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Soil Properties under Nitrogen- vs. Phosphorus-Based Manure and Compost Management of Corn

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Concerns about P enrichment of soil, streams, and lakes, NH_3 emissions from surface-applied manure, and increasing N fertilizer costs have resulted in greater adoption of manure incorporation at rates that approximate P removal. A 5-yr field study was conducted comparing the influence of annual spring applications of N- vs. P-removal-based compost (74 and 46 Mg ha^{-1} wet basis, respectively), liquid dairy manure (196 and 68 kL ha^{-1}, respectively), and sidedress N fertilizer (0 and 112 kg ha^{-1}) on soil pH, soil organic matter (SOM), respiration, NO_3–N, and soil test P (STP) and K (STK) in a corn (*Zea mays* L.) silage cropping system on a calcareous central New York soil. Manure was incorporated with tillage in the P-removal-based system. After 5 yr, soil pH (0–20 cm) remained unchanged compared with its initial level in 2001 regardless of the application rate or source. In P-based manure and inorganic N plots, SOM declined with time but increased by 4 g kg^{-1} with N-based compost. Solvita CO_2 respiration increased only for N-based compost (41 g mg^{-1}), which was greater than for P-based manure (32 g mg^{-1}) in April 2005. After 5 yr, topsoil (0–20 cm) STP and STK were greatest with N-based compost and manure. These results show the benefits of compost application for SOM accumulation and respiration, the benefits of P-based applications for management of STP and STK, and the negative impact on SOM because of tillage incorporation of manure at P-based rates. Manure injection rather than tillage-based incorporation might counteract this negative impact.

Abbreviations: SOC, soil organic carbon; SOM, soil organic matter; STK, soil test potassium, STP, soil test phosphorus.

Core Ideas

- **Annual application of manure to corn at P-removal based rates will reduce P buildup over time.**
- **Lowering manure and compost rates over time will impact SOM.**
- **Tillage-based incorporation of manure at lower rates will aid in N conservation but impact SOM buildup.**

In New York, dairy farming is the largest agricultural industry (National Agricultural Statistics Service, 2009). Manure generated on the dairy farms is typically land applied as liquid or semisolid material. When manure is surface applied at rates to meet the N requirement of a corn crop, the typical result is overfertilization of P and K due to the lower N/P and N/K ratios of manure than plant tissues. Overapplication of P and K increases STP and STK with time (Eghball 1999; Wu and Powell, 2007; Sadeghpour et al., 2016), which may be desirable if initial STP and STK are low but can lead to an increased risk of P runoff (Kleinman et al., 2002) and high-K forages (Cherney et al., 1998) with time.

Some farms separate solids for reuse as bedding or to be composted for sale or application to distant fields. Composting is a useful option to reduce the volume of fresh manure and reduce odor issues (Eghball, 2002). Other advantages of composting are reduced numbers of viable weed seeds and pathogenic microorganisms (Diacono and Montemurro, 2010). A major disadvantage of compost is the loss of C and N during the composting process itself, resulting in N/P and N/K ratios that can be greater than the expected ratios for crop needs than untreated manure (Eghball, 2002).

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The increase in STP with the application of manure or compost at an N-based rate is well documented. For example, Schlegel (1992) reported an increase in Bray-1 STP from an initial value of 13 to 67 mg kg^{-1} with the addition of composted beef cattle feedlot manure at 16.1 Mg ha^{-1} (N-based management) after 3 yr of annual applications. Similarly, greater STP with N-based management systems was reported by Toth et al. (2006) for dairy manure, by Olson et al. (2010) for cattle manure, and by Maguire et al. (2008) for poultry litter, reflecting positive P balances.

An alternative management strategy to reduce the risk of STP and STK buildup with time is to shift from N-based manure management to P-removal-based application rates, with immediate incorporation to capture more N. Such a shift will impact yield if the N needs of the crop are no longer met (Sadeghpour et al., 2016) but can prevent STP buildup with time, as was shown by Eghball and Power (1999).

Similar to STP and STK, soil N changes with the rate of manure application (Gao and Chang, 1996; Eghball, 2002). Gao and Chang (1996) reported that feedlot manure application at 90 Mg ha^{-1} (wet basis) increased total N in the spring at the 0- to 15- and 15- to 30-cm soil depths. Eghball (2002) reported that NO_3–N, sampled in fall after corn harvest, was similar in N-based and P-based treatments with the exception of biennial applications of beef cattle compost, where N-based compost showed 16% higher NO_3–N than P-based rates.

The literature on the effects of fertilizer-, manure-, and compost-based crop management on SOM is inconsistent. Khan et al. (2007) suggested that N fertilizer addition could reduce SOM by accelerating its rate of oxidation or the decay of litter and indigenous organic material. Brown et al. (2014) found improved or no change in soil organic C (SOC) with inorganic N fertilization in grain corn cropping system. They stated that SOC increases if N is a limiting factor for crop growth and that often no change in SOC is observed when N addition does not improve crop yield. Bundy et al. (2011) reported stable or improved SOM in grain corn cropping systems that could be explained by the amount of residue incorporated into the soil. In manure- or compost-based management systems, Lithourgidis et al. (2007) and Jokela et al. (2009) reported no change in SOM after 7 yr (immediate incorporation after application) and 4 yr (surface application) of continuous liquid dairy manure application in a silage corn cropping system, while an increase in SOM was reported in studies by Vitosh et al. (1973) and Eghball (2002).

Soil respiration is a reliable and useful indicator of easily decomposable organic C and an important indicator of soil quality and fertility (Haney et al., 2008; Monaco et al., 2008; Iovieno et al., 2009), and there is generally a positive linear relationship between soil respiration and SOC, with R^2 values ranging from 0.35 to 0.70 (Kaiser et al., 1992; Haney et al., 2012; Miller et al., 2014). Iovieno et al. (2009) reported an increase in SOC with compost application after 3 yr and found that compost application increased soil respiration from 0.68 μg CO_2 g^{-1} dry weight h^{-1} (no compost applied) to 1.18 μg CO_2 g^{-1} dry weight h^{-1} when compost was applied at 45 Mg ha^{-1} yr^{-1}, reflecting the higher available C pool. Similarly, Monaco et al. (2008) reported higher SOC and soil respiration with the addition of slurry manure and composted farmyard manure.

In addition to impacting STP, STK, SOM, and soil respiration, fertilizer, manure, and compost application can influence the soil pH. A decrease in soil pH with the addition of urea or NH_4–containing fertilizers is well documented (Barak et al., 1997; Schroder et al., 2011; Khaliq and Abbasi, 2015). The impact of manure on the soil pH depends on the manure source and soil type. For example, feedlot manure increased pH in a study with alkaline soils by Smith et al. (1980), while also increasing the pH of acid soils (Whalen et al. 2000). In contrast, a study with alkaline soils by Chang et al. (1991) showed a decrease in soil pH with feedlot manure addition, possibly due to nitrification of NH_3 and the production of organic acids during the decomposition of the organic fraction of the cattle manure. The rate of application can impact the change in pH. For example, a study by Eghball (1999) indicated an increase in soil pH when shifting from N- to P-based manure and compost management. He reported that beef cattle manure contained $CaCO_3$ that increased soil pH levels.

Changes in soil properties by shifting from N-based to P-based management can influence a farmer's decisions on field and management practices such as the distribution of manure across farm fields and possibly manure export, the use of lime products to increase soil pH, the use of a cover crop, and implementation of conservation tillage instead of more aggressive tillage operation to increase or maintain SOM. To aid farmers in making these decisions, the effects of a shift from N- to P-based manure and compost management or fertilizer-based management, reflecting a change in application rate and possibly a shift in application method (incorporation in P-based systems to conserve N) needs to be quantified.

The objectives of this study were to evaluate the influence of a change from N-based applications of manure and compost (without incorporation) to P-removal-based management of manure (immediate tillage incorporation) and composted separated dairy solids on soil pH, SOM, and soil C respiration in the top 20 cm of the soil. The effect of N- vs. P-removal-based manure and compost management was also assessed on soil pH, SOM, Morgan-extractable soil NO_3–N, STP, and STK throughout the soil depth (0–50 cm).

MATERIALS AND METHODS

Experimental Site

In 2001, a field experiment was initiated in Aurora, NY (42.73° N, 76.65° W, 253 m asl). The experimental area was under continuous corn production and had no manure history prior to this study. The soil type was a Lima silt loam (a fine-loamy, mixed, active, mesic Oxyaquic Hapludalf). The soil (0–20-cm depth) had an initial pH of 7.5, SOM content of 35 g kg^{-1}, and Morgan-extractable NO_3–N, STP, and STK contents of 5.2, 5.1, and 47 mg kg^{-1}, respectively. The soil was classified as high in P (Ketterings et al., 2003a) and medium in K (Ketterings et al., 2003c).

Mean air temperatures during the corn growth period from May through October in 2001 (17.5°C), 2002 (17.1°C), 2003 (17.0°C), 2004 (17.2°C), and 2005 (18.5°C) were close to the 30-yr average (17.3°C) for Aurora, NY. Cumulative growing season precipitation was 430, 506, 573, 652, and 599 mm in 2001 through 2005, respectively. There was a severe drought during July (21 mm) and August (39 mm) in 2002 and July (52 mm) in 2005. These drought periods impacted crop yields (Sadeghpour et al., 2016).

Compost and Manure Sampling

Two different dairy farms provided the compost during the experiment. For the compost applied during the first 2 yr, separated dairy manure solids were stacked outdoors on a soil pad in windrows and turned infrequently from April through November, with finished compost in nine to 12 mo. In the latter 3 yr of the study, dairy compost was supplied by a farm that stacks separated manure solids indoors for 3 wk at 65°C before moving the material outdoors for aerated pile composting, with turning once a week for 3 to 4 mo. Liquid dairy manure was collected each year from agitated manure storage lagoons. Manure used in this study was, for 3 out of the 5 yr, processed by a screw-press separator, resulting in significant fiber removal before placement in liquid storage. Subsamples of all sources were collected before land application, kept cool at the time of collection, and frozen until laboratory analysis.

Compost and Manure Analysis and Characteristics

Total N was analyzed using the Kjeldahl procedure with NH_3–N determination by distillation (AOAC, 2000). Organic N was calculated by subtracting NH_3–N from the total N. The Morgan extraction was used to determine available NO_3–N, P, and K (Morgan, 1941) according to standard procedures of Cornell University. Both separated dairy solids and liquid dairy manure samples were analyzed for total P and K content by inductively coupled plasma spectrometry (Thermo IRIS Advantage DX inductively coupled plasma radial spectrometer, Thermo Electron Corp.) (Sirois et al., 1994). Total solids were determined gravimetrically (oven at 100°C for 16 h) (Hoskins et al. 2003), and density was determined using a 51.5-mL standard vial (Dairy One, 2007).

Manure and compost compositions in 2001 were used to calculate the application rates for the initial design of the experiment. However, application rates changed from year to year based on variability in the manure and compost composition (Table 1) and equipment availability, as presented by Sadeghpour et al. (2016).

Experimental Design and Treatments

The experimental design was a randomized complete block design with six fertility treatments and five replicates. The study was initiated in 2001, and samples were taken from April 2001 until April 2006. The six treatments were: (i) P-based application (wet basis) of composted dairy solids (46 Mg ha^{-1} averaged across 5 yr); (ii) N-based application (wet basis) of composted dairy solids (74 Mg ha^{-1} averaged across 5 yr); (iii) P-based addition of liquid dairy manure with immediate (<1 h) tillage incorporation (68 kL ha^{-1} averaged across 5 yr); (iv) N-based liquid dairy manure application (196 kL ha^{-1} averaged across 5 yr); (v) a zero-N control (0 kg N ha^{-1}); and (vi) sidedress inorganic N (urea–NH_4NO_3) at the rate of 112 kg N ha^{-1}, which is the recommended sidedress N application rate for the site as derived from Ketterings et al. (2003b). At the time of planting, all treatments received 22 kg N ha^{-1} (28 kg ha^{-1} in 2003), 10 kg P ha^{-1} (12 kg ha^{-1} in 2003), and 18 kg K ha^{-1} (23 kg ha^{-1} in 2003 to all treatments and 109 kg ha^{-1} in 2005 to inorganic N treatments) in the starter band 5 cm below and 5 cm to the side of the seed furrow. Excluding the starter fertilizer, no inorganic N fertilizer was applied to the organic fertility treatments.

Table 1. Application rates and characteristics of liquid dairy manure and composted solids from 2001 to 2005 (nutrient measurements on a dry-weight basis).

Year	Application rate									
	N-based	P-based	Total N	NH_3–N	Organic N	P	K	Total solids	Total N/P	Total N/K
	kL ha^{-1}		g kg^{-1}							
					Liquid dairy manure					
2001	187	66	3.8	2.0	1.8	0.6	2.3	84.9	6.3	1.7
2002	160	66	3.3	1.8	1.6	0.4	2.2	51.8	8.3	1.5
2003	207	61	3.3	1.6	1.7	0.5	2.0	99.1	6.6	1.7
2004	174	74	3.7	1.7	2.0	0.4	1.8	93.8	9.3	2.1
2005	254	72	2.8	1.4	1.4	0.4	1.8	89.6	7.0	1.6
Avg.	196	68	3.4	1.7	1.7	0.5	2.0	83.8	7.5	1.7
					Composted dairy solids					
	Mg ha^{-1}									
2001	78	46	6.1	<0.1	6.1	0.9	2.8	398.7	6.8	2.2
2002	73	46	5.3	0.2	5.1	1.0	2.1	333.4	5.3	2.5
2003	74	45	6.4	0.1	6.3	0.9	3.5	240.9	7.1	1.8
2004	80	45	6.3	0.1	6.2	1.2	3.7	236.0	5.3	1.7
2005	65	48	5.3	0.5	4.8	0.9	3.8	275.0	5.9	1.4
Avg.	74	46	5.9	0.2	5.7	1.0	3.2	296.8	6.1	1.9

Rates of compost and manure application were determined (i) to meet corn N needs in the 3rd yr of application, assuming buildup of the organic N supply in Years 1 and 2, or (ii) to meet the estimated P removal of corn based on projected yield (yield potential). A corn silage yield potential of 18 Mg dry matter ha^{-1} was predicted for Lima silt loam (Ketterings et al., 2003b). Corn P removal was estimated at 95 kg P_2O_5 ha^{-1} based on 2.3 g P kg^{-1} dry matter. Therefore, P-based treatments were designed to supply 73 kg P_2O_5 ha^{-1} with manure or compost plus 22 kg P_2O_5 ha^{-1} applied as starter P fertilizer at planting. Based on these calculations, the initial application rates, in 2001, were 45 Mg ha^{-1} (wet basis) for P-based compost and 63.5 kL ha^{-1} for P-based manure. The corn N requirement was estimated at 125 to 145 kg N ha^{-1} (Ketterings et al., 2003b). Excluding the 22 kg N ha^{-1} application as starter, N-based treatments were designed to supply 113 kg N ha^{-1}. The N-based compost was applied at 77 Mg ha^{-1} (wet basis) and N-based manure was applied at 180 kL ha^{-1}, assuming that 25 and 35% of the organic N was available for corn N uptake in the application year for compost and manure, respectively (Ketterings et al. 2003b). Standard book values were used to estimate the availability of N, which were 12 and 5% in both compost and manure in the second and the third years after application, and N availability for P-based manure was estimated at 65% to credit conservation of NH_3–N due to direct incorporation with a chisel plow, as documented by Ketterings et al. (2003b). The amount of inorganic N in the compost was so small that incorporation would not conserve additional N and thus only the P-based manure treatments were immediately (<1 h) incorporated; NH_3–N was assumed to be lost in P-based compost similar to N-based manure and compost.

Briefly, the 5-yr cumulative P additions and P balance were, respectively, 416 and 279 kg P ha^{-1} for N-based compost, 275 and 155 kg P ha^{-1} for P-based compost, 501 and 367 kg P ha^{-1} for N-based manure, 208 and 85 kg P ha^{-1} for P-based manure, 52 and −54 kg P ha^{-1} for the 0N control, and 52 and −59 kg P ha^{-1} for the optimum N rate (112 kg N ha^{-1}). The positive balances for the P-based systems were primarily due to weather-impacted lower than expected yields in several years (Sadeghpour et al., 2016). Further details about nutrient additions and removals were reported by Sadeghpour et al. (2016).

Cultural Management Practices and Yield

Experimental plots were 54 m long and 12 m wide for organic fertility treatments and 54 m long and 6 m wide for inorganic treatments to accommodate farm-scale application equipment. Composted dairy solids were applied with a New Idea 1.66-m^3 flail-spreader (Agco Inc.), and a Husky spreader (Husky Farm Equipment) was used to apply liquid dairy manure. To conserve inorganic N in the manure, P-based manure plots were incorporated to a 20-cm depth with a chisel plow directly (<1 h) following application. The other treatments were mixed with soil during seedbed preparation, which included one-time disking and then rolling with a cultimulcher at least 1 wk after application, allowing N volatilization where manure and compost were surface applied at N-based rates. A John blue (four-row) sidedress unit with an LM-2450 metering pump (The Pump Co.) was used to apply the optimum N rate (112 kg N ha^{-1}) in mid-June to the designated inorganic N plots.

The plots were under continuous corn production during the course of the study. Corn was planted with a John Deere 7000 Max Emerge planter at rates ranging from 79,000 in 2001 to 101,730 seeds ha^{-1} in 2002 (averaging almost 90,000 seeds ha^{-1} during the 5-yr period) and a row spacing of 76 cm. No irrigation was applied in this experiment because that is not a common practice in New York due to typically adequate rainfall during the growing season. Corn silage harvest was typically initiated when the whole-plant moisture content was between 600 and 700 mg kg^{-1}, ranging from 5 Sept. 2005 to 21 Sept. 2004. Silage yield was determined using a Mex-Profi two-row forage harvester Type MH 444 (Pottinger). Further information on corn silage harvest was reported by Sadeghpour et al. (2016).

Corn silage yield data indicated that shifting from N- to P-based manure and compost management reduced corn silage yields by 7 to 13% and protein concentrations by 8 to 9%. Yield, crude protein, and soil NO_3–N levels suggest that N might have been a limiting factor in the P-based manure and both compost treatments, reflecting less than anticipated N availability based on our N crediting systems current in place in New York (Sadeghpour et al., 2016).

Soil Sampling and Analysis

Soil samples (15 cores in each plot) for soil pH and SOM (0–20-cm depth) were collected before planting, at planting, at sidedressing, and at harvest. Soil samples for soil NO_3–N (0–20-cm depth) were taken in September, November, and April each year from April 2001 to April 2006. Soil samples were analyzed for soil pH, organic matter, and Morgan-extractable soil NO_3–N, P, and K (Morgan, 1941). In addition, soil profile samples (0–5-, 5–20-, 20–30-, 30–40-, and 40–50-cm depths) were taken in April 2004 and 2005, prior to manure and compost application, using a deep core sampler (Giddings Machine Company Inc.). Soil sampling beyond the 50-cm soil profile was not achievable due to subsoil stoniness. These samples were also analyzed for soil pH, SOM, and NO_3–N, P, and K to determine profile differences as affected by the fertility treatments. Soil samples were kept cool while sampling in the field, oven dried (<50°C) for at least 48 h on arrival at the laboratory, and crushed to pass 2 mm before analysis following standard soil preparation procedures at Cornell University (Greweling and Peech, 1965). Soil pH was determined with a 1:1 w/v water extract, and the Morgan extraction was used for NO_3–N, P, and K analysis (Morgan, 1941). Nitrate and P were determined with colorimetric determination (Murphy and Riley, 1962) using a Technicon Autoanalyzer I (Pulse Instrumentation Ltd.), and K was analyzed by inductively coupled plasma atomic emission spectroscopy using a JY70 Type II inductively coupled plasma atomic emission spectrometer (Jobin Yvon). Soil organic matter was determined by loss-on-ignition following exposure to 500°C for 2 h (Storer, 1984). Samples collected in spring 2001

(Year 1) and 2005 (Year 4) were analyzed for soil CO_2 respiration using the Solvita test (Haney et al., 2008). Forty-grams samples of wetted soil were placed in 236-cm^3 jars with a Solvita gel paddle (pH sensitive). At the end of 24 h, each paddle was placed in a digital color reader for analysis.

Statistical Analysis

Initial soil pH, SOM, Solvita CO_2 respiration, and NO_3–N (0–20 cm) varied from plot to plot at the start of the experiment in 2001. Thus, we normalized soil pH, SOM, Solvita CO_2 respiration, and NO_3–N levels of each of the plots at each sampling date and year in reference to the first initial value of the first year, as was done by Klapwyk et al. (2006) and Sadeghpour et al. (2016). First, the average of the initial values of each parameter was determined, and the values of each plot were added or subtracted to reach a similar initial value for all the plots. This was done for all sampling dates.

Data were analyzed using PROC Mixed (Littell et al. 1996; SAS Institute, 2009). Soil organic matter, pH, and NO_3–N were analyzed using a mixed model. The experiment was set up in five blocks, and every plot was repeatedly measured over the years but also repeatedly measured over sampling dates within a year. Thus, block and treatment nested within block (indicating plots) were entered in the model as random effects. In addition, an autoregressive covariance structure was specified for the plots being repeatedly measured over the sampling dates within a year. The fixed effects in the model were year, treatment, sampling date, and all the interactions. For soil pH, because the three-way interaction of year, sampling date, and treatment and a two-way interaction of sampling date and treatment were not significant, we analyzed the data by year, and the results are presented to show differences among treatments in April 2006. For SOM, because of a non-significant three-way interaction of year, sampling date, and treatment, we excluded the three-way interaction from the model. Sampling dates for soil NO_3–N were September, December, and November. A similar statistical approach was used to assess the influence of each fertility source (liquid dairy manure, composted dairy solids, and inorganic N) on soil pH, SOM, and NO_3–N with time. The only difference was that there were three treatments (average of rates for each source) instead of six.

Initial analyses indicated no year × sampling depth × fertility treatment interaction, so the data were analyzed across the 2 yr in which depth sampling was done (2004 and 2005). Analyses were done per depth to evaluate the impact of the fertility treatments on pH, SOM, and nutrients across depths. For Solvita CO_2 respiration analysis, block and treatment nested within block (indicating plots) were entered in the model as random effects. In addition, an autoregressive covariance structure was specified for the plots being repeatedly measured over years. The fixed effects in the model were year, treatment, and their interactions. To evaluate the differences among sources, Solvita CO_2 respiration data (in 2005) were analyzed with treatments (compost, manure, and inorganic N) as fixed effects and block as a random effect.

Least square means were separated using the PDIFF option of LSMEANS in SAS PROC Mixed; least significant differences values are reported at $P \leq 0.05$. We used PROC REG to determine the relationship between SOM and Solvita CO_2 respiration rates as well as soil NO_3–N levels.

RESULTS AND DISCUSSION

Soil pH

After 5 yr, the soil pH (0–20 cm) was greater in N-based manure plots (pH = 7.94) than in plots that had received 112 kg N ha^{-1} (pH = 7.28) (Table 2; Fig. 1A). The difference was due to a tendency of soil pH to increase when manure was applied and decrease when N fertilizer was applied. An increase in soil pH with manure addition is consistent with data presented by Smith et al. (1980), Whalen et al. (2000), and Eghball (1999), who concluded that the increase in soil pH was due to buffering from bicarbonate and organic acids in the cattle manure. The decline in pH (0–20 cm) with N fertilizer addition is consistent with microbial oxidation of NH_3 in the nitrification process when urea or NH_4–containing fertilizer is applied (Jia and Conrad, 2009). However, no differences were found in soil pH between the organic fertility treatments and zero-N control in April 2006, and overall changes were small, most likely reflecting the calcareous nature of the soil in our study. In a soil with neutral pH, a decrease in soil pH with repeated optimum N rate (112 kg N ha^{-1}) addition with time results in a greater need for lime products and hence an increase in the cost of production. Soil pH increased with depth, independent of treatments, also reflecting the calcareous soil parent material in our study (data not shown).

Soil Organic Matter and Solvita Carbon Dioxide Respiration

Soil organic matter (0–20-cm depth) was influenced by fertility treatments and sampling date (year-to-year variability and within-year treatment variability) (Table 2). Soil organic matter increased by 4 g kg^{-1} with 5 yr of N-based compost management vs. no increase with P-based compost (Fig. 1B). Thus, a shift from N-based to P-based compost application can eliminate the

Table 2. Analysis of variance (ANOVA) for soil organic matter (SOM), soil pH and soil NO_3–N in the top 20 cm of soil and for SOM, soil test P (STP), and soil test K (STK) in the top 50 cm of soil.

Source of variation	*P > F*					
	0–20 cm			0–50 cm		
	SOM	Soil pH	NO_3-N	SOM	STP	STK
Year (Y)	***	***	***	ns	ns	ns
Date/depth (D)	***	***	***	***	***	***
Fertility (F)	***	***	***	ns	*	***
Y × D	***	***	***	ns	ns	***
Y × F	***	***	***	ns	ns	ns
D × F	***	ns	***	*	***	***
Y × D × F	ns	ns	***	ns	ns	ns

* Significant at $P \leq 0.05$; ns, not significant.

*** Significant at $P \leq 0.001$.

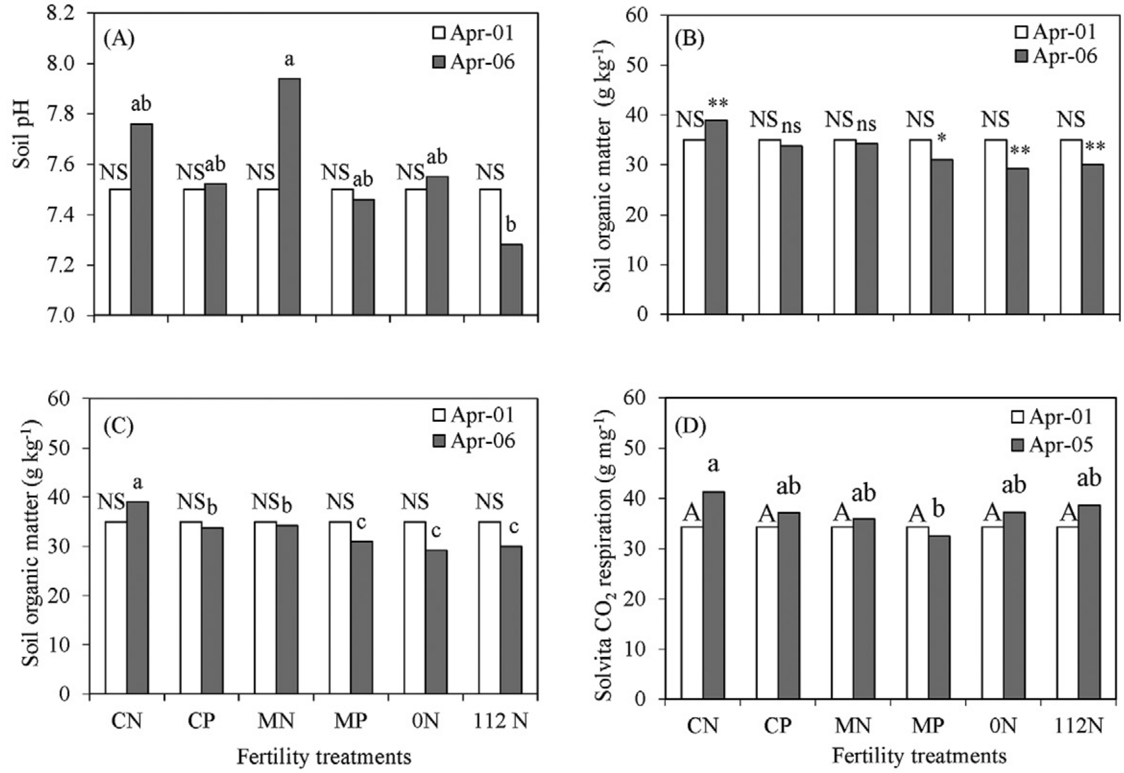

Fig. 1. (A) Soil pH, (B,C) soil organic matter, and (D) Solvita CO_2 respiration at the 0- to 20-cm depth in April 2001 and after 5 yr of corn silage production with annual spring application of composted separated dairy solids, liquid dairy manure, or inorganic N fertilizer (April 2006) in central New York. Specific treatments include: N-based composted dairy solids (CN, 74 Mg ha^{-1}); P-removal-based composted dairy solids (CP, 46 Mg ha^{-1}); N-based liquid dairy manure without incorporation (MN, 196 kL ha^{-1}); P-removal-based liquid dairy manure with incorporation of manure directly following application (MP, 68 kL ha^{-1}); starter N application only (N0); and 112 kg N ha^{-1} sidedressed N (N112). In (A), (C), and (D), means for fertility treatments within each year that are followed by different letters are significantly different ($P \leq 0.05$). Figure (B) is comparing soil organic matter in April 2006 with soil organic matter in April 2001 for each fertility treatment. **Significant at $P \leq 0.01$. *Significant at $P \leq 0.05$. NS, not significant.

benefits of the compost for SOM accumulation. Nitrogen-based manure retained SOM levels (Fig. 1B), while P-based manure with tillage incorporation of the manure resulted in an 11% loss of SOM compared with initial levels (35 g kg^{-1} in April 2001). This decline in SOM in P-based manure compared with its initial value might be a direct effect of the more aggressive tillage operation (chisel plow incorporation of the manure). In comparison, the zero-N control and the sidedress N treatments resulted in an 18% decline in SOM compared with the initial levels in April 2001, reflecting the lack of crop residue return to the soil in corn silage cropping systems. These results indicated that to maintain or improve SOM, farmers need to adopt management practices such as cover crops to compensate for the use of tillage in the P-based management system or change their manure application method from surface application to injection.

Soil organic matter in April 2006 was greater in the N-based compost than the other fertility treatments (Fig. 1C). No differences were found between SOM in P-based compost and N-based manure (Fig. 1C); both inorganic N management and P-based manure had less SOM than compost and N-based manure plots (Fig. 1C), possibly reflecting the lower application rates and negative impact of soil tillage on SOM compared with compost plots (averaged across N- and P-based treatments). The SOM content of the topsoil (0–5 cm) was 25 and 35% less where manure (averaged across N- and P-based treatments) and sidedress N, respectively, had been the fertility treatments. This trend reflected primarily the increase in SOM with the addition of N-based compost and the decline in SOM with P-based manure applications. Soil organic matter remained unchanged in soil layers beyond the 5-cm depth, reflecting the lack of soil inversion due to the conservation tillage practices used in the study. The lack of differences between treatments at depths beyond 5 cm suggests that the influence of fertility treatments on SOM throughout a 50-cm soil profile was not significant, emphasizing the importance of sampling beyond tillage incorporation for assessing SOM changes with time (Gál et al., 2007). The greater C sequestration with composted (35%) than with non-composted (25%) manure in the study of Eghball (2002) for a silty clay-loam soil in Nebraska is consistent with our findings for the N-based compost plots under cool, humid conditions in New York but suggest that a minimum compost application rate might be needed to impact SOM. Our findings for the P-based manure applications seem inconsistent with the findings of Lithourgidis et al. (2007) and Jokela et al. (2009), who showed no change in SOM after 7 yr (immediate incorporation after application) and 4 yr (surface application) of continuous liquid dairy manure application in a silage corn cropping system. However, their findings were in agreement with our results suggesting that N-based manure maintains SOM. Bundy et al. (2011) reported stable or improved SOM with continuous inorganic N fertilization in a corn cropping system, but perhaps harvesting corn for grain in the study by Bundy et al. (2011) vs. harvesting for silage (the current study) influenced the amount of corn residue incorporated into the soil, leading to the apparent inconsistencies.

In 2005, Solvita CO_2 respiration in N-based compost (41 g mg^{-1}) was greater than for P-based manure (32 g mg^{-1}) (Fig. 1D). Compost application (averaged across N-based and P-based treatments) elevated soil respiration to 39 mg C kg^{-1} compared with respiration measured for the manured plots, which averaged 34 mg C kg^{-1} (data not shown), consistent with the greater SOM in the N-based compost plots. These findings are in agreement with those of Iovieno et al. (2009), who indicated that a repeated application of waste compost at high rates improved SOC and soil microbial activity. They suggested that the increased soil respiration of compost-treated soils could be due to microbial growth, stimulation of microbial activity as a result of improved resource availability (increased soil C), and changes in the microbial community composition. Our results seem to disagree with the findings of Monaco et al. (2008), who showed similar soil respiration between composted farmyard manure and cattle slurry manure in the 0- to 15-cm layer of the soil, suggesting that additional studies with varying manure sources and soil types are needed.

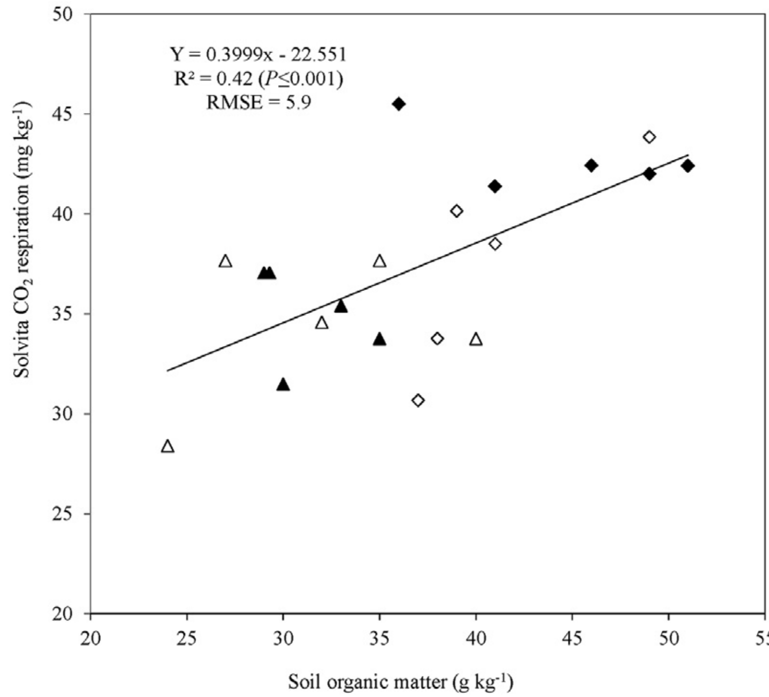

Fig 2. A simple regression between soil organic matter (0–20-cm depth) and Solvita CO_2 respiration rate measured in April 2005 as influenced by 4 yr of compost or manure addition: ◆, N-based composted dairy solids (74 Mg ha^{-1}); ◊, P-removal-based composted dairy solids (46 Mg ha^{-1}); ▲, N-based liquid dairy manure without incorporation (196 kL ha^{-1}); △, P-removal-based liquid dairy manure with incorporation of manure directly following application (68 kL ha^{-1}).

Soil organic matter and the Solvita CO_2 respiration rate were positively related ($R^2 = 0.42$; $P \leq 0.001$; RMSE = 5.9) (Fig. 2). Similarly, a positive linear relationship between soil respiration and SOC was reported by Kaiser et al. (1992), Haney et al. (2012), and Miller et al. (2014), with R^2 values ranging from 0.35 to 0.70. Haney et al. (2012) reported a stronger relationship ($R^2 = 0.84$) between soil respiration and water-extractable SOC than SOC. These relationships indicate that the rate of CO_2 respiration increases with an increase in SOM, but the large variability in the data set in our study also suggests that the Solvita test assesses active soil organic material and plant residues in addition to stable SOM, reflecting a greater emphasis on SOM pools that cycle nutrients and impact soil fertility decisions.

End-of-Season Soil Nitrate

Soil NO_3–N levels at silage harvest time in September increased by 66, 53, 35, and 46% from 2001 to 2005 with N-based compost, P-based compost, N-based manure, and P-based manure applications, respectively (Fig. 3A and 3B). Excluding the data from manure treatments (N-based and P-based) during the

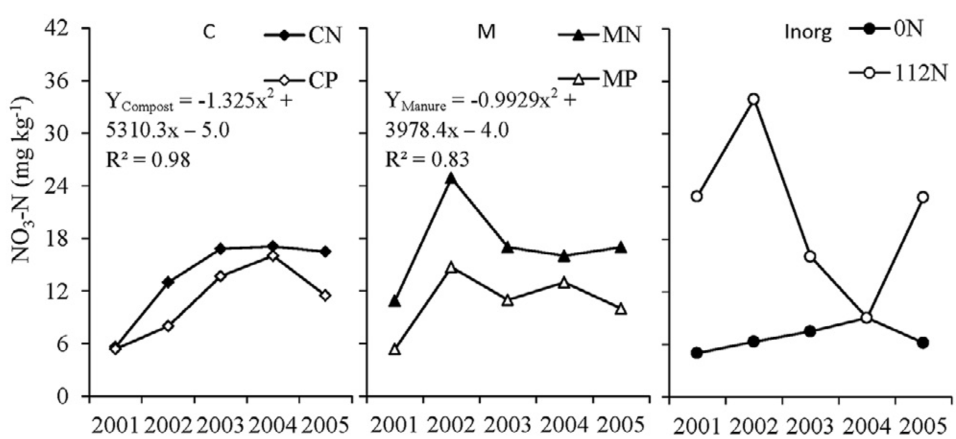

Fig. 3. Trends in soil NO_3–N (0–20-cm depth) at silage harvesting time as influenced by spring application of (A) composted dairy solids at N-based (CN, 74 Mg ha^{-1}) or P-based (CP, 46 Mg ha^{-1}) rates, (B) liquid dairy manure at N-based (MN, 196 kL ha^{-1}) or P-based (MP, 68 kL ha^{-1}, immediately incorporated) rates, and (C) starter N application only, no N sidedress application (N0) or starter N plus 112 kg ha^{-1} inorganic N sidedress application (112N).

2002 growing season (severe drought), soil NO_3–N levels at silage harvest showed a quadratic increase with time ($R^2 = 0.91$; $P \leq 0.001$) (Fig. 3A and 3B), consistent with a 3-yr crediting of organic N in the manure and compost (Klausner, 1997; Ketterings et al., 2003b). Nitrate levels in the zero-N control remained low throughout the study (Fig. 3C). Nitrate levels in the 112 kg N ha^{-1} treatment reflected seasonal (weather) differences, with exceptionally high soil NO_3–N at harvest (September) in 2002, a severe drought year, and the lowest values in 2004, a high-yielding year with elevated rainfall in July and August (280 mm) (Fig. 3C).

Soil NO_3–N levels in the top 0- to 20 cm of soil at harvest (September) and in December just before snowfall were impacted by fertility treatments and varied from year to year (Fig. 4). In December (end of season), the highest soil NO_3–N levels were measured in N- and P-based treatments (both manure and compost), followed by the inorganic N plots (both the zero-N control and 112 kg N ha^{-1}) (Fig. 4). End-of-season soil NO_3–N levels in December did not change with a shift from N- to P-based manure management, with soil NO_3–N levels ranging from 13.6 to 17.3 mg kg^{-1} (Fig. 4). Shifting from N- to P-based compost resulted in 25% lower soil NO_3–N levels in P-based compost than N-based compost in 2005, while no differences in end-of-season soil NO_3–N levels were detected between N-based and P-based compost in 2003 and 2004. Soil NO_3–N in December was always lower in the inorganic N fertilizer treatments than the organic-amended plots except for 2005. Soil NO_3–N ranged from 5.8 mg kg^{-1} in the zero-N control in 2004 to 13.5 mg kg^{-1} at the optimum N rate in 2005.

Averaged across three growing seasons, a 38% loss occurred during September to December where corn had been sidedressed with 112 kg ha^{-1} N vs. an 8% increase in compost-amended plots (both N and P based). A 10% reduction in soil NO_3–N levels between September and December in N-based manure plots indicated greater loss of soil NO_3–N than mineralization in the same time period, whereas soil NO_3–N levels were 21% greater in P-based manure plots in December than September. These results suggest that soil mineralization took place between September and December where manure or compost had been used as the fertility source,

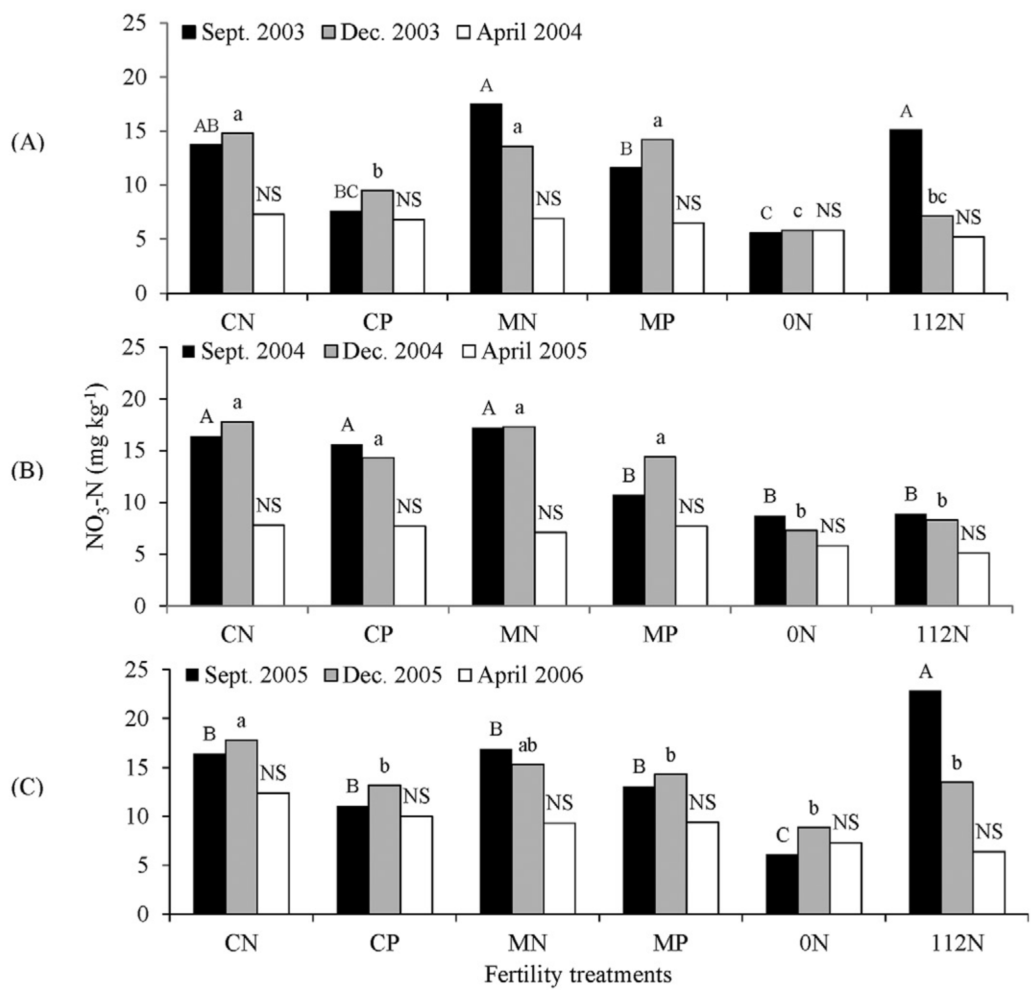

Fig. 4. Soil NO_3–N levels at the 0- to 20-cm depth as influenced by fertility treatments from (A) September 2003 to April 2004, (B) September 2004 to April 2005; and (C) September 2005 to April 2006. Treatments included composted dairy solids at N-based (CN, 74 Mg ha^{-1}) or P-based (CP, 46 Mg ha^{-1}) rates, liquid dairy manure at N-based (MN, 196 kL ha^{-1}) or P-based (MP, 68 kL ha^{-1}, immediately incorporated) rates, and (C) starter N application only, no sidedress N (N0) or starter N plus 112 kg ha^{-1} inorganic N sidedress application (112N). Means for fertility treatments within each year that are followed by different letters are significantly different ($P \leq 0.05$). Uppercase letters compare mean values in September in each year and lowercase letters compare mean values in December within each year. Within each year, there were no significant differences between treatments in April, as shown by NS.

while the decrease in soil NO_3–N with inorganic N management reflected some combination of leaching and denitrification (Fig. 4).

Nitrate levels in April were similar among all treatments (Fig. 4) for each of the years, reflecting weather patterns common for the region (fall showers and spring snowmelt). These findings emphasize the importance of planting cover crop species with the ability to grow rapidly in the fall and to overwinter both for fields that are managed with compost or manure as well as for those fertilized with inorganic fertilizer (Ketterings et al., 2015). As most of the end-of-season N in the sidedressed plots was lost between September and December, rapid fall N uptake is important to reduce N leaching losses.

For the manure- and compost-amended fields, N concentrations increased in the fall, indicating that (i) mineralization exceeded N loss, and (ii) a significant portion of the mineralized N was lost between December and April. The data of this study confirm the importance of the inclusion of overwintering cover crops in corn silage rotations when manure is applied on soils with a high potential for leaching of NO_3–N (Ketterings et al., 2003b). Soil NO_3–N with depth in April of 2004 and 2005 confirmed that NO_3–N lost from the topsoil (0–20-cm depth) layer between September and April was leached beyond the 50-cm depth, with NO_3–N levels <2 mg kg^{-1} at depths beyond 20 cm in both organic and inorganic treatments (data not shown).

Soil Phosphorus and Potassium with Depth

In the top 5 cm, the highest STP levels were measured when compost had been applied for 5 yr at the N-based rate (43.5 mg kg^{-1}) followed by N-based manure plots (29.2 mg kg^{-1}), P-based manure (23.5 mg kg^{-1}) and compost plots (23.0 mg kg^{-1}), and plots that had been fertilized with inorganic sidedressed N (8.3 mg kg^{-1}) (Fig. 5A). The impact of manure and compost on STP depends on the manure composition and soil type (Pagliari and Leboski, 2013). In our study, the higher total solids/P ratio in the composted dairy solids (297) than the manure (167) and the presence of a greater amount of orthophosphate in the manure than the compost probably contributed to a higher STP in the N-based composted dairy solids treatment in 2006 than for the rest of the treatments, including N-based liquid dairy manure (Table 1). After 5 yr of compost application, Morgan-extractable STP in the N-based compost plots was 44 mg kg^{-1}, above the level of 40 mg kg^{-1} at which the New York P index exceeds 100 if the transport risk from the field is high, and slightly less than 10 times the agronomic critical level (Ketterings and Czymmek, 2012). Thus, to reduce the risk of P runoff, STP should be monitored to ensure that levels do not exceed application cutoffs when compost is applied at rates to meet the N needs of crops. A lower STP in the sidedressed N treatment reflected the removal of P by corn harvest (Fig. 5A).

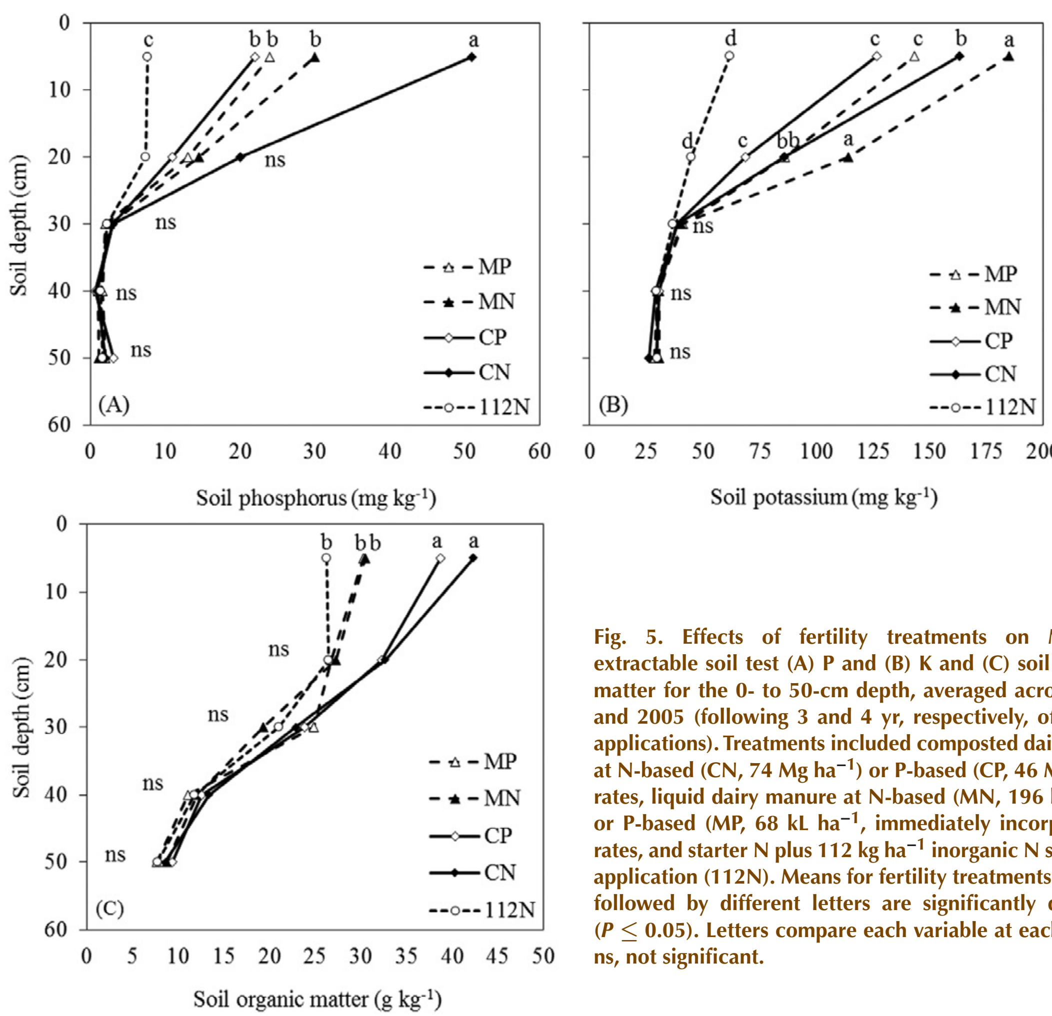

Fig. 5. Effects of fertility treatments on Morgan-extractable soil test (A) P and (B) K and (C) soil organic matter for the 0- to 50-cm depth, averaged across 2004 and 2005 (following 3 and 4 yr, respectively, of annual applications). Treatments included composted dairy solids at N-based (CN, 74 Mg ha^{-1}) or P-based (CP, 46 Mg ha^{-1}) rates, liquid dairy manure at N-based (MN, 196 kL ha^{-1}) or P-based (MP, 68 kL ha^{-1}, immediately incorporated) rates, and starter N plus 112 kg ha^{-1} inorganic N sidedress application (112N). Means for fertility treatments that are followed by different letters are significantly different ($P \leq 0.05$). Letters compare each variable at each depth; ns, not significant.

Soil test P in N-based treatments (0–20-cm depth) exceeded the critical P level (20 mg kg^{-1} Morgan P) beyond which no additional P is recommended for crop growth in New York (Ketterings et al., 2003b). Sadeghpour et al. (2016) reported that the surplus application of P via N-based management (liquid dairy manure and composted solids) beyond crop needs resulted in positive P balances and hence P buildup in the soil over 5 yr. In the 0- to 20-cm depth, shifting from N- to P-based compost and manure resulted in 38 and 7% less P accumulation in the soil, respectively (Fig. 5A), but P buildup in the P-based manure treatment still occurred, reflecting a positive P balance due to less than anticipated yields (Sadeghpour et al., 2016). Soil test P levels decreased with depth beyond 5 cm, independent of treatment, reflecting the application of manure and compost to the topsoil layer and crop P removal from deeper subsoil layers (Yang et al., 2007).

Soil test K was influenced by fertility treatments at different soil depths. In the surface soil (0–5 cm), the STK values were lowest in the inorganic sidedressed N treatment (62 mg kg^{-1}), medium in P-based compost and manure, and highest in N-based manure (185 mg kg^{-1}) and N-based compost plots (163 mg kg^{-1}) (Fig. 5B). A shift from N- to P-based manure resulted in 22 and 24% less STK accumulation in the 0- to 5- and 5- to 20-cm depths, respectively. For compost, the reductions in STK due to shifting from N- to P-based compost were 22% in the top 5 cm and 19% in the 5- to 20-cm layer (Fig. 5B). Soil test K of the plow layer (0–20 cm) was 14% less under P-based compost and 19% less under P-based manure management (Fig. 5B). Soil test K in all organic treatments, excluding P-based compost, exceeded the critical level for corn (83 mg kg^{-1} Morgan K) in New York (Ketterings et al., 2003c). No effects of fertility treatments on STK levels beyond the 30-cm depth in the soil profile were detected.

In summary, (i) after 5 yr, soil pH (0–20 cm) was greater in N-based manure plots (pH = 7.94) than in plots that had received 112 kg N ha^{-1} (pH = 7.28); (ii) 5 yr of annual addition of N-based compost increased SOM by 4 g kg^{-1}, SOM was maintained in P-based compost and N-based manure, while a shift from N- to P-based manure resulted in 11% less SOM than at the start of the experiment, possibly reflecting the tillage operation (chisel plow incorporation of manure) in the P-based manure treatment; (iii) Solvita CO_2 respiration was highest in the N-based compost treatment, consistent with higher SOM levels; (iv) organic treatments resulted in N mineralization from silage harvest (September) to the end of the season (December), while N leaching in inorganic N plots reduced NO_3–N levels in the fall, indicating the importance of planting cover crop species that grow rapidly in the fall and overwinter, thus capturing the available N during September to December and April; and (v) shifting from N- to P-based compost resulted in 38 and 14% lower STP and STK, respectively, in the topsoil (0–20 cm), while P-based manure application reduced topsoil STP and STK by 7 and 19%, respectively, compared with N-based manure management.

CONCLUSION

We concluded that shifting from N- to P-based manure and compost management decreases end-of-season NO_3–N and slows STP and STK buildup in the soil but, when combined with tillage incorporation of the manure, negatively impacts SOM and soil respiration. Manure injection rather than tillage-based incorporation might counteract the negative impacts of a tillage-based manure incorporation system while conserving N and reducing STP and STK buildup with time. Inclusion of overwintering cover crops when manure and compost are applied will aid in capturing N mineralized in the fall, and this could also help with N supply in the spring, as earlier work has shown somewhat suppressed yields with P-based application of manure and compost due to an N limitation.

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