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Alternative Fertility Management for Establishing New Apple Orchards in the Mid-Atlantic

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Abstract. **In the Mid-Atlantic, mineral nitrogen (N) fertilizers are applied in high-density apple (*Malus* ×*domestica* Borkh.) orchards to increase tree vegetative growth and achieve earlier fruiting. However, when applied in excess of plant needs, N fertilizer applications are an unnecessary expense and may lead to N leaching and groundwater pollution. Therefore, it is necessary to develop orchard fertilization programs that simultaneously provide adequate crop nutrition and minimize N loss into the environment. Nitrogen was applied in each of 3 years to newly planted 'Red Delicious cv Schlect'/'M.26' trees at 67 kg N/ha/year in six fertilizer treatments: 1) two equal applications of granular calcium nitrate [$Ca(NO_3)_2$]; 2) chicken litter compost; 3) yardwaste compost; 4) a combination of chicken litter compost and granular $Ca(NO_3)_2$ with equal amounts of N from each fertilizer; 5) a combination of yardwaste compost and granular $Ca(NO_3)_2$ with equal amounts of N from each fertilizer; and 6) fertigation which consisted of eight weekly applications of solubilized $Ca(NO_3)_2$. Nonfertilized trees served as the control. In the third year of this experiment, the two chicken litter compost treatments had the greatest soil extractable P, the yardwaste compost treatment had the greatest soil extractable K, both full-rate compost treatments had greater soil extractable Mg than the other treatments, and all four compost treatments had greater soil extractable Mn than the treatments without compost. The four compost treatments also had greater soil extractable Ca and B than treatments without compost. By the third year of the experiment, the four compost treatments also had greater soil organic matter (OM) and soil C (with the integrated chicken litter compost treatment having similar soil C to the other treatments). Potentially mineralizable nitrogen and soil microbial biomass were similar among the treatments over the course of this experiment. The full rate chicken litter compost treatment and both yardwaste compost treatments had greater soil microbial respiration in 2015. The fertigation treatment performed similarly to the treatment where $Ca(NO_3)_2$ was applied as a granular product to the soil. Treatment differences found for the soil properties did not translate to increased tree size or leaf N content, suggesting that the trees were able to acquire sufficient N from the soil under all of the treatments. Our results suggest that applying fertilizers to fine textured soil with relatively high OM may not increase apple tree growth or productivity within the first 3 years after planting. In addition, compost applications can improve many soil properties, but these differences may not result in improved orchard productivity within 3 years.**

The profitability of high-density apple (*Malus* ×*domestica* Borkh.) orchards depends on rapidly establishing tree biomass and then obtaining high fruit yields as soon as possible after planting. Apple growers will often apply mineral nitrogen (N) fertilizers such as calcium nitrate [$Ca(NO_3)_2$], ammonium nitrate (NH_4NO_3), and urea [$CO(NH_2)_2$], to promote vegetative growth. The effects of N fertilizer timing and concentration on vegetative growth, leaf N concentration, and fruit quality in established high-density orchards in arid regions have been well documented (Dong et al., 2005a; Klein et al., 1989; Neilsen and Neilsen, 2002; Neilsen et al., 2009). However, there is a lack of research-based recommendations for appropriate fertilizer formulation, timing, and application methods to use for young apple orchards in the Mid-Atlantic region of the United States (this includes the states of Delaware, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Virginia, and West Virginia). In addition, there have been few studies describing the effects of carbon-based fertilizers, such as compost, on apple tree growth and productivity in newly planted high-density orchards in this region.

Furthermore, mineral N fertilizers may lead to negative environmental impacts. For example, ground applications of mineral N fertilizers in orchards have been observed to increase N leaching in orchard systems (Dong et al., 2005b; Merwin et al., 1996). This is of growing concern in watersheds, such as the Chesapeake Bay, where agricultural N has become an environmental pollutant. In an effort to reduce N pollution, the Environmental Protection Agency has enacted Total Maximum Daily Load limits on the amount of N that may enter the Chesapeake Bay Watershed (United States Environmental Protection Agency, 2010). Because of these regulations, detailed nutrient management plans are now needed for animal and agronomic productions systems within Chesapeake Bay watershed. It is possible that horticultural crop production systems may need to develop similar nutrient management plans in the future. Given these challenges, it is important to develop fertilizer application approaches and materials that can reduce environmental N loss from apple orchards.

One approach to improving soil fertility and reducing N loss is to use carbon-based amendments, such as composts. In apple orchards, compost applications have been shown to improved edaphic properties, including soil OM, microbial biomass carbon (C), microbial respiration, and soil mineral nutrition in fine- and coarse-textured soils (Forge et al., 2013; Neilsen et al., 2014; Rumberger et al., 2004; Sas-Paszt et al., 2014; Yao et al., 2006). For example, Kramer et al. (2006) observed that compost amended soils had 42% greater OM and 35 and 57% greater microbial biomass C and N, respectively, than soil fertilized with mineral N fertilizer. In addition, compost applications in coarse soil increased apple leaf N by 5%, K by 4%, Mn by 13%, and Zn by 5% compared with an unfertilized control (Sas-Paszt et al., 2014). However, compost applications do not appear to affect the vegetative growth or fruit yield or quality independent of soil texture (Forge et al., 2013; Neilsen et al., 2014; Rumberger et al., 2004; Sas-Paszt et al., 2014; Yao et al., 2006). In contrast to the results observed in apple orchards, Baldi et al. (2010) found that when compost was tilled into fine textured soil to a depth of 25 cm in a 7-year-old peach orchard, fruit yield increased by 38% in the first year, as did soil quality measures such as, OM, soil mineral nutrition, and microbial biomass C compared with the unfertilized control.

It appears that the contrasting results are contingent on soil texture, plant species, and the specific feedstock used to produce the compost. Composts made exclusively from

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plant material, such as yard wastes, have a higher C:N ratio than manure-based composts. Amending soil with a high C:N ratio compost will initially immobilize N, then mineralize N slowly but for a longer period of time than manure-based composts (Hartz et al., 2000). Therefore, it is necessary to determine how compost produced from different feedstocks, such as chicken litter and yard waste, may affect tree growth and productivity in an orchard.

Using an integrated compost–mineral fertilizer strategy may provide trees with N when it is most needed, while also conferring the benefits of compost mentioned previously. In an apple orchard with coarse textured soils, integrated compost–mineral fertilizer applications resulted in 33% more soil OM and 55% less NO_3^- leaching than soil fertilized with mineral fertilizer [$Ca(NO_3)_2$] (Kramer et al., 2006). However, integrated compost–mineral fertilizer applications did not increase soil microbial biomass C and N or potentially mineralizable N compared with the mineral fertilizer treatment. In other horticultural cropping systems, integrated fertilization approaches have been used to increase crop yields while improving soil quality. For example, parsley plants that were fertilized with the integrated treatment, compost and NH_4NO_3, had 69% more biomass than an unfertilized control, whereas plants that received compost alone increased biomass by 18% compared with an unfertilized control (Mylavarapu and Zinati, 2009). In this study, the integrated treatments also increased soil total C and N, microbial biomass C, and microbial respiration similarly to the compost amendments. Similar results have also been documented for broccoli and tomatoes planted in coarse-textured soils (Hernández et al., 2014; Stamatiadis et al., 1999). Thus, integrated compost–mineral fertilizer applications may be an approach to reduce environmental N loss while providing trees with sufficient N and enhancing soil quality.

Fertigation, a method which dispenses soluble fertilizers through irrigation lines, is another strategy that may reduce the negative environmental impacts from mineral fertilizer applications. Studies in arid apple producing regions with coarse soil, such as Israel and British Columbia, CAN, have demonstrated that fertigation can improve fruit quality and yield, tree growth, and leaf N concentration (Dong et al., 2005b; Klein et al., 1989; Neilsen et al., 2009). In a pot culture study, fertigating trees with N increased shoot growth by ≈58% and 82% compared with foliar N applications and the unfertilized control, respectively, and increased fruit yield by 28%, and fruit size by 22% compared with the unfertilized control (Dong et al., 2005a, 2005b). Similar results were observed in temperate regions with fertile, fine-textured clay soils, where N fertigation increased fruit yield by 25%, flower bud formation by 40%, and shoot growth by 85% in established apple orchards compared with broadcast fertilizer use (Kipp, 1992). Results from this study suggest that fertigation may improve apple tree yield and shoot growth in the fine-textured soils of the Mid-Atlantic.

The objectives of our study were to evaluate the effects of fertilizers, including ground applied $Ca(NO_3)_2$, compost, integrated compost-$Ca(NO_3)_2$, and fertigation with $Ca(NO_3)_2$, on tree growth and productivity and soil fertility in a newly planted apple orchard. We hypothesized that the integrated applications of composts and $Ca(NO_3)_2$ would supply apple trees with sufficient nitrogen to maintain adequate growth and productivity while also improving soil quality.

Materials and Methods

The experiment occurred on a Poplimento silt loam, a fine, mixed, subactive, mesic Ultic Hapludalf soil [Natural Resource Conservation Service (NRCS), 2001]. In Apr. 2013, three rows of 49 'Red Delicious cv Schlect'/'Malling 26' (M.26) trees were planted at a spacing of 1.5 m between trees and 4.5 m between rows at the Virginia Tech Alson H. Smith, Jr. Agricultural Research and Extension Center in Winchester, VA (39°06′N, 78°17′W). All trees were trained as a vertical-axis on a single-wire trellis and were uniformly treated for crop damaging arthropods, diseases, and weeds according to regional recommendations (Pfeiffer et al., 2015). Irrigation was supplied through drip irrigation tubing with in-line emitters. In 2013 and 2014, all flower clusters were removed by hand to prevent fruit set and encourage vegetative growth. On 20 May 2015, fruitlets were thinned to three fruit per trunk cross-sectional area (TCSA) on each tree to prevent overcropping young trees (Robinson et al., 2013).

Treatments were replicated four times in a randomized complete block design using five-tree sets for each experimental unit. The two end trees in each five-tree set served as buffers and were not used for data collection. Fertilizer treatments were applied to the soil on 13 May 2013, 19 May 2014, and 14 May 2015. Before treatment applications, there were no significant differences in soil pH, OM, CEC, or Mehlich 1 extractable mineral nutrient among the treatment plots. All treatments, except the control, were applied at a rate of 67 kg of plant available N/ha/year. Fertilizer treatments included: 1) an unfertilized control (CON), 2) a split application of water soluble calcium nitrate [$Ca(NO_3)_2$] (MIN) (Yara, Oslo, Norway), 3) chicken litter (CL) compost, 4) yard waste (YW) compost, 5) a combination of chicken litter compost and $Ca(NO_3)_2$ (CL + MIN) with equal amounts of N from each fertilizer, 6) a combination of yard waste compost and $Ca(NO_3)_2$ (YW + MIN) with equal amounts of N from each fertilizer, and 7) hand fertigation with $Ca(NO_3)_2$ (FGN) for eight weeks beginning in May and ending in July of each year. The first split application of the MIN treatment occurred on 1 June 2013, 28 May 2014, and 28 May 2015, and the second application of MIN occurred on 2 July 2013, 2014, and 2015. Compost was spread by hand from the base of the trunk to the edge of the vegetation free strip (≈83 cm from the trunk), and $Ca(NO_3)_2$ was applied around the base of the trees. The amounts of other mineral nutrients and OM differed among the applied treatments. Before compost application each year, compost nutrient analysis was performed by the Penn State Agricultural Analytical Services Laboratory (University Park, PA) in accordance with standard compost testing methods described by the United States Department of Agriculture and United States Composting Council (2002). Plant available N application rates were calculated, and equalized in all treatments (Table 1). Plant available N was calculated as the sum of 10% the organic N plus the inorganic N (NH_4-N and NO_3-N) (Campbell-Nelson, 2015).

Trunk cross-sectional area was measured 30 cm above the graft union at the time of planting and when trees were dormant in all subsequent years. Central leader length was measured from the end of the previous year's growth to the topmost terminal bud when trees were dormant each year. On 14 Sept. 2015, trees were harvested in their entirety and we recorded total fruit number and weight per tree. Four fruit were randomly selected from each of the three sample trees and used to determine fruit quality and maturity. Fruit size, weight, and flesh firmness were measured using computer integrated calipers, balance, and penetrometer, respectively (Fruit Texture Analyzer; GÜSS Manufacturing Ltd., Strand, South Africa). Flesh firmness was measured once on each side of the fruit after removing part of the peel with an 11.1 mm diameter tip. Starch pattern index was visually assessed using the Cornell Starch-Iodine Index (Blanpied and Silsby, 1992). Peel color was visually assessed as the percentage of the apple surface that was red. Fruit internal ethylene concentration was measured from 1 mL of gas drawn from the apple cortex using a 7890A gas chromatograph (Agilent Technologies, Santa Clara, CA). The soluble solid concentration was measured using a refractometer (PAL-1; Atago, Tokyo, Japan). Flower clusters were counted on 28 Apr. 2015 and 16 Apr. 2016.

On 14 Aug. 2013, 22 Aug. 2014, and 11 Aug. 2015, 20 leaves per sample tree (60 per experimental unit) were removed from the middle of the current year's branch growth, dried in an oven at 80 °C for 3 d, and measured for mineral concentration at the Penn State Agricultural Analytical Services Laboratory (University Park, PA). Leaf N concentration was measured using the combustion analysis method (Horneck and Miller, 1998) on a Vario Max N/C analyzer (Elementar, Hanau, Germany). Leaf P, K, Ca, Mg, B, Cu, and Zn were measured using a 730-ES ICP Optical Emission Inductively Coupled Plasma (OES-ICP) Spectrometer

(Agilent Technologies, Santa Clara, CA) after dry-ashing (Miller, 1998).

On 8 Sept. 2013, 3 Sept. 2014, and 24 Aug. 2015, soil samples were collected 30 cm from the trunk on the north, south, east, and west sides of the center experimental tree to a depth of 15 cm using a 7-cm diameter soil auger. Soil was placed in a bag, homogenized by hand, sieved (U.S. number 10 soil sieve; 2 mm mesh) and then stored at 4 °C until use in biological assays. A subsample of soil samples was sent to the Virginia Tech Soil Testing Laboratory (Blacksburg, VA) for analysis of plant available nutrients, pH, and CEC. Before soil physiochemical analysis, soil samples were air dried and crushed with a hammer mill-type crushing machine (Agvise, Benson, MN). Mehlich 1 solution was used to extract P, K, Ca, Mg, Zn, Mn, Cu, Fe, and B from 4 cm^3 of soil. The mineral nutrient concentration was determined from the extraction by OES-ICP (Acros Spectro, Mahwah, NJ). Cation exchange capacity was estimated by summation of the non-acid-generating cations (Ca, Mg, and K) and Mehlich 1 soil-buffer acidity. Soil pH was measured using a pH meter (WP-80D; TPS Pty Ltd., Springwood, Australia) fitted with a combination pH electrode (Orion model 8165BNWP Ross Sure-Flow; ThermoFisher, Waltham, MA). Total C and total N were measured at the Cornell Nutrient Analytical Laboratory on a CHN Elemental Analyzer-vario EL (Elementar, Hanau, Germany) after soil was ground to a fine powder using a mortar and pestle. Soil OM and soluble salts (SS) were measured at the Virginia Tech Soil Testing Laboratory (Blacksburg, VA) in 2013 and 2014, and at the Cornell Nutrient Analytical Laboratory (Ithaca, NY) in 2015. At the Virginia Tech Soil Testing Laboratory, soil OM was measured after loss on ignition (LOI) at 360 °C for 2 h (Blue M model CW-6680F; New Columbia, PA), and an EC probe was used to measure SS (3100 Conductivity Instrument; YSI, Yellow Springs, OH). At the Cornell Nutrient Analytical Laboratory, soil OM was measured using the LOI method at 500 °C for 2 h, and SS were measured using an electrical conductivity (EC) probe (Symphony SB70C Conductivity Meter; VWR, Radnor, PA).

Soil respiration was measured using the method described by Rodella and Saboya (1999). Briefly, 50 g of soil was placed in an air-tight jar with a vial containing 20 mL of 0.5-M NaOH solution to trap the evolved CO_2 gas. The EC of the NaOH solution was measured weekly for 6 weeks using an EC meter (model 2052; Amber Science Inc., Eugene, OR). The EC of each sample was compared with a blank containing 50 g of autoclaved, dried sand, and to a CO_2 saturated standard of 0.25-M sodium bicarbonate (Na_2CO_3).

Potentially mineralizable nitrogen (PMN) was estimated as the difference in the NH_4-N concentration before and after a 7-d incubation of 10 g of soil extracted in a 2 M KCl solution. The nitrate (NO_3-N) concentration of each sample was also measured to ensure that anaerobic incubation had occurred. The nonincubated sample contained 40 mL of 2 M KCl and was extracted after 1 h of agitation on an orbital shaker at 3.3 $r \cdot s^{-1}$ and centrifugation at 500 g_n for 10 min before filtration

Table 1. The carbon to nitrogen ratio (C:N), organic matter (OM), total C, organic N, nitrogen as ammonium (NH_4-N), nitrogen as nitrate (NO_3-N), phosphorus (P), and potassium (K) content of the chicken litter (CL) and yard waste (YW) composts applied in 2013, 2014, and 2015 to 'Red Delicious' apple trees in Winchester, VA.

Compost	C:N	OM ($g \cdot kg^{-1}$)	C ($g \cdot kg^{-1}$)	Organic N ($g \cdot kg^{-1}$)	NH_4-N ($mg \cdot kg^{-1}$)	NO_3-N ($mg \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)
2013 CL	15.8	458	260	16.5	5	1,012	18.8	7.5
2013 YW	14.4	538	246	17.1	56	21	4.6	11.5
2014 CL	14.9	475	293	19.6	5	501	19.0	8.6
2014 YW	18.8	608	342	18.1	37	44	4.1	11.2
2015 CL	12.9	473	246	19.0	5	601	16.8	6.5
2015 YW	18.1	515	291	16.1	48	92	3.5	7.8

Table 2. Tree size, yield, and fruit maturity and quality of 'Red Delicious'/'M.26' trees and fruit under the unfertilized control (CON) and six fertilizer treatments [calcium nitrate (MIN), chicken litter compost (CL), yard waste compost (YW), integrated chicken litter compost and calcium nitrate (CL + MIN), integrated yard waste compost and calcium nitrate (YW + MIN), and fertigation (FGN)] in Winchester, VA. Trunk cross-sectional area (TCSA) and central leader growth were measured on 3 Dec. 2015; fruit weight, flesh firmness, starch pattern index (SPI), peel color, soluble solids concentration (SSC), and internal ethylene concentration (IEC) were determined from twelve fruit per experimental unit harvested on 14 Sept. 2015.

Treatment	TCSA (cm^2)	Leader growth (cm)	Yield (kg/tree)	Fruit wt (g)	Flesh firmness (N)	SPI (1–8)	Peel color (%)	SSC (°Brix)	IEC ($\mu L \cdot L^{-1}$)
CON	11.8	49.4	6.7 A[z]	276	68.9	4.3	94 AB	14.1	22.1
MIN	11.7	53.2	5.7 A	287	68.5	4.3	95 A	14.6	26.5
CL	11.0	58.3	3.3 B	269	68.9	4.6	94 AB	13.9	20.2
YW	11.5	55.1	5.4 AB	277	68.0	4.5	93 AB	14.3	20.2
CL + MIN	11.2	49.2	5.1 AB	262	68.0	4.3	94 AB	13.8	18.4
YW + MIN	11.6	57.9	5.6 A	258	68.0	4.3	93 AB	13.9	23.9
FGN	11.8	48.9	6.1 A	255	69.8	4.3	92 B	13.7	28.7

[z]Different letters within a column indicate significantly different means at $P \leq 0.05$ using Tukey's HSD test ($n = 4$).

Table 3. Leaf mineral concentration measured in 2013, 2014, and 2015 from 'Red Delicious'/'M.26' trees the unfertilized control (CON) and six fertilizer treatments [calcium nitrate (MIN), chicken litter compost (CL), yardwaste compost (YW), integrated chicken litter compost and calcium nitrate (CL + MIN), integrated yardwaste compost and calcium nitrate (YW + MIN), and fertigation (FGN)] in Winchester, VA.

	N (%)[y]	P (%)	K (%)	Ca (%)	Mg (%)	B ($mg \cdot kg^{-1}$)	Cu ($mg \cdot kg^{-1}$)	Zn ($mg \cdot kg^{-1}$)
CON	2.5	0.171 AB[z]	1.68 B	1.3 AB	0.27	40.5 C	4.5	222
MIN	2.6	0.171 AB	1.70 B	1.4 A	0.28	41.3 BC	4.6	211
CL	2.6	0.177 A	1.76 AB	1.3 AB	0.28	44.5 A	4.4	234
YW	2.5	0.170 AB	1.84 A	1.2 B	0.25	44.4 A	4.7	233
CL + MIN	2.6	0.176 A	1.71 B	1.3 AB	0.28	43.9 A	4.7	212
YW + MIN	2.6	0.174 A	1.84 A	1.3 AB	0.26	43.1 AB	4.5	238
FGN	2.5	0.165 B	1.66 B	1.4 A	0.28	40.4 C	4.4	219
Treatment	NS	**	***	**	NS	***	NS	NS
2013	2.8 A	0.199 A	1.48 B	1.59 A	0.34 A	45.6 A	3.7 B	137 C
2014	2.5 B	0.168 B	2.26 A	1.19 B	0.22 C	44.1 B	4.9 A	230 B
2015	2.4 C	0.149 C	1.49 B	1.21 B	0.26 B	38.1 C	5.0 A	308 A
Year	***	***	***	***	***	***	***	***
Treatment × Year	NS	NS	NS	NS	NS	NS	NS	NS

[z]Different letters within a column indicate significantly different means for the main effects (year and treatment) using Tukey's HSD test.
[y]Measured as a percentage of leaf dry weight.
[NS, *, **, ***]Nonsignificant or significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. Plant available soil mineral concentration measured on soil samples (15-cm depth) taken 30 cm from the trunks of 'Red Delicious'/'M.26' trees in 2013, 2014, and 2015 under the unfertilized control (CON) and six fertilizer treatments [calcium nitrate (MIN), chicken litter compost (CL), yard waste (YW) compost, integrated chicken litter compost and calcium nitrate (CL + MIN), integrated yard waste compost and calcium nitrate (YW + MIN), and fertigation (FGN)] in Winchester, VA.

		P (mg·kg^{-1})	K (mg·kg^{-1})	Ca (mg·kg^{-1})	Mg (mg·kg^{-1})	B (mg·kg^{-1})	Cu (mg·kg^{-1})	Mn (mg·kg^{-1})	Zn (mg·kg^{-1})
CON				1,261 BC[z]		0.575 B	0.98 A		13 BC
MIN				1,278 BC		0.533 B	0.84 AB		10 C
CL				1,861 A		1.000 A	0.70 BC		17 A
YW				1,807 A		1.017 A	0.62 BC		12 BC
CL + MIN				1,769 A		0.925 A	0.65 BC		16 AB
YW + MIN				1,654 AB		0.833 A	0.52 C		12 BC
FGN				1,173 C		0.475 B	0.88 AB		11 C
Treatment		***	***	***	***	***	***	***	***
2013				1,510 B		0.739 B	0.66 B		13 AB
2014				1,361 B		0.657 B	0.86 A		12 B
2015				1,758 A		0.900 A	0.69 B		15 A
Year		***	NS	***	***	***	*	***	**
Treatment × Year		***	**	NS	**	NS	NS	NS	**
Treatment effects within the Treatment × Year interaction:									
2013	CON	22 B	125 C		110 C			50 AB	
2013	MIN	20 B	90 C		97 C			43 AB	
2013	CL	133 A	144 BC		161 AB			39 B	
2013	YW	36 B	241 A		172 A			55 AB	
2013	CL + MIN	110 A	144 BC		152 AB			54 AB	
2013	YW + MIN	33 B	187 B		139 ABC			58 A	
2013	FGN	17 B	113 C		99 C			49 AB	
		***	***		**			***	
2014	CON	27 C	116 C		114 AB			15	
2014	MIN	18 C	77 C		92 B			13	
2014	CL	92 A	189 B		152 AB			16	
2014	YW	27 C	247 A		158 A			19	
2014	CL + MIN	69 B	150 BC		133 AB			13	
2014	YW + MIN	25 C	181 B		127 AB			19	
2014	FGN	14 C	89 C		88 B			11	
		***	***		**			NS	
2015	CON	22 C	101 CD		111 BCD			14 C	
2015	MIN	18 C	74 D		99 CD			15 C	
2015	CL	258 A	217 B		253 A			24 AB	
2015	YW	50 C	326 A		262 A			35 A	
2015	CL + MIN	146 B	165 C		179 B			19 ABC	
2015	YW + MIN	34 C	196 BC		160 BC			26 AB	
2015	FGN	13 C	78 D		78 D			12 C	
		***	***		***			***	

[z]Different letters within a column indicate significantly different means for the main effects (year and treatment) or, for significant interactions, the treatment effects within each year using Tukey's HSD test.
NS, *, **, ***Nonsignificant or significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively.

(FisherBrand G6; Fisher, Waltham, MA). The incubated sample contained 10 mL of de-ionized water and extracted after 7 d at 30 °C, at which time 2.67 M KCl was added before extraction. Samples were placed on an orbital shaker for 1 h at 3.3 r·s^{-1}, and centrifuged at 500 g_n for 10 min before filtration. All samples were stored at –20 °C until NH_4-N and NO_3-N concentrations were measured using a Lachat QuickChem 8500 Series 2 Flow Injection Analysis System (Loveland, CO). Ammonia was measured using protocol #12-107-06-2-A, and NO_3^- was measured using protocol #12-107-04-1-B (Lachat Instruments, 2014).

Microbial biomass C was measured using the direct chloroform ($CHCl_3$) fumigation extraction method (Fierer and Schimel, 2003). Ten grams of soil from each sample and 40 mL of 0.05 M potassium sulfate (K_2SO_4) were placed in two separate 70 mL glass vials with Teflon-lined lids. Fumigated samples received 0.5 mL of amylated $CHCl_3$. Unfumigated samples did not receive $CHCl_3$, but were otherwise treated the same as fumigated samples. Samples were shaken at 2.5 r·s^{-1} on an orbital shaker for 4 h and allowed to settle for 30 min before being decanted into 50-mL conical tubes. Samples were centrifuged for 10 min at 500 g_n and filtered (FisherBrand G6; Fisher). The filtrate was sparged with compressed nitrogen gas for 20 min to remove any remaining $CHCl_3$ from the solution and stored at –20 °C until use. Blank samples with no soil were prepared in the same manner. Before analysis, samples were diluted 1:2 (v:v) with deionized water. The total carbon was quantified using a Shimadzu (Columbia, MD) carbon analyzer model TOC-VCPH + TNM-1 with an auto-sampler, using high-temperature oxidation catalyzed with platinum-coated alumina beads (temperature 720 °C) in nonpurgeable organic carbon mode (Bird et al., 2003). Nonpurgeable organic C was measured using a nondispersive infrared detector. Each sample was run in triplicate. Microbial biomass was calculated by multiplying the difference between the fumigated and unfumigated samples by the k_{ec} value of 0.45 (Joergensen, 1996).

All data were analyzed using PROC GLIMMIX in SAS 9.4 (SAS Institute Inc., Cary, NC). For trunk cross-sectional area, leader growth, yield, and fruit quality/maturity data, Treatment was considered a fixed effect and block a random effect. Mean separation was determined using Tukey's honestly significant differences posthoc test at the $P \leq 0.05$ level. For flower cluster density, leaf minerals, soil minerals and chemical properties, PMN, and microbial biomass C, Treatment, Year, and Treatment × Year were considered fixed effects, and block was a random effect. When interaction effects were significant, treatment effects were partitioned within each year using the LSMEANS values generated with the SLICEDIFF command and mean separation was determined using the least squares differences (LSD) test at the $P \leq 0.05$ level. Soil microbial respiration data were analyzed as a repeated measure using treatment as a fixed effect, and block and block × treatment as random effects, and significance was determined using the LSD test at the $P \leq 0.05$ level.

Table 5. Soil total carbon, total nitrogen, the C:N ratio, cation exchange capacity (CEC), organic matter (OM), pH, and soluble salts (SS) measured on soil samples (15-cm depth) taken 30 cm from the trunks of 'Red Delicious'/'M.26' trees in 2013, 2014, and 2015 under the unfertilized control (CON) and six fertilizer treatments [calcium nitrate (MIN), chicken litter compost (CL), yard waste (YW) compost, integrated chicken litter compost and calcium nitrate (CL + MIN), integrated yard waste compost and calcium nitrate (YW + MIN), and fertigation (FGN)] in Winchester, VA.

	OM ($g \cdot kg^{-1}$)	C ($g \cdot kg^{-1}$)	N ($g \cdot kg^{-1}$)	C:N	CEC ($meq \cdot 100\ g^{-1}$)	pH	SS ($mmhos \cdot cm^{-1}$)
CON			2.1 C[z]	6.91	7.8 BC	6.6 AB	0.2
MIN			2.3 BC	6.42	7.5 C	6.6 AB	0.38
CL			2.8 BC	9.11	11.4 A	6.8 A	0.35
YW			3.4 A	9.45	11.4 A	6.9 A	0.36
CL + MIN			2.6 BC	8.88	10.5 A	6.9 A	0.35
YW + MIN			2.9 AB	8.85	9.8 AB	6.9 A	0.34
FGN			2.3 BC	9.03	7.3 C	6.3 B	0.4
Treatment	***	***	***	NS	***	**	NS
2013			2.9 B	6.06 B	9.2 B	6.6 B	0.39
2014			1.6 C	12.34 A	8.4 B	6.7 AB	0.31
2015			3.3 A	6.74 B	10.7 A	6.9 A	0.36
Year	**	*	***	***	***	**	NS
Treatment × Year	*	*	NS	NS	NS	NS	NS
Treatment effects within the Treatment × Year interaction:							
2013	CON		29 B	13.7 B			
2013	MIN		31 B	14.3 B			
2013	CL		38 A	17.8 B			
2013	YW		47 A	28.5 A			
2013	CL + MIN		43 A	17.0 B			
2013	YW + MIN		46 A	24.1 AB			
2013	FGN		29 B	13.8 B			
			*	**			
2014	CON		28 AB	14.6 AB			
2014	MIN		22 B	12.2 B			
2014	CL		29 AB	21.6 AB			
2014	YW		39 A	20.7 AB			
2014	CL + MIN		39 A	24.1 A			
2014	YW + MIN		35 A	19.8 AB			
2014	FGN		23 B	20.7 AB			
			*	**			
2015	CON		24 C	12.6 C			
2015	MIN		26 C	14.6 C			
2015	CL		44 B	29.9 B			
2015	YW		61 A	46.1 A			
2015	CL + MIN		38 B	22.1 BC			
2015	YW + MIN		39 B	28.4 B			
2015	FGN		24 C	12.2 C			
			***	***			

[z]Different letters within a column indicate significantly different means for the main effects (year and treatment) or, for significant interactions, the treatment effects within each year using Tukey's HSD test.
NS, *, **, ***Nonsignificant or significant differences at $P \leq 0.05$, 0.01, or 0.001, respectively.

Results

No differences in TCSA or leader growth were observed during any year of our study and by the end of the 3 years there were no differences in tree size (Table 2). Red peel color was the only fruit quality or maturity parameter affected by the treatments. In 2015, fruit yield was 68%, 53%, and 59% greater from the CON, MIN, and FGN trees, respectively, than the CL trees. Fruit from trees fertilized with MIN had on average 3% greater red peel color than fruit from FGN trees, but all treatments had fruit with greater than 92% red blush. Flower cluster density ranged between 6 and 9 blossoms/cm^2 TCSA and did not differ among treatments in 2015. In 2016, flower cluster density ranged between 8 and 14 blossoms/cm^2 TCSA. The MIN and YW treatments had significantly greater flower cluster density than the CL treatment (data not shown).

There were no detectable differences in leaf N concentration among the treatments, but there was an overall reduction in N leaf content from 2013 to 2015 (Table 3). Leaf P concentration was greater the CL, CL + MIN, and YW + MIN treatments than the FGN treatment; however, none of the treatments had greater P relative to CON. The YW and YW + MIN treatments had greater leaf K concentrations than the CON, MIN, CL + MIN, and FGN treatments. The FGN and MIN treatments had greater leaf Ca concentration than the YW treatment, but not compared with CON. All compost and compost + mineral fertilizer treatments had greater leaf B concentrations compared with the CON and FGN treatments.

Over the course of this study, the CL and CL + MIN treatments had greater extractable soil P than the other treatments, though there was some overall year-to-year variability in the amount of P that was measured (Table 4). In 2014 and 2015, CL had greater extractable soil P content than CL + MIN. All of the compost and compost + mineral treatments had greater extractable soil K than the CON, MIN, and FGN treatments, but there was some year-to-year variability among the compost treatments. By 2015, the YW treatment had the greatest extractable soil K concentration while CON, MIN, and FGN had the lowest. The CL, CL + MIN, and YW treatments had greater extractable soil Ca than the CON, MIN, and FGN treatments.

The compost and compost + mineral treatments had greater extractable soil Mg and B than the CON, MIN, and FGN treatments. The CON had similar extractable soil Cu concentration to the MIN and FGN treatments and a greater concentration than the four treatments with compost. There were small or no differences for soil extractable Mn in 2013 and 2014, but the CL, YW, and YW + MIN treatments had greater Mn concentration in 2015 than the CON, MIN, and FGN treatments. The CL treatments had a greater extractable soil Zn concentration than the other treatments, though the CL + MIN treatment was similar to the CON, YW, and YW + MIN treatments.

In 2013 and 2015, the CL, YW, CL + MIN, and YW + MIN treatments had greater soil OM than the CON, MIN and FGN treatments (Table 5). In 2014, the YW, CL + MIN, and YW + MIN had a greater OM content than MIN and FGN, with the CON and CL treatments being intermediate. In 2015, the CL, YW, CL + MIN, and YW + MIN treatments had

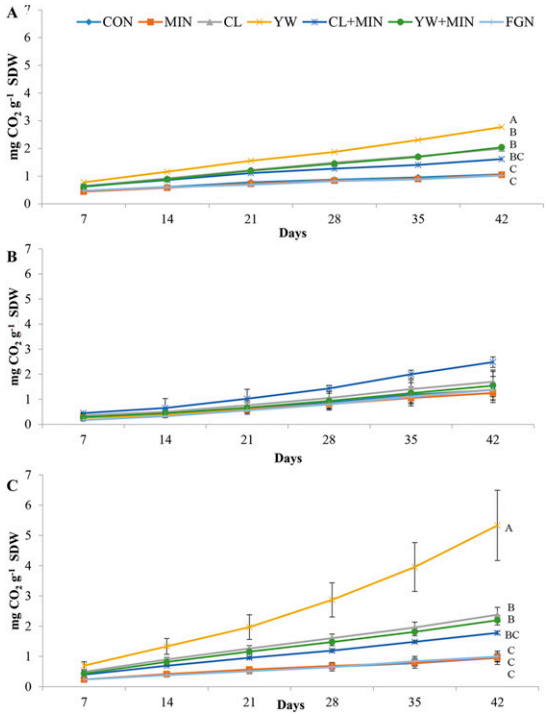

Fig. 1. Cumulative soil microbial respiration [reported as the amount of carbon dioxide (CO_2) captured weekly on a soil dry weight basis (SDW)] in 2013 (**A**), 2014 (**B**), and 2015 (**C**). Data were measured on soil samples (15-cm depth) taken 30 cm from the trunks of 'Red Delicious'/'M.26' trees under the unfertilized control (CON) and six fertilizer treatments [calcium nitrate (MIN), chicken litter compost (CL), yard waste (YW) compost, integrated chicken litter compost and calcium nitrate (CL + MIN), integrated yard waste compost and calcium nitrate (YW + MIN), and fertigation (FGN)] in Winchester, VA. Data were analyzed as repeated measures. Different letters indicate significantly different means at $P \leq 0.05$ using the least significant differences test ($n = 4$). Error bars are SE.

45%, 61%, 37%, and 38% more OM than the CON soil, respectively. By 2015, the CL, YW, CL + MIN, and YW + MIN treatments also had greater C concentration than the CON, MIN and FGN treatments. Throughout this study, total soil N was greater in the YW and YW + MIN treatments than the CON, but the other treatments had similar N concentrations. There were no treatment differences in the C:N ratio among the treatments. The CL, YW, and CL + MIN treatments had greater CEC than the CON, MIN, and FGN treatments, and the YW + MIN was intermediate. The CL, YW, CL + MIN, and YW + MIN treatments had a less acidic soil than the FGN treatment. There were no differences among the treatments for the soluble salt content.

In 2013 and 2015, the fertilizer treatments affected soil microbial respiration, but not in 2014 (Fig. 1). Soil fertilized with YW had greater microbial respiration rates than all other treatments in 2013 ($P = 0.0006$) and 2015 ($P < 0.0001$). Soil microbial respiration was 2.5 times greater in YW fertilized soil than in the CON soils in 2013, and 5 times greater in 2015. Soil microbial respiration was greatest in the YW, CL, and YW + MIN soils (Fig. 1). On average, PMN was 17 $\mu g \cdot g^{-1} \pm 1.7$ and microbial biomass carbon was 928 µg C/g SDW ± 54, but there were no differences among treatments (data not shown).

Discussion

During the first 3 years of apple orchard establishment, none of the fertilizer treatments increased tree growth or leaf N status compared with the unfertilized control (CON). However, within three months after the initial fertilizer application, the compost treatments increased soil mineral content and OM and these changes persisted through the length of the study. Our results are similar to other studies in that we demonstrated that compost, integrated compost-mineral fertilizer, or fertigation applications may not always increase orchard productivity in young orchards, but these treatments can affect soil quality and therefore the potential long-term productivity and environmental impacts of the orchard system (Forge et al., 2013; Kramer et al., 2006; Neilsen et al., 2004, 2009; Sas-Paszt et al., 2014; Yao et al., 2006). The integrated CL + MIN and YW + MIN treatments, which we hypothesized would supply apple trees with sufficient nitrogen to maintain adequate growth and productivity while also improving soil quality, did not increase tree growth or leaf N more so than the other treatments or the control. Fine-textured soils with higher OM content, like those in the Shenandoah Valley of Virginia where our research took place, mineralize more N than soils with lower OM content, resulting in increased plant productivity (Bauer and Black, 1994). Trees in our study were likely supplied with adequate N, P, and K nutrition from existing soil OM, thus the addition of fertilizers, in the form of mineral N or as compost may have not been necessary for this orchard.

Composts, regardless of feedstock, soil type, or crop, have been reported to enhance edaphic factors, such as OM, microbial activity, and soil mineral concentration, including P and K, in orchard systems (Baldi et al., 2010; Forge et al., 2013; Kramer et al., 2006). Despite significant increases in OM and total C in 2013 and 2015, neither CL nor YW increased PMN or microbial biomass carbon. These results were unexpected because soil OM and carbon additions typically increase microbial biomass carbon and microbial activity (Schnurer et al., 1985; Wardle, 1992). Peck et al. (2011) demonstrated that additions of OM in the form of wood chips to the orchard floor increased microbial biomass carbon, but additions of composted chicken litter did not, indicating that the specific C:N ratio of the amendment influences microbial biomass. Kramer et al. (2006) found that compost and calcium nitrate [$Ca(NO_3)_2$] increased soil OM, but did not affect microbial biomass or potentially mineralizable N, compared with mineral fertilizer application in an established apple orchard planted on coarse, sandy soil in an arid environment. In our study, soil microbial respiration increased in compost-amended soils compared with CON, MIN, and FGN treatments in 2013 and 2015 indicating that soil microbes used the added C to sustain their populations throughout the duration of the experiment. Soil microbes mineralize N and P from OM slowly throughout the growing season, potentially leading to increased leaf mineral nutrient content in future years.

Applications of the compost and integrated compost–mineral N fertilizers increased soil P, K, and B concentration, which led to increased leaf concentrations of these minerals. However, greater leaf P, K, and B concentrations were not associated with increased tree growth, flower cluster density, or fruit yield or quality during this study. In addition, increased soil Mn and Zn concentrations in the compost treatments did not increase leaf concentrations of these minerals. Leaf Mn and Zn concentrations were above the adequate level for all treatments, but Ca and Mg leaf concentrations were deficient among all treatments, indicating that in the short-term compost may not provide sufficient Ca and Mg to overcome these deficiencies. Calcium is somewhat mobile in the soil; however, in apple trees, translocation of Ca occurs very slowly (Vang-Petersen, 1980). Although Mg is readily translocated in plants, Mg deficiencies commonly occur because of reduced mobility, long term soil depletion, or unbalanced fertilization practices that significantly increase soil K (Gransee and Fuhrs, 2013). Thus, foliar applications of Ca and Mg would likely be necessary in commercial orchards to prevent common nutrient disorders regardless

of the N fertilizer being used (Vang-Petersen, 1980).

In summary, the fertilizer treatments and rates used in our experiment did not affect leaf N or tree growth and only minimally affected fruit yield and quality within the first 3 years after planting the orchard. Because unnecessary applications of N fertilizer in orchards can lead to reduced fruit quality and N leaching, these results suggest that apple growers should carefully consider site history, leaf mineral content, soil texture, and OM before making fertilizer applications in young orchards. The lack of treatment differences in our experiment for tree growth and fruit quality were likely due to adequate soil nutritional status and OM content before fertilizer applications. However, compost increased soil properties that are associated with long-term soil fertility, such as OM, soil C, and microbial respiration. It is possible that these increases will positively impact orchard productivity in future years. Increased soil mineral nutrition, OM, CEC, and microbial activity from compost may also reduce the need for future applications of N, P, and K. However, longer-term studies are needed to understand the effects of these fertilization practices as the orchard matures and reaches full productivity.

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