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ORIGINAL ARTICLE

Winter and growing season nitrogen mineralization from fall-applied composted or stockpiled solid dairy manure

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Abstract Adequate characterization of nitrogen (N) mineralization with time from manure and other organic sources is needed to maximize manure N use efficiency, decrease producer costs, and protect groundwater quality. The objective of our 2-year field study at Parma, ID, was to quantify in situ N mineralization with time as affected by a one-time fall application of solid dairy manure, either composted or stockpiled. The experiment included five treatments: a non-N fertilized control, two first-year rates of stockpiled solid dairy manure (21.9 and 43.8 Mg ha^{-1}, dry wt.) and two rates (53.1 and 106.1 Mg ha^{-1}, dry wt.) of composted dairy manure (hereafter termed compost). Net N mineralized (mineralization less immobilization) was determined to a depth of 0.3 m by repeatedly measuring soil inorganic N (NH_4-N + NO_3-N) concentrations in buried polyethylene bags. Overwinter mineralization was measured between amendment incorporation in fall and sugarbeet (*Beta vulgaris* L.) planting the following spring. In-season mineralization was measured in situ for seven consecutive incubation periods during the c. 220-day growing season for furrow-irrigated sugarbeet. Net N mineralized often varied among amendments and from year to year through mid-season, likely due to seasonal variation in soil temperature, annual differences in amendment properties, and other factors. In early spring 2003 after a warmer-than-normal winter, immobilization exceeded mineralization, regardless of treatment. In-season net N mineralized peaked between mid-August and early September (DOYs 230–251) each year, regardless of treatment. Annual (c. 11-month) net N mineralized in 2003 averaged 52 kg N ha^{-1}, similar among treatments. In 2004, annual net N mineralized was similar between rates within amendments and averaged 250 kg N ha^{-1} where manure treated, 150 kg N ha^{-1} where compost treated, and 106 kg N ha^{-1} where untreated. On average in 2004, 31 % of compost's annual net N mineralized occurred before the growing season and 69 % during the season while essentially all of manure's net N mineralized occurred during the season. None of the amendments' total N was, in net, mineralized in 2003 but in 2004 on average, 2 % of compost's and 16 % of manure's total N was mineralized, similar between rates

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within amendments. When estimating annual net N mineralized from fall-applied organic amendments, one must account for abnormal temperatures, including those overwinter.

Keywords Dairy manure · Nitrogen recovery · Nitrogen use efficiency · Nutrient management · Organic fertilizer

Abbreviations

DAA	Days after amendment application
DOY	Day of year
NUE	Nitrogen use efficiency
WFPS	Water-filled pore space

Introduction

Dairy manure and composted dairy manure are available as organic N sources in many agricultural areas of western North America's intermountain region. In 2015, Idaho's approximate 579,000 dairy cattle will generate nearly 13.7 million Mg of manure (Nennich et al. 2005; NASS 2015). Organic amendments like these benefit soils. Manure added to soils decreases bulk density and increases soil organic C, particularly in the short term (Haynes and Naidu 1998; Edmeades 2003). Dairy manure typically increases bacterial populations and the substrate diversity for microbes (Larkin et al. 2006). Judicious manure additions restore the productivity of eroded calcareous soils in both the western and central U.S. soon after application (Robbins et al. 1997; Mikha et al. 2014) and for years thereafter (Lentz et al. 2011). Applications of manure, compost, or both provide P, K, and other nutrients to subsequent crops (Robbins et al. 1997; Eghball 2002; Eghball et al. 2004; Moore et al. 2009).

While the composting of dairy cattle manure reduces the material's weight and volume to ease handling, transport, and field application (Draycott and Christenson 2003; Larney et al. 2006), the composting process also emits NH_3 and the greenhouse gases CO_2, CH_4, and N_2O to the atmosphere (Larney et al. 2006). Composting also requires inputs of energy, land, equipment, and labor, and decreases the organic sources' N availability by increasing the stability of the remaining organic compounds (Eghball 2000; Eghball et al. 2002; Gutser et al. 2005).

Dairy cattle in Idaho now produce nearly 6.3 billion kg of milk annually (NASS 2015). Much of the milk in the state's south-central region is supplied as the principal or key ingredient to processing plants that manufacture cheese, yogurt, and energy bar-type snack foods. To minimize the costs for transporting the milk, dairies are frequently located near the processing plants. This concentration of milk production in the region thereby concentrates the manure from the dairy cattle. Some of this manure, with nearly all of its N in organic forms (Lehrsch and Kincaid 2007), ideally can be used by crop producers as a substitute for relatively expensive conventional inorganic N fertilizers (Lehrsch et al. 2015a).

The use of manure as an organic N source is hindered by producer concerns related to both the rate and, especially for some crops, the timing of the mineralization of the manure N. Net N mineralized results collectively from four major microbially mediated processes: (1) ammonification and (2) nitrification that increase the soil's inorganic N pool while (3) immobilization and (4) denitrification decrease the inorganic N pool (Tisdale and Nelson 1975). All microbial processes occur simultaneously with their relative magnitudes determining net N mineralized (Cabrera et al. 2005). The key roles of microbes indicate that fluctuating temperature and water content will affect these processes, especially seasonally (Cassman and Munns 1980; Eghball et al. 2002; Cabrera et al. 2005). Due to its importance, N mineralization and its management have often been reviewed (e.g., Cabrera et al. 2005; Schoenau and Davis 2006; Webb et al. 2013; Müller and Clough 2014).

Numerous methods have been developed to measure N mineralization in the laboratory (e.g., Chae and Tabatabai 1986; Shi et al. 2004; Agehara and Warncke 2005; Gale et al. 2006) and the field (e.g., Eghball 2000; Khanna and Raison 2013). Of the field methods, the buried bag technique of Lentz and Lehrsch (2012a), as adapted from Eno (1960), gives representative estimates of in situ net N mineralized for the region's irrigated soils (Westermann and Crothers 1980; Meek et al. 1994; Lentz et al. 2011). The technique utilizes polyethylene film, permeable to O_2 and CO_2 but nearly impermeable to water vapor, to encase moist soil collected from, then replaced within a few hours into cavities in the soil profile. Once placed, the native microbial population either decomposes the nitrogenous organic compounds in the soil, utilizes any inorganic N present, or both, as the encased soil undergoes the same diurnal and seasonal temperature changes as the soil surrounding it but none of the N losses due to leaching or plant uptake, as roots do not penetrate the film. Changes in the bagged soil's inorganic N concentration between placement and subsequent removal accurately reflect microbial activity in the interim. These inorganic N changes in the encased soil serve as an index of N cycling in the bulk soil surrounding the bag. The buried bag data are an index because root exudates that normally stimulate N mineralization are no longer present. This lessened N mineralization, however, is partly or wholly offset by a stimulation of N mineralization as soil is disturbed by sieving during bag preparation.

Manure's agronomic N use efficiency (NUE), defined as the harvested mass of an agronomic crop per unit mass of manure N applied (Wen et al. 2003), can be optimized by synchronizing N mineralization with plant N uptake (Westermann and Crothers 1980, 1993; Appel 1994; Schoenau and Davis 2006; Spiertz 2010). For example, incorporating organic sources in late fall, at lower soil temperatures, rather than in early fall at higher temperatures, slows or delays (1) N mineralization (van Es et al. 2006), (2) nitrification (Brown 1988), or both. On the other hand, if (or as) crop N uptake slows later in the growing season but mineralization of manure N continues unabated, manure's NUE will decrease and the potential to impair groundwater quality may increase (Mallory et al. 2010). One crop for which synchrony between mineralization and uptake is especially critical is sugarbeet, *Beta vulgaris* L. (Carter and Traveller 1981). Sugarbeet must have adequate inorganic N in the upper profile during vegetative growth to enable quick and full canopy establishment but, later in the growing season, relatively little mineral N should be present in the root zone or else crop quality and producer economic return will suffer (Carter and Traveller 1981; Martin 2001). Adequate characterization of N mineralization with time will enable producers to improve the synchrony of crop N demand with N supply, thereby increasing NUE (Cassman et al. 2002).

Sugarbeet growers who apply organic N sources, manure for example, seldom apply them at high rates but others in the region may. If an Idaho dairyman wishes to use manure as a fertilizer on his field, he must apply the manure at a P-based rate if a soil test reveals P present at a level that exceeds a soil P threshold, among other factors (ISDA 2012). Farmers who own no dairy cattle have no such restriction and typically apply manure at greater rates, at times approaching or exceeding N-based rates. When they do, more P is applied than crops require, in general (Eghball and Power 1999). As a consequence, many soils in the region contain excessive P.

Despite widespread investigation of the N cycle, further study is needed on N flows and transformations in soil–plant systems, and on temperature and water content effects (Cabrera et al. 2005; Müller and Clough 2014). In particular, irrigated soils in the western U.S. experience unique environmental conditions, including those overwinter, that affect N cycling from post-harvest, fall-applied organic sources (Lentz et al. 2011, 2014; Lentz and Lehrsch 2012a). In-season mineralization of organic N is critically important, of course. Though less studied, off-season transformations of organic N can also increase soil inorganic N by spring. This newly mineralized N, in turn, can be acquired efficiently by, for example, winter wheat (*Triticum aestivum* L.) or any spring-seeded crop that requires much N relatively early in the growing season (Westermann and Crothers 1993). The N mineralized during the non-growing season should be available by spring provided that nitrification proceeds more slowly than ammonification, overwinter leaching is minimal, or both. The contribution of N mineralized overwinter may also be important for a producer who wishes to ensure that sufficient inorganic N is available to satisfy a crop's needs during its rapid-N-uptake growth stage (Sullivan et al. 1999). Studying net N mineralized over the winter enables one to better understand the N dynamics associated with the fall incorporation of crop residue and the planting of winter catch crops (Stenger et al. 1996).

An improved understanding of the competing processes of N mineralization and N immobilization, along with their temporal dynamics, may improve our ability to manage N cycling, increase NUE by minimizing N losses whatever the form, and increase the sustainability of agricultural systems that utilize typically applied organic N sources (Cabrera et al. 2005; Spiertz 2010). The objective of our 2-year field study was to improve our understanding of N availability from organic sources by monitoring N mineralization with time from fall-applied dairy manure, either composted or stockpiled. We studied the rate and duration of N mineralization in soil at moderate, rather than optimum, water contents. In our investigation, we also accounted for transient changes in soil temperatures on both a diurnal and seasonal basis, as recommended by Cabrera et al. (2005).

Materials and methods

Site, soils, and amendments

The experiment was conducted at the University of Idaho Research and Extension Center in Parma, ID, on two fields, each situated on a Greenleaf silt loam (fine silty, mixed, superactive, mesic Xeric Calciargid; Soil Survey Staff 2014). The same soil was studied since mineralization varies among soils (Honeycutt et al. 2005). We studied Field A in 2002 and 2003 and Field B in 2003 and 2004. A different field was used in 2003 to avoid carry-over impacts from previous applications of manure and compost. Properties of each field's soil are shown in Table 1. An estimated 9.0 Mg ha^{-1} of winter wheat residue was disked into Field A in September 2002 and into Field B in August 2003. Other than previous crop residues, no organic N source had been applied to either field for at least a decade prior to this study. Soil temperatures were obtained from an on-site weather station located about 130 m southwest of Field A and 420 m northwest of Field B (USDI 2015).

Amendments were applied to Field A in fall 2002 and to Field B in fall 2003. We assumed, in the 12 months following application, that 200 g N (kg total $N)^{-1}$ would be mineralized from compost (Richard 2005) and that 400 g N (kg total $N)^{-1}$ would be mineralized from manure (Eghball and Power 1999). We used these assumed values to determine each year's application rates of solid manure (never a slurry) and compost. The dairy manure was supplied by a local dairyman who scraped it from open pens and stockpiled it through the summer in temporary, unconfined piles. Mature composted dairy manure was obtained from a south-central Idaho supplier who processed scraped, solid manure with an initial moisture content of c. 65 % (wet mass basis) by mechanically turning 1.8-m-high by 5.5-m-wide windrows every 7 days, on average, for about 3.8 months. The windrows, that received no water other than precipitation, maintained a temperature of

Table 1 Soil properties of the Greenleaf silt loam in fall prior to amendment application (after Lehrsch et al. 2015a)

Soil properties (0- to 0.3-m depth, or as noted)	Field A 2002–2003[a]	Field B 2003–2004[a]
Particle size distribution (g kg^{-1})		
Sand (0.05–2 mm)	330	300
Silt (0.002–0.05 mm)	600	550
Clay (<0.002 mm)	70	150
Bulk density (g cm^{-3})		
0–0.3 m	1.47	1.47
0.3–0.6 m	1.37	1.37
Organic C (g kg^{-1})	6.4	5.5
pH (aqueous sat. paste)	7.8	7.6
Electrical conductivity (dS m^{-1})	0.56	0.54
$CaCO_3$ equivalent (g kg^{-1})	67	42
Residual inorganic N[b]		
0–0.3 m (mg kg^{-1})	8.1	15.2
0.3–0.6 m (mg kg^{-1})	7.0	8.8
0–0.6 m (kg ha^{-1})	66	105
P (mg kg^{-1})	10	14
K (mg kg^{-1})	110	180
B (mg kg^{-1})	0.13	0.24

[a] Amendments were applied in fall of the first year shown with sugarbeet grown in second year

[b] NO_3-N + NH_4-N

c. 58 °C for 2 months during active composting. Thereafter, compost in windrows (1) with temperatures within 7 °C of ambient and (2) that emitted little or no ammonia was deemed mature. After we collected, then dried samples of each amendment applied in fall 2002, we ground them to pass a 1-mm screen then determined their total C and N concentrations by dry combustion (Tabatabai and Bremner 1991) of an approx. 400-mg sample in a vario MAX carbon-nitrogen-sulfur analyzer (Elementar, Hanau, Germany). After collecting samples the following year, we determined their total N content via a micro-Kjeldahl analysis using a block digester (Watson et al. 2003). We weighed a fresh, 1-kg sample before and after drying at 60 °C to determine each amendment's dry matter content (Hoskins et al. 2003). Properties of the compost and manure applied each fall are shown in Table 2. Since dry matter (DM) contents are typically greater for compost than manure (Larney et al. 2006; Lehrsch and Kincaid 2007), the identical DM between amendments in 2003 is somewhat surprising. The manure in 2003 may have been collected from an older or smaller stockpile, one that had lost more water to evaporation. In any case, manure properties, including DM, vary greatly (Lindley et al. 1988).

Treatments and field operations

The experiment, described in detail by Lehrsch et al. (2015a), was a randomized complete block with four replications and eight treatments. The current study reports data from the five treatments on which N mineralization was measured (Table 3): a control (that received no N fertilizer), two first-year rates of stockpiled solid manure (21.9 and 43.8 Mg ha^{-1}, dry wt.) from dairy cattle replacement heifers, and two first-year rates (53.1 and 106.1 Mg ha^{-1}, dry wt.) of composted dairy cattle manure (hereafter termed compost). The optimum conventional N fertilizer rate recommended for sugarbeet (Gallian et al. 1984) was 202 kg N ha^{-1}, chosen to achieve a sugarbeet yield goal of 67.2 Mg ha^{-1}, after allowing for the 66 kg ha^{-1} of inorganic N in the 0.6-m-deep soil profile at study initiation in fall 2002 (Table 1). The low and high amendment rates were selected to provide the sugarbeet with plant–available N at the optimum and twice the optimum rate, respectively, for the 12 months following application. These N-based rates for compost, in particular, likely supplied 2–3 times more P than the sugarbeet required (Moore et al. 2009). Off-site transport of P, both dissolved and on suspended sediment, in irrigation runoff has been and continues to be a concern (Lehrsch et al. 2014). While N is mineralized from organic amendments, especially manure, for several years after application (Eghball et al. 2002; Lentz and Lehrsch 2012a), the focus of the current study was upon N mineralization within the first 12 months after application. No additional inorganic N fertilizer was applied to any of the manure- or compost-treated plots.

Due to an apparent error in a commercial laboratory's preliminary analysis of our fall 2002 manure sample (discussed by Lehrsch et al. 2015a), the estimated available N supplied by the 2003 manure treatments was about 31 % less than our two targeted rates, 202 and 403 kg N ha^{-1} (Table 3). In consequence, the two compost treatments in 2003 supplied on average about 1.55-fold more estimated available N than the two corresponding manure treatments (Table 3). In southern Idaho, bulk application rates (dry wt. basis) can be as great as 28 Mg ha^{-1} for compost and 55 Mg ha^{-1} for manure.

Field activities are summarized in Table 4. After incorporating wheat crop residue, eight soil samples

Table 2 Properties of the compost and manure applied to each field in the fall preceding the year shown

Property	2003		2004	
	Compost	Manure	Compost	Manure
Total C (g kg^{-1})	282	162	–	–
Total N (g kg^{-1})	20.5	16.0	15.7	22.1
C:N ratio	13.8	10.1	–	–
Dry matter content (kg kg^{-1})	0.65	0.65	0.65	0.40

Other than dry matter content, all measurements are on a dry-weight basis

–, not determined

Table 3 Treatment application rates (dry wt. basis) and total N for sugarbeet grown in the year shown

Treatment	Appl. rate (Mg ha^{-1})		Total N appl. rate (kg ha^{-1})		Estim. avail. N[a] (kg ha^{-1})	
	2003	2004	2003	2004	2003	2004
Control	0	0	0	0	0	0
Compost1	53.1	64.2	1089	1008	218	202
Compost2	106.1	128.4	2175	2016	435	403
Manure1	21.9	22.8	350	504	140	202
Manure2	43.8	45.6	701	1008	280	403

Also given are estimates of each treatment's nitrogen that became available via mineralization in the year ending at sugarbeet harvest

[a] Calculated assuming a first-year mineralization of 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure (Eghball and Power 1999; Richard 2005)

Table 4 Schedule of field activities

Activity	Date (DOY)	
	Field A (2002–2003)	Field B (2003–2004)
Disked to incorporate wheat residue	4, 9, 24 September 2002 (247, 252, 267)	28 August 2003 (240)
Plots rototilled	14 October 2002 (287)	23 October 2003 (296)
Soil sampled (pre-treatment)	16 October 2002 (289)	24 November 2003 (328)
Amendments applied, then rototilled	8 November 2002 (312)	28 November 2003 (332)
Beds formed	8 November 2002 (312)	2 December 2003 (336)
Buried bags placed in fall	18 November 2002 (322)	10 December 2003 (344)
Fertilized (topdressed) with P, K, and B	1 April 2003 (91)	NA[a]
Buried bags removed in spring	3 April 2003 (93)	29 March 2004 (89)
Bed tops removed	3 April 2003 (93)	29 March 2004 (89)
Sugarbeet planted	4 April 2003 (94)	1 April 2004 (92)
Buried bags placed in spring	14 April 2003 (104)	2 April 2004 (93)
Sugarbeet stands thinned	17 May 2003 (137)[b]	14 May 2004 (135)
Cultivated	22 May 2003 (142)	27 April 2004 (118)
Buried bags removed	28 May 2003 (148)	30 April 2004 (121)
Cultivated	18 June 2003 (169)	21 May 2004 (142)
Buried bags removed	7 July 2003 (188)	28 May 2004 (149)
Cultivated	9 July 2003 (190)	8 June 2004 (160)
Buried bags removed	28 July 2003 (209)	25 June 2004 (177)
Buried bags removed	18 August 2003 (230)	23 July 2004 (205)
Buried bags removed	8 September 2003 (251)	20 August 2004 (233)
Buried bags removed	29 September 2003 (272)	17 September 2004 (261)
Buried bags removed	20 October 2003 (293)	15 October 2004 (289)
Sugarbeet harvested	27 October 2003 (300)	22 November 2004 (327)

[a] NA = not applicable (no non-N fertilizer was applied)

[b] Day is approximate

(0–0.3 and 0.3–0.6 m) were collected from the field, then composited by depth to determine the site's baseline contents of inorganic N (calculated as NO_3-N + NH_4-N), P, K, and micronutrients (Table 1). After applying the organic amendments by hand to the 12-row, 6.7-m-wide × 15.2-m-long plots in the fall, we incorporated them to a depth of 0.1 m with a rototiller, then formed beds for the sugarbeet using toolbar-mounted shovels. Amendments were incorporated within 31 h of application (1) to avoid N loss via ammonia volatilization (Eghball et al. 2002; Webb et al. 2013), and (2) to increase crop N recovery (Schoenau and Davis 2006).

About 9 days after the organic N sources were fall applied and after beds were formed (Table 4), we installed one buried bag in a bed center in each plot to measure overwinter N mineralization (described below). These bags were recovered just prior to spring planting. After fertilizer was applied and sugarbeet was planted in the spring, we installed seven new buried bags in bed centers in each plot. In-season net N mineralized was measured periodically by retrieving one set of buried bags on each of seven dates during the growing season (Table 4).

Based upon the analyses of the pre-treatment soil test samples collected the previous fall, Field A was uniformly fertilized in spring with P (as triple superphosphate at a rate of 13.2 kg P ha^{-1}), K (as KCl at 33.5 kg K ha^{-1}), and B (as Solubor at 1.15 kg B ha^{-1}). In Field B, all nutrients save N were present in adequate amounts, based upon pre-treatment soil tests. All nutrients applied on 1 April 2003 were incorporated that day but only coincident to the removing of any peaks on the beds as they were reformed and furrows reestablished using tool bar-mounted shovels. After removing the buried bags that were installed the previous fall, sugarbeet was planted to a depth of 25 mm in a row centered on each bed.

Plots were furrow irrigated 15 times in 2003 and 14 times in 2004, using furrows spaced 1.12 m apart and separated by two beds. Locally standard production practices were used to manage the sugarbeet crop (Panella et al. 2014). As the season progressed, we periodically cultivated the field and removed buried bags from the plots (Table 4). After being mechanically topped, the sugarbeet was harvested. Sugarbeet yield, quality, N uptake, and N use efficiency were reported earlier (Lehrsch et al. 2015a, b).

Measuring net N mineralized

We studied N mineralization at the 0- to 0.3-m depth because (1) most mineralization occurs there in the region's soils (Carter et al. 1976; Lentz et al. 2011), and (2) sugarbeet preferentially acquire inorganic N from there (Zinati et al. 2001). We employed the buried bag method of Westermann and Crothers (1980), one subsequently adapted by Lentz and Lehrsch (2012a). From each plot one (fall) or seven (spring) 57-mm-diameter soil cores, 0- to 0.3-m deep, were collected using a bucket auger, composited, and passed through a 4-mm screen. Tap water was added, if necessary, to achieve a soil water content of c. 0.20 kg kg^{-1} (c. −86 kPa matric potential and c. 39 % water-filled pore space, WFPS). The 39 % WFPS did not limit gas exchange and maintained adequate aeration to prevent denitrification (Linn and Doran 1984). After collecting a subsample to determine residual NO_3-N and NH_4-N (described later) at bag placement, the soil was vertically shaken into a 10-µm-thick, 50-mm-diameter polyethylene tube that had been knotted on one end to seal it. After expelling excess air, the remaining open end was knotted. Thereafter, the resulting 0.3-m-long soil column was placed into one of the sampling cavities created earlier. Sieved soil was then (1) placed by hand around the tube filling the cavity and (2) mounded above the tube to eliminate water flow along the buried tube's sidewalls and to shed water at the soil surface. Nitrogen mineralization was also monitored in the 0.3- to 0.6-m depth, though only in the control, in a similar manner (data not reported). Soil collected at bag placement and from each bag when removed was analyzed to determine its NO_3-N and NH_4-N concentrations after being air dried and ground to pass a 2-mm sieve. After extracting soil inorganic N with a 2-mol L^{-1} KCl solution, we colorimetrically determined each soil sample's NO_3-N concentration after cadmium reduction and its NH_4-N concentration after reacting with salicylate and hypochlorite (Mulvaney 1996). Net N mineralized at each removal date was calculated by subtracting the bagged soils' inorganic N concentration at placement from that at removal. Calculated this way, net N mineralized accounted for the inorganic N in the soil and in any added amendment and was thus a measure of the mineralization of only organic N. Each treatment's annual net N mineralized was the inorganic N concentration in the soil at bag removal at growing season's end less that at bag placement in fall of the preceding year. The net N mineralized on an annual basis was also converted to kg N ha^{-1} by multiplying the mg N (kg dry soil)$^{-1}$ values by the field's bulk density (Table 1) and the sampled depth, 0.3 m, then adjusting units as needed. The apparent N mineralization rate (ANMR, as % of total N applied) for each treatment except the control was calculated as:

$$ANMR = \frac{(N\ min_{Ann,Trt} - N\ min_{Ann,Ctrl})}{N\ Applied_{Tot,Trt}}(100) \qquad (1)$$

where N $min_{Ann,Trt}$ was the treatment's annual net N mineralized (now expressed as kg N ha^{-1}), N $min_{Ann,Ctrl}$ was the control's annual net N mineralized (kg N ha^{-1}), and N $Applied_{Tot,Trt}$ was the treatment's total N applied (kg N ha^{-1}, Table 3). Priming effects, if any, of the added amendments were not considered.

Data handling and statistical analyses

Before analyzing our data, we first tested for stable variances by regressing the logs of each response variable's within-treatment standard deviations on the logs of its corresponding treatment means. If the resulting linear regression was not significant, then one had evidence for stable error variances for that variable (Box et al. 1978; Lehrsch and Sojka 2011). Alternatively, if the regression was significant we stabilized that variable's error variance by transforming the variable's raw data using the transformation suggested by the fitted coefficient of the regression's independent variable (Box et al. 1978). We then analyzed the data by date using a mixed-model ANOVA using PROC Mixed in SAS (SAS Institute Inc. 2014) with a significance probability (*P*) of 0.05. Our statistical model had treatment as the fixed effect and block as the random effect. We used ANOVA grouping options, if needed, to account for heterogeneous variances among treatments for each response variable. When a fixed effect was significant, we separated least-squares means using the Tukey–Kramer test with letter groupings assigned using the technique of Saxton (1998). Where needed, means were back-transformed into original units for presentation.

We used PROC NLIN in SAS to model in-season cumulative net N mineralized with time for each treatment each year by fitting experimental data to a logistic-type growth curve:

$$y = y_{asym}/\{1 + \exp[-k(DOY - DOY_m)]\} \qquad (2)$$

where y was the cumulative net N mineralized (mg N kg^{-1}) on a particular day of year, DOY, y_{asym} was the asymptotic value of the cumulative net N mineralized (mg N kg^{-1}), k was a unitless parameter that controlled the steepness of the curve, and DOY_m was the DOY at the inflection point of the curve (Archontoulis and Miguez 2015). Due to an oversight, NH_4-N was not measured on the soil in the buried bags collected on 30 April 2004. We used PROC NLIN to estimate each soil sample's NH_4-N concentration by also fitting Eq. 2 to each treatment's NH_4-N concentrations for the entire 2004 growing season. For each treatment, the 30 April 2004 estimate of NH_4-N from Eq. 1 was added to the measured NO_3-N concentration of every replicate to obtain that replicate's inorganic N concentration for that date.

Results

Overwinter mineralization

The five treatments were ranked, in terms of fall soil inorganic N, identically in Fields A and B (Table 5). Though the inorganic N in fall was 1.5-fold greater, on average, in Field B than A, the ranking of the treatments was identical with Compost2 > Manure2 > Compost1 > Manure1 > control. The ranking followed, in general, the rates of total N applied by the treatments (Table 3). When comparing the amendments, the inorganic N for Compost2 was greatest in Field A and greatest in magnitude in Field B. All other amendment treatments in Field B had similar organic N concentrations. In contrast to Field A, inorganic N in Field B did not differ between the two manure treatments nor among them, Compost1, and the control (Table 5).

Net N mineralized over the winter and spring was either negative or nearly zero, except for compost in Field B (Table 5). In Field A, net N mineralized during the period from fall 2002 to spring 2003 was negative for all treatments. Thus in the buried bag soils during that winter, less N was mineralized than was immobilized in microbial tissues. Similarly in Field B's control and manured soils by spring, immobilization either exceeded mineralization or nearly equaled it (Table 5). Only did Field B's compost treatments produce small, but positive net N mineralized by spring.

By spring in Field B, overwinter net N mineralized in Compost2 was the greatest in magnitude, though it significantly exceeded only those of the two manure

Table 5 Soil inorganic N in fall and overwinter net N mineralized in spring (0–0.3-m depth) in Fields A and B as affected by compost and manure

Treatment	Field A (2002–2003)[a]		Field B (2003–2004)	
	Inorganic N in fall[b] (mg N kg^{-1} dry soil)	Overwinter net N mineralized by spring[c] (mg N kg^{-1} dry soil)	Inorganic N in fall[b] (mg N kg^{-1} dry soil)	Overwinter net N mineralized by spring[c] (mg N kg^{-1} dry soil)
Control	7.5 d[d]	−4.5 a	13.4 b	0.1 b
Compost1	19.7 b	−13.9 bc	26.8 b	8.1 ab
Compost2	35.8 a	−19.6 c	48.5 a	12.7 a
Manure1	13.0 c	−10.1 b	20.0 b	0.1 b
Manure2	20.4 b	−16.2 bc	29.4 ab	−1.8 b

[a] In Field A only, the estimated available N differed between amendments within rates (Table 3), thereby making comparisons between amendments within rates inappropriate

[b] Soil inorganic N (NO_3-N + NH_4-N) was measured in fall in Field A on 18 November 2002, 10 days after amendment application (DAA) and in Field B on 10 December 2003, 12 DAA

[c] Overwinter net N mineralized was the soil inorganic N concentration in spring at bag removal less the buried bag inorganic N concentration in fall. Nitrogen was measured in spring in Field A on 3 April 2003, 147 DAA, and in Field B on 29 March 2004, 122 DAA

[d] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$

treatments and the control (Table 5). At the same time, mineralization for each of the manure treatments in Field B was similar to the control, suggesting that N immobilization played a greater role over winter in soil amended with manure than compost. In contrast with spring data in Field A, immobilization exceeded mineralization only for the Manure2 treatment. Lentz et al. (2011) also reported that manure added in the fall increased immobilization by the following spring.

Soil inorganic N measured in fall about 11 days after applying the amendments increased with amendment application rate, both years for compost and one for manure (Table 5). By the following spring, however, net N mineralized was similar between rates within amendments. Stated succinctly, amendment rates affected inorganic N in fall but not net N mineralized by spring, their effects having been negated in the interim by the processes of immobilization, mineralization, or most likely a combination of both.

In-season mineralization

The inorganic N concentrations in the soil that was placed into the spring buried bags trended upward with amendment rate, but the difference was significant only in Field B where the inorganic N was 2.7-fold greater for Compost2 than Compost1 (Table 6). In general, the inorganic N in the control was similar to that in the lower amendment rates but was less than that in the higher amendment rates (Table 6).

In the 2003 growing season, cumulative net N mineralized never differed between the Compost1 and Compost2 treatments and seldom differed between the Manure1 and Manure2 treatments (Table 7). In contrast, Shi et al. (2004) found differences in mineralization between compost rates of 100 and 200 kg available N ha^{-1}, roughly half those we studied (Table 3). One would think it would be harder to detect mineralization differences with lower rather than higher rates. In addition to lesser rates, different findings may have been due to differing soils and techniques used to measure net N mineralized.

Early in the 2003 growing season, net N mineralized in the Compost2 treatment generally was greater than that of the control (through 28 July, DOY 209) but, by 18 August (DOY 230) this difference had disappeared (Table 7). Likewise, mineralization for both the Manure1 and Manure2 treatments was generally greater than the control but only through 28 July, approximately mid-season (Table 7). From 18 August (DOY 230) onward, however, mineralization was similar among both compost treatments, both manure treatments, and the control, in general.

In 2003, net N mineralized was greater from DOY 188 through 209 where the high rate of compost or either rate of manure was applied, relative to the control (Table 7). This finding reveals that compost

Table 6 Soil inorganic N (NH_4-N + NO_3-N) at the 0–0.3-m depth when the buried bags were installed in spring after planting sugarbeet

Treatment	Field A[a] (mg N kg^{-1}) 14 April 2003 (DOY[b] 104)	Field B (mg N kg^{-1}) 2 April 2004 (DOY 93)
Control	5.1 c[c]	16.0 b
Compost1	9.7 a	19.6 b
Compost2	15.4 a	52.1 a
Manure1	5.8 bc	21.0 b
Manure2	8.2 ab	26.5 b

[a] In Field A only, the estimated available N differed between amendments within rates (Table 3), thereby making comparisons between amendments within rates inappropriate

[b] DOY = day of year

[c] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$

Table 7 Growing-season cumulative net N mineralized (0–0.3-m depth) in buried bags as affected by compost and manure

Treatment	Cumulative net N mineralized[a] (mg N kg^{-1}) Field A (2003)[b]						
	28 May (DOY 148)	7 July (DOY 188)	28 July (DOY 209)	18 August (DOY 230)	8 September (DOY 251)	29 September (DOY 272)	20 October (DOY 293)
Control	2	7 b[c]	13 c	20 ab	24	19	20
Compost1	5	14 ab	19 bc	23 ab	32	−2	21
Compost2	7	19 a	23 ab	27 ab	14	15	23
Manure1	2	16 a	24 ab	15 b	37	31	22
Manure2	5	21 a	30 a	39 a	30	19	22

[a] Cumulative net N mineralized was the inorganic N (NO_3-N + NH_4-N) concentration in the soil at bag removal on the dates shown less the inorganic N concentration at bag placement on 14 April 2003 (DOY 104) (Table 6)

[b] The estimated available N differed between amendments within rates in Field A (Table 3), thereby making comparisons between amendments within rates inappropriate

[c] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$. No letters are shown if the effect was not significant in the ANOVA

had to be applied in 2003 at a bulk application rate 2.4–5 times that of manure (Table 3) to achieve the similar benefit of greater plant available N relative to the control in early to mid-season, that is, about 90–120 days after sugarbeet planting.

Through mid-season, organic N was mineralized fastest where soil was amended with manure, intermediate with compost, and slowest where untreated, when soil N was measured as the net of mineralization less immobilization (Table 7). From 28 May to 28 July (DOY 148–209), N was mineralized at a net rate of 0.38 mg N kg^{-1} day^{-1} for manure, 0.25 for compost, on average, and 0.17 for the control. Peak net N mineralized occurred between 18 August and 8 September (DOY 230 and 251), regardless of treatment. Thus, where fall fertilized with an organic N source, on average in 2003 net N mineralized peaked 60 days before sugarbeet harvest.

From 8 September onward, net N mineralized decreased slightly with time, in general, and did not differ among treatments (Table 7). The growing season net N mineralized total of 21 mg N kg^{-1} for the Compost1 treatment (Table 7) was similar to that measured using buried bags by Monaco et al. (2010) for a similar rate of compost annually applied to a northern Italian calcareous loam.

Cumulative net N mineralized in 2004 for the control, Manure1, and Manure2 treatments are shown in Fig. 1. Since the cumulative mineralization was similar, in general, for the Compost1, Compost2, and Manure1 treatments, data are shown in Fig. 1 only for the representative Manure1 treatment. As in 2003, despite Compost2 supplying twice the available N as Compost1 (Table 3), not once throughout the 2004 season did mineralization differ significantly between compost rates (data not shown). An increase in gross mineralization commensurate with an increase in gross immobilization with increasing compost rates could account for these similar year-to-year findings. Another possible explanation is that some limiting factor may have constrained mineralization where more compost substrate was added. In any case, simply adding larger quantities of compost's predominantly recalcitrant organic compounds did not result in greater net N mineralized during the growing season. The nature, rather than the amount, of the compost's organic N was the factor controlling the in-season net N mineralized of compost, as noted by Eghball (2000) and Gutser et al. (2005). Compared to compost, manure's greater amount of more readily oxidizable nitrogenous organic compounds had a decisive effect on season-long mineralization (Fig. 1). From 28 May 2004 (DOY 149) onward, cumulative mineralization was twofold greater in the Manure2 than Manure1 treatment, on average.

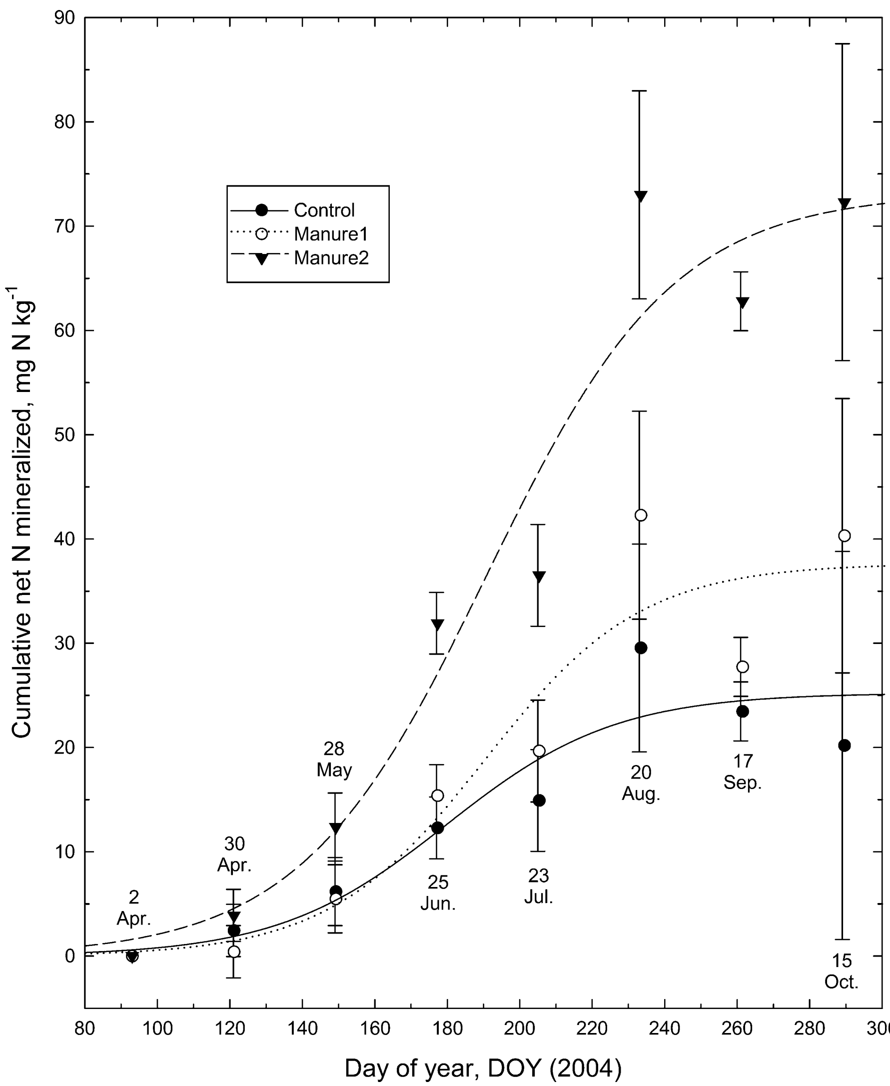

Fig. 1 Cumulative net N mineralized by treatment in 2004. Data shown for the Manure1 treatment were representative of that for the Compost1 and Compost2 treatments (not shown). Means ($n = 4$, shown with 95 % confidence limits) whose confidence intervals overlap were not significantly different at $P \leq 0.05$

Beginning on 28 May (DOY 149) and continuing for the remainder of the 2004 growing season, the N mineralized in the high rate manure treatment exceeded that of the other treatments plotted (Fig. 1). This was expected because the Manure2 treatment applied twice the estimated available N as the Compost1 and Manure1 treatments (Table 3). After the warmer 2002–2003 winter, mid-season net N mineralized was often greater for Manure1 than the control (Table 7). Following the cooler more representative 2003–2004 winter, however, N mineralization never differed between Manure1 and the control (Fig. 1).

As occurred in 2003, organic N was mineralized at a faster rate from 28 May to 23 July 2004 (DOY 149–205) where organically amended than where not (Fig. 1). During that 56-day period, N was mineralized at 0.35 mg kg^{-1} day^{-1} for manure, 0.20 for compost, and 0.16 for the control, quite similar to the rates for the same period in 2003. Moreover, cumulative net N mineralized was greatest on 20 August 2004 (DOY 233) for every treatment, again similar to that found the earlier year. These net N mineralized maximums occurred 94 days before sugarbeet was harvested in 2004 (Table 4).

Twenty-eight days after peaking on 20 August 2004, net N mineralized decreased notably for every treatment (Fig. 1), revealing that immobilization exceeded mineralization during the interim. Lentz et al. (2011) reported similar findings. Surprisingly, net N mineralized for the Manure1 and Manure2 treatments increased nearly as much after 17 September as it had decreased before 17 September. The slight late-season decline in N mineralization for each treatment from its peak on 20 August to its last measurement on 15 October was less pronounced in 2004 than 2003.

Annual net N mineralized

In Field A by the end of the 2003 growing season, 347 days after the amendments were applied, annual (c. 11-month) net N mineralized did not differ among treatments, averaging 11.7 mg N kg^{-1} (Table 8), equivalent to 52 kg N ha^{-1}. In contrast, by the end of the 2004 growing season in Field B mineralization was greater where we applied the high rate of manure than either the control or the low rate of compost. Relative to the control, net N mineralized increased threefold where we applied 403 kg ha^{-1} of estimated available N in the high rate manure treatment (Table 3). Also, when averaged across rates that year, the net N mineralized from manure, 55.7 mg N kg^{-1} (250 kg N ha^{-1}), was nearly 1.7-fold greater ($P < 0.01$) than the 33.4 mg N kg^{-1} (150 kg N ha^{-1}) from compost, according to a single-degree-of-freedom contrast. The N mineralized in the control was least, 23.6 mg N kg^{-1} (106 kg N ha^{-1}).

Surprisingly, in each year the annual net N mineralized was similar among the control, both rates of compost, and the low rate of manure (Table 8). In addition, in Field A where less N was mineralized than in Field B, neither the high rate of compost nor manure led to more N being mineralized than the control.

Apparent N mineralization rate

The apparent N mineralization rate was the annual net N mineralized in excess of the control expressed as a percent of the total N applied, Eq. 1. The apparent N mineralization rate in Field A (2003) was negative, signifying that the year-long cumulative inorganic N in the buried bags was less than the total N applied the preceding fall, differing little among amendment treatments (Table 9). By the end of the 2004 season in Field B, however, the apparent N mineralization rate was positive, reflecting a net gain in buried bag inorganic N relative to total N applied in every amended treatment (Table 9). The apparent N mineralization rate where compost-treated was very low, reflecting compost's generally recalcitrant organic compounds (Eghball et al. 1997). The apparent N mineralization rate of the Manure2 treatment, similar to that of Manure1, exceeded that of both compost treatments. On average, 8.2-fold more inorganic N was recovered in buried bags from the manure than compost treatments in 2004. The apparent N mineralization rates shown in Table 9 for compost both years and for manure in 2003–2004 compare favorably with rates reported by Lentz et al. (2011) and Lentz and Lehrsch (2012a). Data in Table 9 reveal that the apparent N mineralization rate and, by extension, net N mineralized can differ greatly from year to year.

Table 8 Annual net N mineralized (0–0.3-m depth) in buried bags as affected by compost and manure

Treatment	Cumulative net N mineralized[a] (mg N kg^{-1} dry soil)	
	Field A[b] (2002–2003) To 20 October 2003 (347 DAA[c])	Field B (2003–2004) To 15 October 2004 (322 DAA)
Control	17.9	23.6 b[d]
Compost1	10.8	27.1 b
Compost2	4.5	39.6 ab
Manure1	14.8	41.0 ab
Manure2	10.4	70.4 a

[a] Cumulative net N mineralized was the inorganic N (NO_3-N + NH_4-N) concentration in the soil at bag removal on the date shown less the buried bag inorganic N concentration at bag placement in fall of the preceding year

[b] In Field A only, the estimated available N differed between amendments within rates (Table 3), thereby making comparisons between amendments within rates inappropriate

[c] DAA = days after amendment application

[d] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$. No letters are shown if the effect was not significant in the ANOVA

Table 9 Apparent N mineralization rate (0–0.3-m depth) by compost and manure for the year following application

Treatment	Apparent N mineralization rate[a] (%)	
	Field A (2002–2003)	Field B (2003–2004)
Compost1	−3	1 b[b]
Compost2	−2	3 b
Manure1	−4	14 ab
Manure2	−4	19 a

[a] Apparent N mineralization rate was the annual net N mineralized in excess of the control expressed as a percent of the total N applied (Table 3)

[b] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$. No letters are shown if the effect was not significant in the ANOVA

Discussion

Immobilization processes were apparently more active during the winter period in Field A than B (Table 5). This may have occurred for several reasons. First, this greater immobilization relative to mineralization was likely a consequence, assuming adequate soil moisture, of increased microbial activity spurred by warmer-than-normal soil temperatures experienced during the 2002–2003 winter (Fig. 2). For example, the mean monthly soil temperature at the 5.1-cm depth was greater than the 15-years average by 2.0 °C in December 2002, by 3.2 °C in January 2003, and by 1.9 °C in February 2003. In addition, relative to Field B in January 2004, Field A's January 2003 soil temperature was 2.7 °C greater (Fig. 2). These warmer winter temperatures probably increased N immobilization (Nicolardot et al. 1994) and in turn, decreased overwinter net N mineralized in every treatment from fall 2002 to spring 2003 (Table 5). Immobilization after organic N sources were applied then incorporated have been reported by others (Stenger et al. 1996; Gutser et al. 2005; Gale et al. 2006). Why abnormally warm winter temperatures should increase microbial immobilization more than mineralization is unclear.

Second, amendments were applied 20 days earlier to Field A in 2002 than to Field B in 2003 (Table 4). During this c. 3-week fall period when local soils were relatively warm (Fig. 2), microbes had ample opportunity to multiply due to readily available organic C as substrate (Larkin et al. 2006). In consequence, these microbes apparently immobilized N by incorporating the inorganic N already present or newly mineralized into organic N forms in their tissues (Stenger et al. 1996). This N, once immobilized in microbial biomass in the fall, had not yet been mineralized by early spring (Table 5), as Stenger et al. (1996) found as well. Soil microbial populations can increase markedly shortly after adding easily decomposable organic compounds. In such situations, population increases have been so substantial that microbial biomass obstructed pores

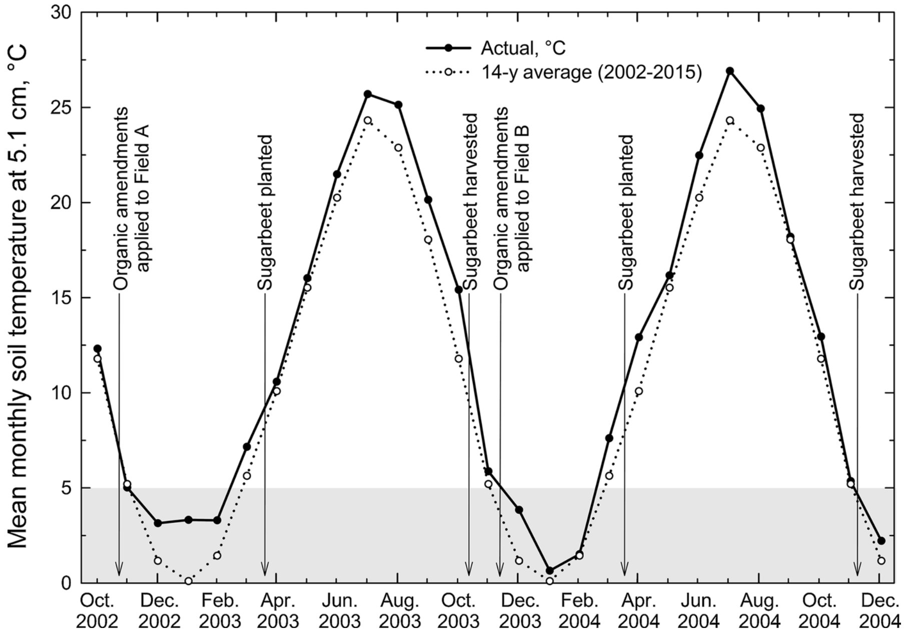

Fig. 2 Mean monthly soil temperatures at a depth of 5.1 cm for the 2-year study. For reference, 14-y-average soil temperatures are also shown

and, in turn, decreased soil hydraulic conductivities (McAuliffe et al. 1982; Lehrsch and Robbins 1996).

Third, residue management in fall 2002 may have limited decomposition in early fall while enhancing overwinter immobilization. Wheat residue was incorporated by disking but only to a depth of about 0.1 m that left much crop residue within the tilled zone. Moreover, to better shred the straw the site was disked three times in 20 days in 2002 (Table 4), drying the soil more each time, thereby limiting microbial activity and slowing residue decomposition prior to that fall's amendment applications and subsequent buried bag placement.

In this study we detected no late season flush of mineralized N in soil fall fertilized with either compost or manure (Table 7; Fig. 1), a concern previously expressed for its deleterious effect on sugarbeet quality (Carter and Traveller 1981). This similar late-season mineralization explains, at least in part, why sugarbeet sucrose yield and quality did not decrease due to late-season N uptake (Lehrsch et al. 2015a, b), as is often suspected where an organic N source such as manure is applied before planting sugarbeet (Carter and Traveller 1981; Moore et al. 2009).

In general, net N mineralized decreased slightly for all treatments from September 8 onward in 2003 (Table 7). This late-season decrease in net N mineralized may reflect increased N immobilization as a narrowing of the C/N ratio after mid-season spurred microbial activity. Studying another of the region's irrigated silt loams, Lentz et al. (2011) also reported net N mineralization rates that (1) were low to moderate during winter through spring, (2) decreased in early summer due to immobilization, (3) increased to a maximum in late summer, then (4) decreased in late fall. Similar trends of growing-season net N mineralization were reported by Monaco et al. (2010), despite great differences in climate, manure application history, and water availability.

The net N mineralized from 28 May 2004 onward was greater for the Manure2 than Compost2 treatment (the latter not shown but similar to the Manure1 treatment shown in Fig. 1). This occurred despite the fact that we applied compost at twice the total N rate of manure in 2004 to account for differences in assumed mineralization (Table 3). Apparently, the mineralization of N from compost was less than our assumed rate of 200 g N (kg total N)$^{-1}$. Another point to note is that the net N mineralized from the Manure1 treatment in 2004 was not only similar to that of both compost treatments as noted earlier but also to the control (Fig. 1). Two explanations are possible. First, the net

N mineralized from the unamended control may have been substantial, equaling that where moderate rates of manure were added. Second, less N may have been mineralized, when measured as the net of mineralization less immobilization, from the manure than we had estimated. In other words, our estimate of net N mineralized from manure, 400 g N (kg total N)$^{-1}$, should have been about 160 g N (kg total N)$^{-1}$. The latter explanation may be more plausible, at least for the 2003–2004 winter with temperatures being nearer to average (Fig. 2).

One might speculate as to why annual net N mineralized where organic amendments were applied was 2.5- to 8.8-fold greater in 2004 than in 2003 (Table 8). Four reasons are possible. First, less uniform residue incorporation into drier soil likely limited early fall decomposition more in 2002 than 2003, thereby delaying much of the decomposition until the following spring, as discussed earlier. Second, greater mineralization in the second year may have been due to the amendments being applied and incorporated 20 days later in fall 2003 than fall 2002, Table 4 (Brown et al. 2006). Later incorporation in fall 2003 coupled with cooler soil temperatures may have altered the relative timing of the immobilization and mineralization processes (Brown 1988) such that the buried bag retrieved the following spring measured an accumulation of inorganic N. Third, N immobilization was likely greater in 2003 in Field A than in 2004 in Field B because there was 47 % less residual inorganic N in the uppermost 0.3 m of Field A than B (Table 1). Besides less inorganic N, less total N was supplied by the manure treatments, but not the compost, in 2003 than 2004 (Table 3). This view that substantial immobilization occurred in Field A is supported by overwinter net N mineralized data in Table 5 that showed that, for every treatment, N immobilization exceeded mineralization in the spring 147 days after the amendments were applied. Fourth, the warmer-than-average soil temperatures in July and August of 2003 (Fig. 2) may have contributed to greater microbial activity (not measured) leading to greater immobilization of the inorganic N that had been mineralized up to that time during the 2003 growing season. Watts et al. (2010) and Lentz and Lehrsch (2012b) reported data that also suggested that a portion of their applied organic N that had been mineralized earlier in the growing season was immobilized during the early summer.

One can compare the net N mineralized to early spring (Table 5) with that mineralized to mid-October (Table 8) to gain insight into the mineralization that occurred from growing season's beginning to its end. In Field A at season's beginning (spring, Table 5), mineralization was less than immobilization in every treatment with net N mineralized always less where amended than unamended. In Field A by season's end (20 October, Table 8), however, mineralization was greater than immobilization in every treatment. Though the ranking of treatments remained the same from season's beginning to end, by 20 October there were no longer any differences in net N mineralized among treatments. In Field B, net N mineralized was greater than the control only for Compost2 at season's beginning (Table 5) but only for Manure2 at season's end (Table 8). Though not always significant, net N mineralized in Field B in 2004 was generally greater where compost- than manure-treated at season's beginning but greater where manure- than compost-treated by season's end.

These differences in net N mineralized between amendments in 2004 suggest that, relative to the control, more compost N than manure N was mineralized overwinter but more manure N than compost N was mineralized during the growing season. Of Field B's annual net N mineralized (Table 8), by season's start in early spring (Table 5) 30 and 32 % had already occurred in the Compost1 and Compost2 treatments, respectively, but <1 % in the Manure1 treatment while net immobilization had occurred in the Manure2 treatment. A favorable, in-season microbial environment (i.e., warm soil temperatures and wet soil) allied with relatively large quantities of readily oxidizable carbonaceous compounds from the added manure led to more net N being mineralized where manure rather than compost had been applied. As found for the Manure1 treatment, <1 % in the control's annual net N mineralization occurred overwinter. During the 2004 growing season, in essence 100 % of the manure's annual total net N was mineralized but an average of only 69 % of the compost's was mineralized.

The unexpected finding that less inorganic N was recovered than total N applied to Field A in 2003 (Table 9) was due in large measure (1) to the little net N mineralized in the treatments relative to the control by season's end (Table 7) and (2) to the inorganic N that was immobilized by spring 2003 (Table 5). As discussed earlier, this immobilization was likely a consequence of Field A's relatively low residual inorganic N (Table 1), temperatures during the warmer-than-average 2002–2003 winter (Fig. 2), residue management in fall 2002, and other factors.

Conclusions

1. There was no late season flush of mineralized N in soil fall fertilized with either compost or manure, even at relatively high N-based rates. In-season cumulative net N mineralized peaked 60 days or more before sugarbeet harvest, regardless of treatment or year.
2. On average in 2004, 31 % of compost's annual net N mineralized occurred before the growing season and 69 % during the season while essentially all of manure's occurred during the season.
3. Annual net N mineralized in 2003 averaged 52 kg N ha^{-1}, similar among all treatments. In 2004, annual net N mineralized averaged 250 kg N ha^{-1} for manure, 150 kg N ha^{-1} for compost, similar between rates within amendments, and 106 kg N ha^{-1} where untreated.
4. Abnormal temperatures, including those overwinter, must be accounted for when, the following spring, one estimates annual net N mineralized from fall-applied organic amendments.

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