and compost application at Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC) in eastern Nebraska.

	RMF		ARDC	
Tillage treatment	No compost	Compost	No compost	Compost
Chisel, 30-cm depth	0.096†	0.161	0.026	0.118
Chisel, 20-cm depth	0.094	0.149	NA‡	NA
Disk	0.121	0.192	0.036	0.077
Mini-moldboard plow	NA	NA	0.036	0.079
Moldboard plow	0.046	0.045	0.024	0.048
No-till	0.118	0.141	0.037	0.060
	ANOVA			
Tillage (T)	***		0.082	
Compost (C)	***		***	
T × C	NS§		0.062	

*** Significant at $P \leq 0.001$.
† The percentages were determined from Bray-P1 and total phosphorus concentration for the 0- to 2.5-cm and 2.5- to 5-cm depths combined with no adjustment for possible differences in bulk density.
‡ NA, not applicable.
§ NS, not significant at $P \leq 0.05$.

Soil pH

Soil pH was not affected by the three-way interaction of tillage × compost × depth at either site (Table 3). The tillage × compost and the compost × depth interactions were significant at ARDC. The first interaction was due to a relatively less decrease in pH with compost than without compost applied for the 0- to 2.5-cm depth with CH30 tillage, while the second interaction was due to increased soil pH with compost applied at 0 to 2.5 cm with no effect at deeper depths (Table 4, Fig. 3). The tillage × depth interaction was significant for both sites primarily due to lower soil pH at the 0- to 5-cm depth and higher pH at the 10- to 20-cm depth with MP compared with the other tillage treatments.

Compost application increased soil pH for the 0- to 5-cm depth at ARDC (Table 4). The tillage time × compost application interaction and the main effect of compost application were not significant at RMF.

Arbuscular Mycorrhizal Colonization

The root concentration of C16:1*cis*11 in corn and soybean roots was not affected by the tillage × compost interaction, but this interaction was significant for sorghum at V6 (Table 6). This interaction was due to less C16:1*cis*11 in sorghum roots with compost application for all tillage treatments except for MP tillage ($\alpha < 0.1$). Compost application resulted in reduced concentration of C16:1*cis*11 at RMF at V6 in soybean and sorghum, and at R6 in sorghum. At ARDC, the effect of compost application on the concentration of C16:1*cis*11 in soybean and corn roots was inconsistent and not statistically significant. Bray-P1 at ARDC was low before compost

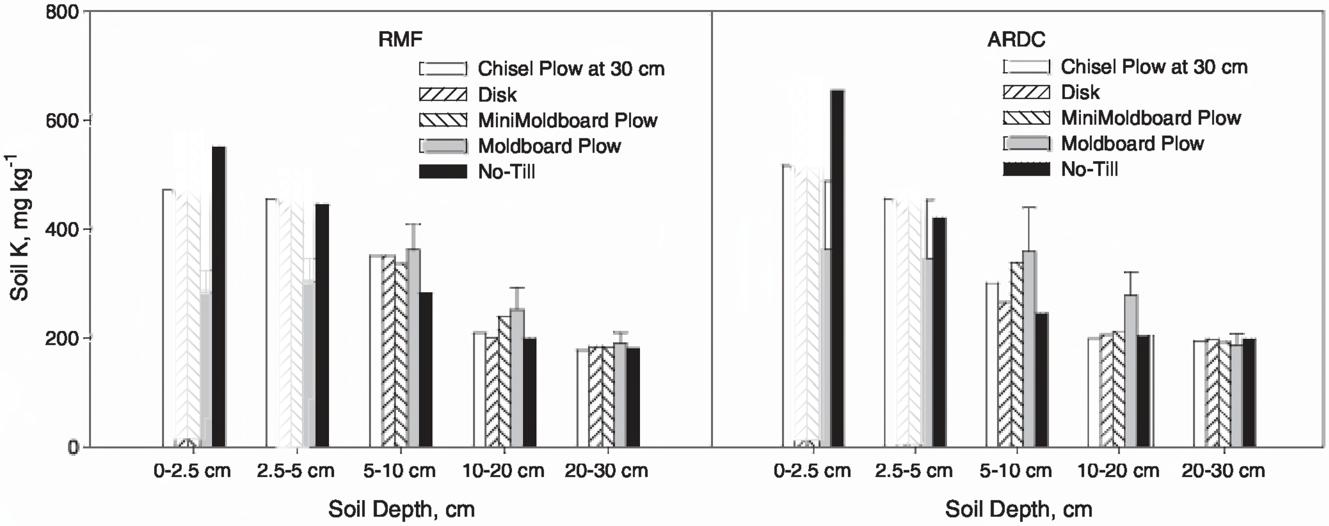

Fig. 2. Tillage effect on soil K for compost and no compost application combined at Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC), respectively. The Y-bars are the LSD 0.05 values for tillage effects.

application and application may not have increased P availability sufficiently to affect AM colonization.

The concentration of C16:1*cis*11 at V6 in the roots of sorghum and soybean was affected by tillage treatments at RMF but not in crop roots at ARDC (Table 6). The tillage effect at V6 was a reduced concentration of C16:1*cis*11 with MP tillage. At R6, however, C16:1*cis*11 was generally reduced in all crops. The concentration of C16:1*cis*11 at R6 was similarly reduced compared with no-till for all one-time tillage treatments at ARDC, but MP tillage tended to cause the greatest reduction at RMF.

Mycorrhizal colonization of plant roots was greatest for corn and least for sorghum (Table 6). The density of AM colonization increased from V6 to R6 (Table 6). The relative difference in C16:1*cis*11 concentration between tilled treatments and no-till indicates AM colonization had not recovered during the nearly 22 mo following tillage.

Plant Phosphorus Uptake

Phosphorus uptake was more affected by treatments at V6 than at R6 (Tables 7 and 8). The tillage × compost interaction was not significant for P uptake at V6 and R6 for all site-years except for sorghum at R6. This interaction was due to greater plant P uptake with no compost applied for MP and disk tillage, while uptake was increased with compost application for chisel tillage and unchanged for no-till.

Plant P uptake at V6 was affected by tillage in all site-years, and uptake was often least with NT and most with MP tillage. Plant P uptake with chisel tillage was similar or less than with MP tillage. Compost application

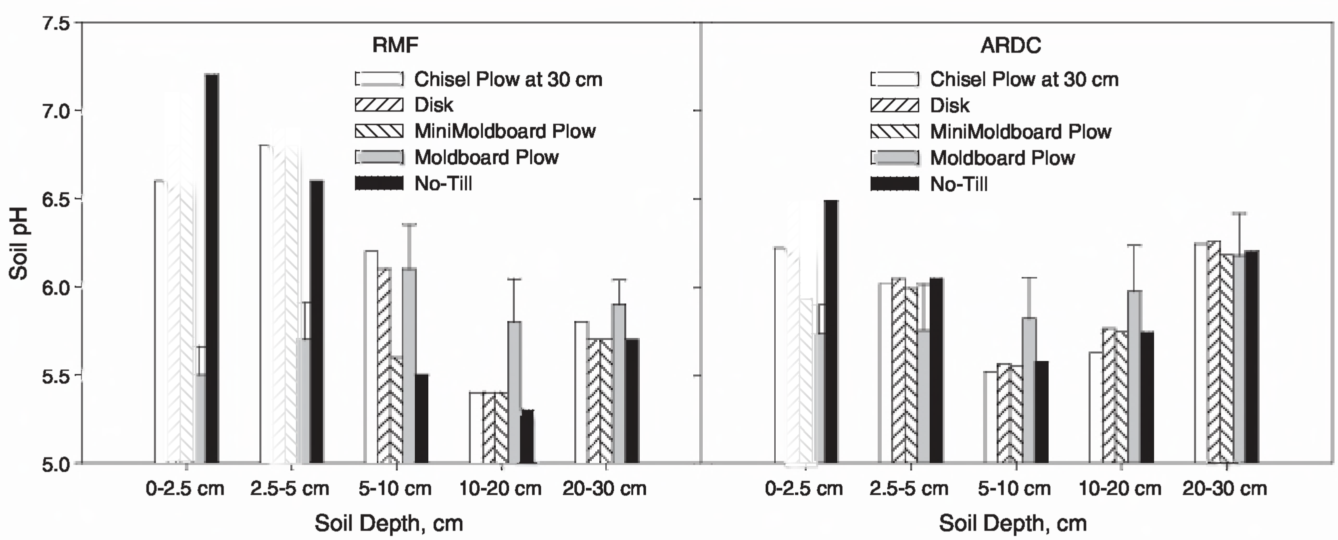

Fig. 3. Tillage effect on soil $pH_{1:1}$ for compost and no compost application combined at Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC), respectively. The Y-bars are the LSD 0.05 values for tillage effects.

Table 6. Tillage and compost effect on C16:1cis11 concentration (nmol g^{-1} root) of soybean, corn, and sorghum roots for two growth stages† at the Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC) in eastern Nebraska.

	ARDC				RMF			
	Soybean		Corn		Soybean		Sorghum	
Treatments	V6†	R6†	V6	R6	V6	R6	V6	R6
Chisel tillage, 30-cm depth								
No compost	123	477	302	500	145	857	3.0	63
Compost	130	313	246	529	111	592	2.4	54
Disk								
No compost	130	350	313	361	121	901	4.1	140
Compost	166	419	258	569	72	739	2.4	105
Moldboard plow								
No compost	136	362	306	501	89	515	1.5	19
Compost	88	354	245	284	91	380	1.7	32
No-till								
No compost	117	1319	310	987	155	1108	2.2	228
Compost	120	949	230	681	112	1439	1.8	160
				ANOVA, $P > F$				
Tillage (T)	NS‡	**	NS	**	§	*	*	**
Compost (C)	NS	NS	NS	NS	*	NS	*	***
T × C	NS	NS	NS	NS	NS	NS	§	NS
LSD (0.05), T	59.3	371.2	83.4	207.0	47.1	179.9	1.12	115.6
LSD (0.05), C	25.9	297.6	91.7	203.3	20.9	108.9	0.50	16.7

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† V6 = Six leaf stage; R6 = end of seed enlargement for soybean, and physiological maturity of corn and sorghum.
‡ NS, not significant at $P \leq 0.05$.
§ Significant at $P \leq 0.1$.

resulted in increased P uptake at ARDC (Table 8) but not at RMF (Table 7), where the initial Bray-P1 was considerably higher than at ARDC.

The early differences in P uptake, however, did not translate to differences in final P uptake by soybean, which was not affected by treatments at R6. The main effects of tillage and compost were not significant at R6 for sorghum in 2005. Phosphorus uptake by corn at R6 was least with NT and disk tillage, and most with MP and chisel tillage. Compost application did not affect P uptake by corn at R6 even though Bray-P1 was low at ARDC.

Plant P uptake was not directly related to AM colonization except for soybean at R6 at ARDC where the correlation was negative (Table 9). The negative correlation was less expected for this site than for RMF where Bray-P1 was relatively high. Tillage and compost treatments apparently had other effects on plant P uptake that overcame the effects of reduced AM colonization.

Root Phosphorus Concentration and Arbuscular Mycorrhizae Colonization

Tillage effects on root P concentration were not consistent for the two sampling dates (Table 10). While root P concentration was generally higher with MP tillage, concentration was generally lowest for either NT or disk tillage. Root P concentration was higher at R6 than at V6 except for soybean at ARDC. The ARDC soybean crop was affected by soil water deficits during

Table 7. Phosphorus uptake (kg ha^{-1}) as affected by one-time tillage and compost application conducted in the fall of 2003 at the Rogers Memorial Farm in eastern Nebraska.

	Soybean, 2004				Sorghum, 2005			
	V6		R6		V6		R6	
Tillage treatment†	No compost	Compost	No compost	Compost	No compost	Compost	No compost	Compost
CH30	5.61	6.82	40.76	32.80	8.48	9.72	39.59	59.14
CH20	4.62	5.94	32.05	36.68	7.93	8.19	41.67	42.58
Disk	6.97	5.76	35.00	33.21	10.65	10.40	56.06	40.07
MP	7.20	6.44	40.14	32.43	9.25	9.47	52.99	42.25
No-till	4.97	5.48	36.40	20.63	7.54	7.08	39.48	42.52
				ANOVA				
Tillage (T)	*		NS‡		*		NS	
Compost (C)	NS		NS		NS		NS	
T × C	0.05		NS		NS		*	
LSD (0.05), T	1.06		7.79		2.10		24.38	
LSD (0.05), C	0.63		8.59		1.10		9.49	
LSD (0.05), T × C	1.40		15.66		2.45		21.22	

* Significant at $P \leq 0.05$.
† Tillage treatments are: CH30, chisel at the 30-cm depth; CH20, chisel at the 20-cm depth; Disk, tandem disk; MP, moldboard plow.
‡ NS, not significant at $P \leq 0.05$.

Table 8. Phosphorus uptake (kg ha^{-1}) as affected by one-time tillage and compost application conducted in the fall of 2003 at the Agricultural Research and Development Center in eastern Nebraska.

	Soybean, 2004				Corn, 2005			
	V6		R6		V6		R6	
Tillage treatment†	No compost	Compost	No compost	Compost	No compost	Compost	No compost	Compost
CH30	7.28	8.56	23.63	21.45	3.53	4.64	44.01	38.32
Disk	6.01	6.29	21.38	26.71	3.07	4.22	31.60	39.28
MMP	7.10	10.99	21.63	25.44	3.28	5.23	36.38	38.05
MP	9.47	8.83	24.41	24.93	4.72	7.18	37.80	42.32
No-till	5.92	7.60	16.19	18.80	3.68	3.85	38.98	33.37
			ANOVA					
Tillage (T)	*		NS‡		**		*	
Compost (C)	*		NS		**		NS	
T × C	NS		NS		NS		NS	
LSD (0.05), T	1.83		7.27		1.01		5.87	
LSD (0.05), C	1.30		4.23		0.93		3.76	
LSD (0.05), T × C	2.75		9.46		1.79		12.48	

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
† Tillage treatments are CH30 = chisel at 30-cm depth; Disk = tandem disk; MMP = mini-moldboard plow; MP = moldboard plow.
‡ NS, not significant at $P \leq 0.05$.

the reproductive stages, which may have interfered with late P uptake to cause a low root P concentration. The tillage × compost interaction was significant in all site-years except for corn. Compost application generally resulted in increased root P, but the increases tended to be relatively small with chisel tillage and occasionally with disk tillage. The compost × sampling time interaction was significant for soybean at RMF due to a relatively smaller increase in P concentration with compost applied at V6 than at R6. The significant tillage effect was largely due to higher P concentration with MP tillage as compared to no-till and the other one-time tillage treatments.

Root P concentration was negatively correlated with the concentration of C16:1*cis*11 for corn and sorghum at R6, and for soybean at ARDC (Table 9). The correlation is largely due to the relatively high root P concentration and the relatively low concentration of C16:1*cis*11 for MP tillage at both V6 and R6 at both sites, while root P concentration and C16:1*cis*11 concentration were relatively low and high, respectively, with no-till.

Table 9. Pearson correlation coefficients of root P concentration and plant P uptake to C16:1*cis*11 in roots for two growth stages† at the Rogers Memorial Farm (RMF) and the Agricultural Research and Development Center (ARDC) in eastern Nebraska.

	ARDC		RMF	
Growth stage	Soybean	Corn	Soybean	Sorghum
	Root P concentration			
V6†	−0.30 NS‡	−0.65§	−0.41 NS	0.35 NS
R6†	−0.10 NS	−0.75*	−0.65§	−0.90**
	Plant P uptake			
V6	−0.32 NS	−0.52 NS	0.09 NS	0.49 NS
R6	−0.82**	−0.49 NS	0.12 NS	−0.33 NS

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
† V6 = six leaf stage; R6 = end of seed enlargement for soybean, and physiological maturity of corn and sorghum.
‡ NS, not significant at $P \leq 0.05$.
§ Significant at $P \leq 0.1$.

DISCUSSION

Soils under NT were stratified, especially for Bray-P1, but also for soil test K and pH (Table 2). Moldboard plow tillage was most effective in redistributing P, K, and soil acidity while the trends for the various tillage implements was MP > CH30 > CH20 = NT > disk at RMF and MP > MMP > CH30 = disk = NT at ARDC (Fig. 1–3). The largest reduction in Bray-P1 at the 0- to 5-cm depth was with MP, followed by MMP, probably due to the mixing of low and high P soil that resulted in dilution of soil P and an increase in overall P sorption with reduced extractability. The evidence for decreased sorption is the reduced ratio of Bray-P1 to TP in the surface 5 cm of soil due to MP at RMF, which had relatively higher surface soil P (Table 5). This is supported by the finding of Guertal et al. (1991) that NT surface soil has been found to have less P retention capacity than deeper soil, and by Sharpley (2003) who reported that mixing high P surface soil with low P subsoil by profile inversion increased the overall P sorption capacity of the mixed soil. Assuming that the one-time tillage does not result in increased runoff and erosion, the combined effects of dilution of high P surface soil and increased P sorption can potentially reduce the risk of P enrichment of runoff water while increasing Bray-P1 in the subsurface soil.

Tandem disk tillage caused no effect on Bray-P1 except for an increase with compost application at RMF in the 0- to 5.0-cm depth (Fig. 1). The disk tillage was conducted to a depth of 7.5 cm, apparently with significant mixing but little inversion of the surface soil. The mixing may have caused more compost P to be extractible as Bray-P1, possibly due to enhanced microbial activity and nutrient mineralization.

The increase in surface soil Bray-P1 with compost application was expected due to the large amount of P applied (Fig. 1) (Griffin et al., 2003; Lucero et al., 1995; Reddy et al., 1999; Sharpley, 2003), and possibly enhanced P solubility due to the applied organic material (El-Buruni and Olsen, 1979). The proportion of TP that was Bray-P1 extractible was increased as well with com-

Table 10. Tillage and compost effect on root P concentration (mg g^{-1}) of soybean in 2004 and corn and sorghum in 2005 for two growth stages† at the Agricultural Research and Development Center (ARDC) and Rogers Memorial Farm (RMF) locations in eastern Nebraska.

	Soybean, ARDC		Soybean, RMF		Corn, ARDC		Sorghum, RMF	
Treatments	V6†	R6†	V6	R6	V6	R6	V6	R6
Chisel tillage at the 30-cm depth								
No compost	0.60	0.45	0.90	1.22	1.37	1.91	1.40	2.01
Compost	0.75	0.43	0.70	1.78	1.70	2.25	1.46	2.25
Disk								
No compost	0.65	0.23	0.94	1.16	1.32	1.97	1.39	1.88
Compost	0.94	0.53	0.95	1.54	1.74	2.29	1.40	2.22
Moldboard plow								
No compost	0.59	0.53	0.83	1.65	1.53	2.96	1.38	2.24
Compost	1.21	1.04	1.78	2.07	2.03	3.41	1.50	2.74
No-till								
No compost	0.56	0.39	0.77	0.95	1.39	1.58	1.42	1.14
Compost	0.81	0.68	1.05	1.19	1.82	2.06	1.56	1.56
			ANOVA, $P > F$					
Sample time (S)	***		***		***		***	
Tillage (T)	***		***		***		***	
Compost (C)	***		***		***		***	
T × S	0.084		***		***		***	
T × C	**		*		NS‡		***	
C × S	NS		***		NS		NS	
T × C × S	NS		0.082		NS		NS	

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† V6 = Six leaf stage; R6 = end of seed enlargement for soybean, and physiological maturity of corn and sorghum.
‡ NS, not significant at $P \leq 0.05$.

post application (Table 5), indicating reduced P sorption capacity as discussed above.

Tillage effects on the distribution of soil K and pH followed patterns similar to that of Bray-P1 with stratification most reduced by MP tillage (Fig. 2 and 3). Soil K availability was increased with compost application at RMF (data not presented), as observed by Kingery et al. (1994) and Whalen et al. (2000). This increased soil K was probably due to the added K rather than increased availability of total K (the lowest rate of compost-K was 169 kg ha^{-1}, Table 1). The effect of compost application on available soil K was greater at RMF than at ARDC, probably due to the relatively higher soil K level at ARDC in the surface soil before compost application. Surface soil pH was increased with compost application at ARDC (data not shown), an effect due to excretion of dietary lime as reported by Eghball (1999). The effect of compost on soil pH at RMF was not significant, probably due to high surface soil pH resulting from previous surface applications of lime.

Tillage resulted in reduced AM colonization of crop roots. Others have reported that the disruption of the hyphal network reduces AM colonization (Evans and Miller, 1990; Johnson et al., 2001; Goss and de Varennes, 2002; Jansa et al., 2002). The hyphal network is the main source of AM inoculum in soils and tillage is likely to reduce root colonization as the overall infectivity of the resulting hyphal fragments is reduced (Evans and Miller, 1990; Johnson et al., 2001). The tillage disruption of root channels of previous crops, a source of AM inoculum, also may have contributed to reduced C16:1*cis*11 concentration (Kabir et al., 1999). In the current study, the degree of soil disturbance was in the order MP > chisel > disk > NT, which is somewhat inversely related to C16:1*cis*11 concentration at RMF. Spring tillage may reduce AM colonization less than fall tillage due to the shorter time from spring tillage until establishment of the next crop (McGonigle et al., 1990). In this study, the effect of fall tillage followed by winter may have contributed to reduced mycorrhizal infectivity compared with NT. AM colonization of roots was also less as root P concentration increased (Table 9). High root P concentration is known to impede AM colonization in agricultural soils (Mengue et al., 1978; Olsson et al., 1997; Joner, 2000; Grant et al., 2005). Given limited recovery of the AM hyphal network during the 22 mo following tillage (Quincke, 2006), it appears likely that both mechanisms decreased AM colonization.

Root colonization by AM was also reduced with compost application at RMF at V6 in soybean and sorghum, and at R6 in sorghum, probably due to high soil P availability (Table 6) (Mengue et al., 1978; Lu and Miller 1989; and Liu et al., 2000). The effect of compost application was less at ARDC where initial Bray-P1 was lower compared with RMF, and the increased P availability may not have been sufficient to affect AM colonization.

Phosphorus uptake was generally increased with MP compared with NT, and increased with compost applied at ARDC, despite the decrease in AM colonization (Tables 7 and 8). The effects were more apparent at V6 when P uptake, on average, was 39% more with MP than with NY. Earlier effects on P uptake, however, did not translate to P uptake at R6 when tillage effects were often not significant. The increase in early P uptake contrasts with the findings of McGonigle et al. (1990), who found reduced P uptake with tillage which was attributed to reduced colonization of roots by AM. In the current study, the increased early P uptake with MP compared with NT, despite reduced AM colonization, was likely due partly to improved distribution of P and increased P availability for the 5- to 20-cm depth. The increased early uptake of P with MP tillage could also be due to reduced surface soil density with MP (bulk density = 0.81 g cm^{-3}) compared with no-till (bulk density = 1.2 g cm^{-3}) and less impedance to root extension (Chassot and Richner, 2002; Otani and Ae, 1996). The increased P uptake may result in increased yield in some situations. There may be a loss in productivity where maintaining high levels of AM colonization is important to adequate P uptake, although recovery of AM colonization after tillage may be more rapid in such situations if root P concentration is not much increased.

CONCLUSIONS

Stratification of soil properties develops over several years of NT, with relatively high P and K levels in the surface soil and with increased potential for nutrient runoff. This stratification was enhanced with surface application of compost. Greater redistribution of nutrients, and incorporation of compost P, resulted from one-time MP tillage than from tillage with other implements. Root colonization by AM was, however, reduced by MP tillage and recovery did not occur during the duration of this study. Increased root P concentration following tillage may have contributed to reduced mycorrhizal colonization. Additional research is needed to better understand the factors affecting AM recovery. Since soil test P is related to runoff P concentration, infrequent MP tillage, such as once in 12 or more years, is a potential practice to reduce the risk of P loss to surface waters in cases of very high soil test P in the surface soil of no-till land if the tillage can be done without significantly increasing the risk of erosion. While risk of P runoff can be reduced with one-time MP tillage on NT, the results do not justify such tillage if P runoff is not a concern.

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