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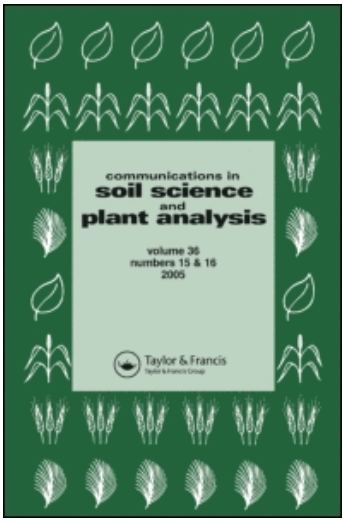

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Mineralization of Nitrogen from Biofuel By-products and Animal Manures Amended to a Sandy Soil

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Transformations of nitrogen (N) from poultry litter (PL), dairy manure compost (DMC), anaerobically digested fiber (ADF), Perfect Blend 7–2–2 (PB), a compost/litter mixture (C/L), dried distillers grains from ethanol production (DG), and mustard meal from biodiesel production (MM) applied to a Quincy fine sand were investigated in an incubation experiment over 210 days. The cumulative release totals of available N after 210 days were 61, 61, 56, 44, 29, 2, and –2% for the total N in MM, PB, DG, PL, C/L, DMC, and ADF, respectively. With application of MM and DG, ammonium (NH_4-N) accumulated initially in the soil with very little nitrification, possibly because of inhibition of nitrification related to chemical compounds in the amendments. Mineralization of organic N to NH_4-N and nitrate (NO_3-N) was relatively slow from MM- and DG-amended soils, indicating the potential for using biofuel by-products as slow-release N sources for plants.

Keywords Biofuel by-products, dairy manure compost, distillers grains, mineralization, mustard meal, nitrogen, nutrient cycling, poultry litter, soil fertility

Introduction

With expanding animal production, rising fuel and fertilizer costs, and increasing markets for organically cultivated food, the number of growers in the United States relying on by-products as a source of nutrients for crop production is increasing rapidly. In comparison to chemical fertilizers, the benefits of using by-products as fertilizers may include lower cost, accumulation of organic carbon (C) and nitrogen (N) in the soil, and a prolonged release of nutrients to the plant.

Poultry litter (PL) is a raw animal manure by-product commonly applied to agricultural fields in the United States. An estimated 17.8 million tons (dry mass) of PL were produced in the United States in 1997, which is equivalent to 1.97 million tons of manure N (USDA ERS 2001). Litter is also an approved raw manure fertilizer for organic cropping systems in the U.S. (National Organic Program 2007). It is estimated that 60–70% of N in PL is either in the forms of ammonia or uric acid, which are both rapidly available forms of N to plants (Nahm 2003). To account for the lack of slowly mineralizeable organic compounds released in the latter portion of a growing season, consultants to certified organic

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growers often advise supplementing litter with dairy manure compost (DMC: McElrich, personal communication, 2006). In material that has been properly composted, N is tied up in organic forms as proteins, amino acids, and other biological components (Kuepper 2000). The stability of the organic N in compost and other by-products directly impacts the N mineralization rates of the material.

Many organic fertilizer companies combine a variety of by-products with mineral nutrients to prolong N release and provide available N to plants throughout the growing season. Also, as dairy producers consider anaerobic digestion to convert waste into energy, the digested fiber residue contains organic N compounds that could be useful as an N fertilizer source (Burke 2001).

In addition to manure by-products, the recent expansion of the biofuel industries is drastically increasing the production of dried distillers grains (DG) and oilseed meals. Large quantities of dried DG and oilseed meal by-products are projected to be readily available in the United States. These materials also have chemical and physical properties ideal for providing N and other nutrients to plants. Mustard seed oil extraction leaves a protein-dense meal, supplying a readily mineralized form of N available for plant use. For DG, proteins are degraded during the fermentation of corn grain, leaving decomposable organic N compounds with reduced levels of C. Mustard seed meal is being tested in Ethiopia and other areas as a fertilizer source because of its low cost, wide availability, N content (5.8–6.1%), and availability of primary and secondary plant nutrients (Balesh, Zapata, and Aune 2005). Mustard seed meal is of particular interest to organic growers, as the isothiocyanate compounds in the meal may provide the added potential benefit of weed, insect, fungus, and nematode suppression (Rice et al. 2007; Vaughn et al. 2006; Norsworthy and Meehan 2005; Chung et al. 2002; Walker 1997, 1996). Weed suppression characteristics have also been identified with dried DG, although the mechanism is poorly understood at this time (Boydston et al. 2007; Vaughn et al. 2006; Liu and Christians 1994).

Because N is the most limiting plant nutrient in the soil, it is critical to understand N mineralization rates for any organic by-product used as a N fertilizer. The dominant form of N in by-products is organic N, which must be converted, or mineralized, by soil microbes to ammonium (NH_4-N) and nitrate (NO_3-N) to be available to plants. By-product characteristics that affect N mineralization rates include C/N ratios, proportions of slow and rapidly mineralizeable organic N, and concentrations of chemicals toxic to N-mineralizing bacteria.

The purpose of this study was to determine and compare the N mineralization rates and the amount of available N to plants over a 210-day growing season for the following by-products when applied to a sandy soil: PL, DMC, DG, mustard meal (MM), a commercially available litter and feather meal fertilizer, and anaerobically digested fiber (ADF).

Materials and Methods

Mustard seed meal, DG, DMC, PL, ADF, and a commercially available USDA organically certified mixture of litter, feather meal, and mineral nutrients (Perfect Blend 7–2–2, PB) were added to a Quincy sand (mixed mesic Xeric Torrispamment) at a rate equivalent to 200 mg N kg^{-1} soil (based on total N) and incubated for 210 days in polyethylene bags at temperatures typical of a spring growing season in the Pacific Northwest. Soil samples were extracted at days 0, 1, 3, 7, 14, 21, 28, 42, 56, 70, 84, 98, 126, 154, and 210. Concentrations of 2 M potassium chloride (KCl)–extractable NO_3-N and NH_4-N were measured.

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Soil

A Quincy fine sand (mixed, mesic Xeric Torripsamment) collected from the top 22.5 cm of soil was selected. The Quincy soil series is favored in eastern Washington for the production of potatoes, onions, corn, and small grains. The sampling site for the soil was located in a native, uncultivated desert steppe in Benton County, Washington. Initial soil pH was 7.8, and initial concentrations of NO_3-N and NH_4-N in the soil were 3.0 and 4.5 mg kg^{-1}, respectively. Distilled water was added to bring the air-dried soil up to 12% moisture content (by weight), which is approximately 80% field capacity for the Quincy fine sand. Phosphorus (P) was added to the soil at a rate of 50 mg kg^{-1} to prevent P-limiting conditions for microbial growth.

By-product Amendments

Two biofuel by-products and five animal by-product treatments were evaluated in this study. Biofuel by-products selected for evaluation were MM and DG. White mustard seed meal (*Sinapis alba*), cv. Ida Gold, was obtained from triple cold-pressed mustard seed, and DG was obtained from a commercial ethanol plant that uses corn as the primary feedstock. The ADF used in this study was derived from dairy manure separated from effluent after processing for 21 days in an anaerobic digester from a dairy in Benton County, Washington. The remaining amendments included PB, derived from chicken manure, feather meal, and mineral nutrients (Perfect Blend, LLC, Bellevue, Wash.), PL from a layer hen house, and DMC from a predairy heifer farm, where the dairy manure was composted with hay and apple pummus. The DMC and PL were combined at a 2:1 ratio by dry weight as an additional amendment (C/L), following standard recommendations for organically certified preplant fertilization in the Pacific Northwest (McErlich 2006). The ADF, PL, and DMC were oven-dried at approximately 38 °C. All amendments were ground to pass a 2.0-mm sieve. Total C and N content were determined for each amendment via combustion with the Leco CNS-2000 carbon (C), N, and sulfur (S) analyzer (Leco, St. Joseph, Mich.). Chemical properties of amendments are listed in Table 1.

Table 1
Total nutrient content of soil amendments evaluated in this study

Element	DMC[a]	PL	MM	DG	PB	ADF
Total N (mg g^{-1})	14	45	58	41	70	22
C (mg g^{-1})	146	280	493	494	380	447
Ca (mg g^{-1})	4	46	1	0	13	4
K (mg g^{-1})	4	5	3	4	6	2
P (mg g^{-1})	1	11	3	3	4	2
S (mg kg^{-1})	685	1222	362	428	2940	727
Mg (mg kg^{-1})	1559	1616	1118	911	918	1259
Fe (mg kg^{-1})	1698	261	54	104	313	186
B (mg kg^{-1})	26	54	15	15	31	30
Cu (mg kg^{-1})	9	14	1	2	66	22
Mn (mg kg^{-1})	79	110	8	6	156	35
Zn (mg kg^{-1})	32	188	23	20	188	36

[a]DMC, dairy manure compost; PL, poultry litter; MM, mustard meal; DG, distillers grains; PB, Perfect Blend 7–2–2; and ADF, anaerobically digested fiber.

Incubation

Amendments were added to 2 kg of air-dried soil at a rate of 200 mg total N kg soil^{-1} (based on total N in each by-product) and incubated in 30-cm × 30-cm polyethylene resealable bags. The selected N rate, which is equivalent to 448 kg total N ha^{-1} incorporated to a 15-cm depth, was selected to represent a typical preplant N application for most crops growing in the region, with the assumption that no more than 60% of the N would be available to the plant in the first growing season. Eight treatments (one unamended soil plus seven amended soils) were replicated five times in a completely randomized design. The bags were incubated in a dark temperature-controlled growth chamber. Soil samples were analyzed for NO_3-N and NH_4-N concentration along with soil moisture content at 0, 1, 3, 7, 14, 21, 28, 42, 56, 70, 84, 98, 126, 154, and 210 days of incubation. Three g of moist soil were weighed into 50-mL polystyrene tubes, shaken with 20 mL of 2 M KCl solution for 30 min, and filtered through No. 2 Whatman filter paper. The concentrations of NO_3-N and NH_4-N in the filtrate were measured using a rapid flow analyzer (Flow Injection Analyzer 8000, Lachat Instruments, Milwaukee, Wisc.). Soil pH was determined at 7, 42, 70, 98, 154, and 210 days of incubation with a pH meter using a 2:1 ratio of distilled water and moist soil. Incubation chamber temperature was changed biweekly to simulate the mean (2002–2004) soil temperature at 20 cm deep for a typical growing season from midspring to early fall in eastern Washington (Table 2).

Nitrogen Availability: First-Order Reaction

A nonlinear regression model (SAS PROC NLIN) was used to predict the concentration of available N as a function of potentially available N (adapted from Chescheir, Westerman, and Safley 1986) as follows:

Table 2
Soil temperature regimes used for incubation of the moist soil with various amendments

Target date	Incubation length (days)	Incubator temperature (°C)
14 Apr	0	13.0
28 Apr	14	13.8
12 May	28	15.6
26 May	42	17.1
9 Jun	56	19.2
23 Jun	70	20.3
7 Jul	84	22.0
21 Jul	98	22.8
4 Aug	112	22.8
18 Aug	126	22.2
1 Sep	140	20.9
15 Sep	154	19.8
29 Sep	168	17.9
13 Oct	182	16.7
27 Oct	196	14.3

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$$N_t = N_o\left(1 - e^{-kt}\right) + N_{os}$$

where N_t is total inorganic N concentration of soil amended with an organic amendment minus that of unamended soil at time t (mg N kg^{-1}); N_o is potentially available organic N (mg N kg^{-1}); k is first-order rate constant (day^{-1}); t is time (day); and N_{os} is total inorganic N concentration of soil amended with an organic amendment minus that of unamended soil at time = 0 (mg N kg^{-1}).

Values for N_{os}, N_o, and k were fitted into the model with SAS PROC NLIN (SAS 1998). Predicted values for each of these parameters are shown in Table 3.

Results and Discussion

Nitrogen Mineralization Trends

With the addition of PL, C/L, PB, MM, and DG, NH_4-N concentrations increased initially through the mineralization process of ammonification, and peaked from 7 (PL and C/L) to 42 days after addition to soil. Ammonium concentrations declined after peaking but remained higher than in the control soil for a minimum of 28 days for PL and C/L to a maximum of 210 days for MM (Figure 1). The accumulation of NH_4-N in the soil suggests some nitrification inhibition. Nitrification proceeds at a slower rate at cool temperatures than ammonification because of the slower growth rate and less efficient metabolism of nitrifying bacteria compared to heterotrophic ammonifiers (Sylvia et al. 1999; Belser 1979). Temperatures ranged from 13 to 17 °C during the first 42 days of incubation. At 13 °C, nitrification rates are estimated to range between 35 and 60% of the maximum nitrification rate at the optimal temperature for nitrification, which is estimated

Table 3
Prediction of N mineralization rates for a Quincy find sand combined with amendments at a rate of 200 mg N kg^{-1} using the first-order N mineralization equation $N_t = [N_o\,(1 - e^{-kt})] + N_{os}$ (Chescheir et al. 1986)

Amendment	First-order N mineralization equations	r^2
DMC	NA	0.27
PL	$N_t = [62.7 \times (1 - e^{-0.0476*t})] + 24.8;\ t < 210$	0.87
C/L	$N_t = [37.8 \times (1 - e^{-0.0218*t})] + 20.3;\ t < 210$	0.85
MM	$N_t = [135.9 \times (1 - e^{-0.0305*t})] - 13.0;\ t < 210$	0.92
DG	$N_t = [121.2 \times (1 - e^{-0.0315*t})] - 8.7;\ t < 210$	0.97
ADF	NA	0.66
PB	$N_t = [108.0 \times (1 - e^{-0.0716*t})] + 14.8;\ t < 210$	0.99

Notes. N_t = total inorganic N concentration of soil amended with an organic amendment minus that of unamended soil at time = t (mg N kg^{-1}); N_o = potentially available organic N (mg N kg^{-1}); k = first-order rate constant (day^{-1}); t = time (day); and N_{os} = total inorganic N concentration of soil amended with an organic amendment minus that of unamended soil at time = 0 (mg N kg^{-1}) (Chescheir et al. 1986). DMC, dairy manure compost; PL, poultry litter; C/L, poultry litter and dairy manure compost mixture; MM, mustard meal; DG, distillers grains; PB, Perfect Blend 7–2–2; and ADF, anaerobically digested fiber.

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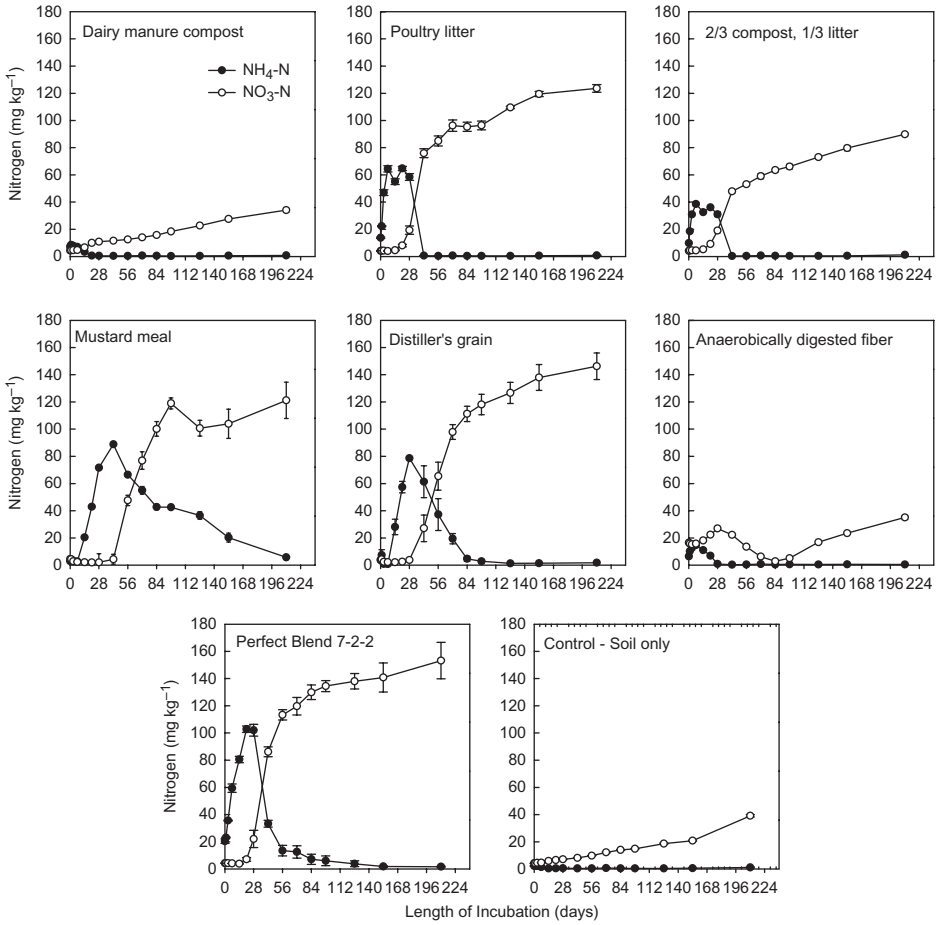

Figure 1. Concentrations of NH_4-N and NO_3-N during incubation of a Quincy fine sand amended with organic amendments to supply 200 mg kg^{-1} total N. Vertical line at data point represents standard error (n = 5).

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to be in the temperature range of 20 to 30 °C (Gilmour 1984; Addiscott 1983; Malhi and McGill 1982; Bhat, Flowers, and O'Callaghan 1980; Sabey, Frederick, and Bartholomew 1969). Delayed nitrification due to cool soil temperatures in the early spring is beneficial for minimizing NO_3-N leaching and potential NO_3-N loading into groundwater. However, increased NH_4-N accumulation can be toxic to plants, particularly for seed germination and seedling establishment (Westwood and Foy 1999; Barker et al. 1970; Megie, Pearson, and Hiltbold 1967; Hunter and Rosenau 1966; Cooke 1962).

The delay in nitrification well beyond the length for PL-, C/L-, and PB-amended soils suggests that factors beyond temperature were inhibiting nitrification. Isothiocyanate (SCN) in MM has suppressed nitrifying bacteria. Van Schreven, Lindenbergh, and Koridon (1970) found an accumulation of NH_4-N over the first 49 days of incubation for an Amitrole-T (a component of SCN)–amended sandy loam and deduced that the accumulation was caused by nitrification inhibition. In both sandy and clay-loam soils, Bending and Lincoln (2000) found that SCN both reduced populations and inhibited the growth of nitrifying bacteria. Regarding DG, we speculate that the chemical compounds in the grain

that suppress weeds may also affect nitrifying bacteria. However, this effect has not been reported previously.

The ADF (with a C/N ratio of 20:1; calculated from Table 1) immobilized all of the available N in the soil after 84 days of incubation (Figure 1). Calderon et al. (2004) reported immobilization of N when manures with an average C/N of 19:1 were land-applied. The immobilization of available N in the soil with application of ADF suggests that additional N sources are necessary to decompose the ADF and to satisfy the N required for crops in the early growing period. However, 2 weeks after all of the N was immobilized (day 98 of incubation), organic N mineralization in the ADF-amended soil initiated. It is likely that once the microbes in the soil had converted C to carbon dioxide (CO_2), the C/N ratio in the soil had lowered to a level that was suitable for microbial N mineralization.

Estimated N Availability

The amount of plant-available N (NH_4-N + NO_3-N) after 210 days of incubation was estimated using the first-order equation for N mineralization (Chescheir, Westerman, and Safley 1986) for all amendments except for DMC and ADF. The r^2 value representing the fit of the observed inorganic N concentrations in the soil to the first-order equation was 0.27 for DMC and 0.66 for ADF, indicating that the equation did not suitably represent the N mineralization processes in soils amended with these materials. The first-order N mineralization equation was designed to model a progressive and increasing release of NH_4-N and NO_3-N compounds in the soil. Virtually no organic N was mineralized from the addition of DMC, making it difficult to illustrate with the model. The dominant organic N transformation process in the ADF-amended soil was immobilization instead of mineralization from day 26 to 84. For the purpose of discussion, we use the measured quantities of NH_4-N and NO_3-N for DMC and ADF to represent the expected amount of available N from these amendments.

For DMC-amended soils, the cumulative amount of plant available N after 210 days of incubation accounted for 1% of the total N in the amendment (Table 4). Gale et al. (2006) reported similar results with –2 to 14% of total N mineralized in 70 days from four different DMCs amended to silt loam and sandy loam soils at 25 °C. In the current study, the C/N ratio of the DMC was 10:1, which typically represents a favorable C/N ratio for N mineralization. Van Kessel and Reeves (2002) and Van Kessel, Reeves, and Meisinger (2000) reported that lignin was 10% of dairy manure dry matter, which would explain the relatively slow breakdown and subsequent mineralization of N. The extremely slow rate of N mineralization from DMC even after 210 days of incubation suggests that this organic source applied before planting would be ineffective in providing plant-available N for an annual crop.

Approximately 44% of the total N content in PL was in plant-available forms after 210 days of incubation, which is comparable to 197 kg plant-available N ha^{-1}. When the DMC and PL were combined at a ratio of 2:1 based on dry weight at the same rate of total N, the amount of N available over 210 days decreased to 29%, or approximately 130 kg plant-available N ha^{-1}. To meet the target N rate of 200 mg N kg $soil^{-1}$, 8.8 g of litter were added to the PL treatments, and 5.4 g of litter were added to the C/L treatments in combination with 11.0 g of compost. With the 38% reduction in the amount of litter added to the soil from the PL to the C/L treatment, available N contributed by the litter reduced by 34%. This indicates a slight increase in the amount of available N released from the compost material when combined with the litter in comparison to the soil amended by compost alone. A grower interested in supplementing PL with DMC should assume that

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Table 4
Predicted cumulative N mineralization using a first-order equation for N mineralization, as percentage of total N in the amendment, from various organic N sources applied to a Quincy fine sand at 200 mg total N kg^{-1}

Soil temp. (°C)	Incubation length (day)	DMC[a]	PL	C/L	MM	DG	ADF	PB
13.0	0	3	12	10	−7	−4	12	7
13.8	14	2	28	15	17	17	9	42
15.6	28	2	35	19	33	31	6	54
17.1	42	2	40	21	43	40	4	59
19.2	56	2	42	23	49	46	3	60
20.3	70	2	43	25	53	50	1	61
22.0	84	2	43	26	56	52	1	61
22.8	98	2	43	27	58	53	0	61
22.8	112	2	44	27	59	54	0	61
22.2	126	2	44	28	60	55	−1	61
19.5	154	2	44	28	61	56	−1	61
15.0	210	2	44	29	61	56	−2	61

[a]DMC, dairy manure compost; PL, poultry litter; C/L, poultry litter and dairy manure compost mixture; MM, mustard meal; DG, distillers grains; PB, Perfect Blend 7–2–2; and ADF, anaerobically digested fiber.

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the majority of available N originates from the litter over the first growing season after application.

Nitrogen availability for the 210-day incubation period was 61% for MM and 56% for DG, which is comparable to 273 and 251 kg plant-available N ha^{-1}, and could therefore potentially meet the N requirements for crops without chemical fertilizer supplements. The MM and DG used in this study had C/N ratios of 8:1 and 12:1. The C/N ratios less than 20:1 in the soil are ideal for N mineralization processes (Sylvia et al. 1999). Because of the high percentage of available N, these biofuel by-products are comparable to PL in their total N release but maintain NH_4-N concentrations for a longer period after the initial increase. The biofuel by-products, if competitively priced, should be of interest to conventional growers as an alternative N source to expensive chemical fertilizers and to organic growers as an alternative N source to raw manures.

At the conclusion of the study, NO_3-N and NH_4-N concentrations in the ADF-amended soil were comparable to the unamended control soil. This in turn suggests that the ADF would not be an appropriate source of organic N for annual crops.

Available N for PB was 61% over the 210-day incubation, which is comparable to 273 kg plant available N ha^{-1}. Organic N in the litter and feather meal was readily converted to plant-available forms. The PB had the lowest C/N ratio of all of the amendments, at 5:1, which would suggest a high percentage of available N in this product. Although it may not be economical to use this product on a field scale, PB would be a viable source of N for the home and garden market.

Potentially Available Organic N (N_o)

Estimates for N_o 210 days after application for PL, C/L, MM, DG, and PB are listed in Table 3; DMC and ADF are assumed to have N_o values of 0 mg kg^{-1} 210 days after

application. The portion of potentially available N from the organic fraction (N_o) over the 210-day period for soils amended at a rate of 448 total N ha^{-1} was 304, 271, 242, 140, and 84 kg N ha^{-1} for MM, DG, PB, PL, and C/L, respectively (derived from Table 3). The MM, DG, PL, and PB amendments have C/N ratios less than 12:1 and consist of mostly proteins, which are readily decomposed by ammonifiers in the soil. Of the amendments tested in this experiment, ADF and DMC had no net N released from the organic N fraction and therefore would have the greatest potential for building labile organic N and C pools in the soil. Application of organic amendments with large labile pools of organic N contributes to the release of available N in the soil over a prolonged period after application. Lack of reliable estimates of these organic N pools in the soil may lead to application of N in excess of what is needed for the crop uptake.

Nitrogen Mineralization Rate (k)

The rate constant of N mineralization was greater for the litter-based amendments (PB = 0.07, PL = 0.04) than for the biofuel by-products (DG = 0.03, MM = 0.03) and the C/L mixture (0.02) (Table 3). A lower mineralization rate constant indicates a slower release of N from the organic pool into the plant-available forms. Numerous studies illustrate the rapid mineralization of organic N compounds in PL (Alva, Paramasivam, and Sajwan 2006; Hanselman, Graetz, and Obreza 2004; Preusch et al. 2002; Pengthamkeerati et al. 2006). For PL and PB, 91 and 95% of the total N mineralized was completed in 42 days of the 210-day incubation, indicating that the organic N mineralized was readily available. The C/L had 72% of total N released by day 42, which does support the recommendation that adding compost to litter would slow the release of N to plants, and MM and DG had 70 and 71% of total N released by day 42, indicating the potential for biofuel by-products to be used as slow-release N sources.

Soil pH

Soil amendments with the greatest proportion of mineralizeable N had the greatest acidifying affects on the soil pH (Table 5). Over the 210-day incubation period, soil pH decreased from 7.5 (control soil) to 6.6, 5.9, 5.7, and 5.4 with the addition of PL, PB, DG, and MM, respectively (Table 5). This is to be expected, since nitrification is inherently an acidifying process. During periods when ammonification was the dominant N mineralizing process, as was seen between days 7 and 56 for the MM and between days 7 and 42 for DG, the soil pH increased (Table 5 and Figure 1). This is also to be expected, as ammonification is an alkalinizing process. It should be noted that the effects of mineralization on soil pH are amplified in a polyethylene sealed environment, in which chemical compounds are not leached out of the soil.

Conclusion

The MM had the greatest N fertilizer value of all of the amendments tested in this study, with 61% net N mineralization over a 210-day period, and a slow mineralization rate of 0.03 day^{-1}. Organic N was rapidly mineralized from PL and PB and relatively more slowly mineralized from the biofuel by-products. Compounds in MM and DG delayed the process of nitrification, thus increasing NH_4-N accumulation in the soil. Nitrogen mineralization from DMC was negligible during the 210-day incubation period, and therefore DMC would not be an effective sole source of readily available N for crops over a growing season.

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Table 5
Soil pH during incubation of various organic N sources applied to a Quincy fine sand at 200 mg N kg^{-1} (standard error values among five replications are listed in parentheses)

	Days after incubation					
Amendment[a]	7	42	70	98	154	210
DMC	8.0	8.0	7.6	7.9	7.8	7.6
	(0.028)	(0.028)	(0.474)	(0.005)	(0.016)	(0.012)
Control	7.5	7.6	7.5	7.4	7.3	7.1
	(0.018)	(0.016)	(0.028)	(0.009)	(0.026)	(0.012)
PL	8.2	7.1	7.0	6.9	6.8	6.6
	(0.040)	(0.026)	(0.026)	(0.017)	(0.011)	(0.030)
C/L	8.2	7.4	7.3	7.3	7.2	7.0
	(0.042)	(0.014)	(0.024)	(0.009)	(0.009)	(0.012)
MM	6.8	8.4	6.7	6.4	5.8	5.4
	(0.027)	(0.029)	(0.047)	(0.016)	(0.141)	(0.057)
DG	6.8	7.4	5.8	5.5	5.5	5.7
	(0.023)	(0.432)	(0.129)	(0.146)	(0.119)	(0.361)
ADF	7.8	7.6	8.1	7.9	7.5	7.1
	(0.017)	(0.011)	(0.016)	(0.004)	(0.015)	(0.093)
PB	8.1	6.4	6.0	5.9	5.8	5.9
	(0.040)	(0.107)	(0.197)	(0.172)	(0.136)	(0.413)

[a]DMC, dairy manure compost; PL, poultry litter; C/L, poultry litter and dairy manure compost mixture; MM, mustard meal; DG, distillers grains; PB, Perfect Blend 7–2–2; and ADF, anaerobically digested fiber.

Further investigation is needed to evaluate the N mineralization and plant uptake of these materials under field conditions to determine the N mineralization rates of these amendments after the first crop growing cycle, the varying rates of application, and the effect of applying these materials on concentrations of P, potassium, and other critical plant nutrients in the soil.

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