Dairy Manure Nitrogen Availability in Eroded and Noneroded Soil for Sugarbeet Followed by Small Grains

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ABSTRACT

Efficient recycling of abundant manure resources from regional dairy industries in the semiarid West requires a better understanding of N availability in manure-amended soils. We measured net N mineralization using buried bags, and crop biomass, N uptake, and yields for sprinkler-irrigated, whole (noneroded) and eroded Portneuf soils (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) subject to a one-time manure application. Treatments included a control, fertilizer, two rates of composted dairy manure (28.4, 64.3 Mg ha^{-1}, dry wt.), and two rates of stockpiled dairy manure (23.3, 45.7 Mg ha^{-1}, dry wt.) applied in the fall before the Year 1 cropping season. Plots were planted to sugarbeet (*Beta vulgaris* L.), winter wheat (*Triticum aestivum* L.), and spring barley (*Hordeum vulgare* L.) during the 3-yr study. Overall, net N mineralization rates were low to moderate during winter through spring, decreased in early summer due to N immobilization, then increased to a maximum in late summer, followed by a decrease in fall. The mean mineralization rate (as a percentage of the added organic N) for Years 1, 2, and 3 was −4.2 (N immobilization), 4.3, and 4.8% for compost and 17.4, 17.0, and 11.4% for manure, respectively. Relative to controls, compost and manure treatments as a group increased total 3-yr net N mineralization more for eroded (1.77×) than for whole soils (1.55×). At higher rates, manure also increased immobilization and mineralization in 30- to 60-cm soil depths (below the zone of incorporation). To optimize the use of N mineralized in southern Idaho's manure-amended soils, one should consider the type manure employed and the erosion status of the soil receiving the amendment.

The U.S. dairy herd of 9 million animals produces an estimated 20 million Mg manure annually. In regional dairy centers (0.5 million cows) such as southern Idaho, 1.1 million Mg manure are generated each year. Manure and composted manure amendments improve soil physical properties, supply nutrients to crops, and can aid in rebuilding eroded soils, which are common in this historically furrow irrigated region (Robbins et al., 1997). To maximize their use of manure and minimize losses of N to the environment, growers need to understand how manure or composted manure additions influence soil N availability and how availability may vary with soil erosion status, that is, between whole (noneroded) soils and eroded soils.

Research evaluating manures as a source of soil nutrients has been underway for decades (Heck, 1931; Herron and Erhart, 1965), yet questions remain especially with regard to the N derived from these organic residues (Cabrera et al., 2005). Much of the N in manure is in the organic form and is released to soil via the microbially mediated process of mineralization. This process is strongly influenced by the character of the manure applied, soil abiotic environmental factors such as soil temperature, water content, and soil characteristics, such as clay content (Eghball et al., 2002). Laboratory studies have evaluated N mineralization rates at optimal soil water content and temperature for different soils or manures (Chae and Tabatabai, 1986; Qian and Schoenau, 2002; Van Kessel and Reeves, 2002; Griffin et al., 2005; Honeycutt et al., 2005; Azeez and Van Averbeke, 2010) and quantified the effects of varying soil temperature and water content on N mineralization (Honeycutt et al., 2005; Watts et al., 2007). Carpenter-Boggs et al. (2000) used variable-temperature incubations that mimicked field temperature regimes to quantify effects of crop rotation and N fertilization on N mineralization. Comparison studies found that N-mineralization rates derived from laboratory incubations generally tended to overestimate rates measured in the field (Adams and Attiwill, 1986; Honeycutt, 1999; Sistani et al., 2008).

Nitrogen-mineralization rates of soils are measured in the field (in situ) to obtain values that better reflect the environmental factors and dynamic conditions and that are specific to an individual region or management conditions (Jansson and Persson, 1982; Stenger et al., 1996; Hanselman et al., 2004). Direct in situ measurements of net N mineralization are typically accomplished by isolating small soil volumes (<750 cm^3) in the field and monitoring inorganic N concentration in these volumes over time. The advantages and disadvantages of the methodologies devised to accomplish this task have been discussed by Motavalli et al. (1989), Honeycutt (1999), and Hanselman et al. (2004). Given its successful application in previous southern Idaho research (Westermann and Crothers, 1980; Westermann and Crothers, 1993; Meek et al., 1994), the buried bag approach was used in this study. The frailty of buried bags can be problematic, the plastic may be perforated by insects or roots, which may ultimately compromise the obtained N mineralization data (Eno, 1960; Westermann and Crothers, 1980; Monaco et al., 2010).

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Abbreviations: DOC, dissolved organic carbon; ET, evapotranspiration; NDF, neutral detergent fiber.

Table 1. Description of N source and soil erosion status treatments.

Erosion status and N-source treatment	Added N source	Bulk application rate, dry Wt.	Total N† added in amendment	Total C† added in amendment
		Mg ha^{-1}	kg ha^{-1}	Mg ha^{-1}
Whole and eroded soil				
Control	none	0	0	0
Fertilizer	urea	0.18	82	0.02
Compost 1	composted manure	28.4	403	5.8
Compost 2	composted manure	64.3	913	13.1
Manure 1	dairy manure	23.3	433	7.0
Manure 2	dairy manure	45.7	850	13.8
Eroded soil only				
Manure 3‡	dairy manure	66.5	1237	20.1

† Derived from analysis of collected manure/compost samples.

‡ The manure 3 treatment was applied only to the eroded soil.

However, the durability of the tube-shaped polyethylene bags used in this experiment proved to be quite adequate; during our 3-yr study the average bag failure rate was <5 in 100.

Researchers have also determined N recovery from manure soil amendments by measuring N uptake in crops, which estimates N availability over the entire growing season (Motavalli et al., 1989; Klausner et al., 1994; Wen et al., 2003). Mallory et al. (2010) extended this approach by splitting the 11 wk growing season into 1-to-2-wk intervals. Typically, field studies that directly measured net N mineralization have evaluated surface soils to a depth of 30 cm or less for a 2-to-6-mo period during the growing season (Adams and Attwill, 1986; Adams et al., 1989; Honeycutt, 1999; Eghball, 2000; Abril et al., 2001; Sistani et al., 2008). Mikha et al. (2006) and Monaco et al. (2010) measured net N mineralization for two or more individual soil layers, but not for depths below 30 cm. Some researchers have measured net N mineralization for 0-to-45-cm soils (Westermann and Crothers, 1993; Meek et al., 1994) or during nongrowing-season periods (Westermann and Crothers, 1993; Stenger et al., 1996) but these studies did not include soils treated with manure, and did not distinguish between 0-to-30-cm and 30-to-45-cm soils. Few studies have evaluated N availability after manure or compost applications to field soils in the irrigated semiarid northwestern United States, where climate and soils can differ markedly from other regions. Our objective was to (i) evaluate the temporal patterns of net N mineralization relative to crop uptake under irrigated conditions of the Intermountain West and (ii) determine the effect of N source (stockpiled dairy manure, composted dairy manure, or fertilizer), soil erosion status, and soil depth on net N mineralization.

MATERIALS AND METHODS

We conducted the experiment from October 2002 through September 2005 at a site located 1.7 km southwest of Kimberly, ID (42°31' N, 114°22' W, elevation of 1190 m). The site has a mean rainfall of 251 mm occurring mainly during winter and late spring months. The location had a history of manure applications, receiving 40 to 75 Mg ha^{-1} (dry wt.) every 3 yr between 1969 and 1986. The site last received manure in 1994, 8 yr before the start of the current study. The site was fallow early in the 2002 cropping season.

Experimental Design

The experiment was performed on a field developed in 1991 for an eroded soil experiment and described in detail by Robbins et al. (1997, 2000). Robbins laid out four experimental blocks in a rectangular pattern and topsoil (0–30 cm) was removed from three strips of land that passed through the long dimension of the blocks. Thus the eroded and whole soil (noneroded) strips were aligned in each pair of two blocks (this allowed Robbins to furrow irrigate the field). Robbins et al. (1997) plowed the entire study area to 0.3 m to remove compaction caused by heavy earth moving equipment. To simplify the application of amendment treatments in our sprinkler irrigated study, stockpiled dairy manure or composted manure treatments were applied in strips perpendicular to the whole and eroded soil strips. This resulted in a split strip-plot experimental design (sometimes referred to as a split split-block) with soil erosion status (erosion status) as main plots and N-source treatments as subplots in strips across each block of main plots, with four replicates. Whole and eroded soil main plots were separated from each other by a 3-m buffer zone. Each experimental plot was 9-m wide by 21-m long.

Treatments applied in the experiment are described in Table 1, and included six applied to whole soils and seven applied to eroded soils. The control treatment received no amendments, while the fertilizer treatment received urea-N. The fertilizer-N rate was determined using the fall 2002 soil-test N values as an estimate for spring 2003 soil N content, and following recommendations provided to growers by Amalgamated Sugar Co. (Twin Falls, ID). The manure 1 application (23.3 Mg ha^{-1}) represented a common application rate in the region. This rate was doubled for manure 2 (45.7 Mg ha^{-1}) and tripled for manure 3 (66.5 Mg h^{-1}). The compost 1 application rate (28.4 Mg ha^{-1}) provided a roughly equivalent amount of available N as that of manure 1, and compost 2 (64.3 Mg ha^{-1}) aimed to double the compost 1 rate. Because a laboratory analysis of amendments was not done before application, the total N in amendments and that portion available to crops in the first year was estimated based on unpublished local data (A. Leytem, personal communication, 2002: total N = 15 g kg^{-1} for manure and 19 for compost, and the proportion of total N available the first year = 400 g kg^{-1} for manure and 200 for compost). Shortly after applying the amendments, samples were analyzed to obtain the actual N content. These measured values

Table 2. Selected characteristics of 0- to-30 cm and 30- to 60-cm soil layers for whole and eroded Portneuf silt loam.

Soil depth	Whole (uneroded)					Eroded				
	Total C	OC†	Total N	EC†	pH	Total C	OC†	Total N	EC†	pH
cm	g kg^{-1}			S m^{-1}		g kg^{-1}			S m^{-1}	
0 to 30	18	8.4	0.8	0.08	7.1	34.5	8.6	0.6	0.09	7.4
30 to 60	31	5.1	0.4	0.07	7.4	30.0	2.9	0.3	0.03	7.8

† OC, organic carbon; EC, electrical conductivity.

were used to compute the actual total N applied in applications, which are reported in Table 1. A compost 3 treatment was not included in the experiment because it exceeded the maximum, locally-recommended, commercial application rate by 750% and may have resulted in excessive salt loads. Manure, compost, and urea were applied in October 2002 before bed preparation. In the 3-yr experiment sugarbeet was planted in Year 1, followed by winter wheat, and spring barley in subsequent years.

Soils and Amendments

The field plots were prepared in Portneuf silt loam soils. These are deep calcareous soils, dominated by silt loam or very fine sandy loam textures, with silica and calcium carbonate cemented horizons (20–60% cementation) occurring between depths of 33 to 130 cm. The surface soil (0–15 cm) is a silt loam and contains on average 200 g kg^{-1} clay, 620 g kg^{-1} silt, 180 g kg^{-1} sand, has a mean cation exchange capacity of 190 $mmol_c$ kg^{-1} and exchangeable sodium percentage of 1.5. Selected properties of the 0- to 30-cm and 30- to 60-cm layers in whole and eroded soils are listed in Table 2.

Solid manure from dairy cattle (*Bos* spp.) was obtained in fall 2002. The manure had been scraped from open pens and stockpiled through the summer in temporary 1.7-m high, unconfined piles at a local dairy. It contained relatively little straw bedding material. Composted dairy manure was supplied by a local producer who employed a windrow composting process (1.8-m high by 5.5-m wide windrows). The compost feedstock was dairy manure that had been scraped from open pens in late spring, and so contained a relatively large component of bedding straw. Total C and total N of the organic amendments were determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CNS analyzer (CE Elantech, Lakewood, NJ) and neutral detergent fiber (NDF) for freezed-dried manure/compost samples using an ANKOM 200 Fiber Analyzer (ANKOM Technology, Macedon, NY) (ANKOM Technology, 2006). The manure contained 302 g kg^{-1} C, 18.6 g kg^{-1} total N, and 367 g kg^{-1} NDF, resulting in a C/N ratio of 16.2. The compost contained 163 g kg^{-1} C, 14.2 g kg^{-1} total N, and 329 g kg^{-1} NDF, resulting in a C/N ratio of 11.5.

Field Operations

The experimental plots, which were fallow early in the 2002 cropping season, were planted to spring wheat in mid-August 2002 to provide cover and reduce weed growth. The cover crop was sprayed with glyphosate on 4 Oct. 2002 and plots disked to 0.1-m depth, then roller harrowed on 9 Oct. 2002. Before manure application we measured residual inorganic soil N, P, K, and Zn in 0- to 30-cm and 30- to 60-cm depths for both whole and eroded soil plots. Levels of P and K in the soils were adequate for a sugarbeet crop, while Zn levels were marginal in the eroded plots. Manure was applied to designated plots (Table 1) on 10 Oct. 2002 using a commercial spreader truck equipped with rooster-comb beaters. Three 1.6- by 2.4-m tarps were placed at random locations in each block to collect manure and quantify its application rate. The manure intercepted by each tarp was weighed, mixed, and subsampled, then returned to the soil surface where it had been collected. Manure subsamples were composited, a portion was collected, and the remainder stored in the open air in the field. Incorporation of the manure was delayed until the compost was applied so that only a single tillage operation would be required (and thus minimize dispersion of amendments across plot boundaries). A subsample of the field-stored manure was collected for analysis on the day that both the manure and compost were incorporated into the field plot soils, 24 Oct. 2002. These values were used to compute C and N application amounts reported in Table 1. Immediately thereafter both manure and compost were incorporated with a disk to 0.1-m depth. On 29 Oct. 2002 urea was applied to the appropriate plots with a hand-held spreader and Zn (as $ZnSO_4$) was applied in eroded soil plots (11.2 kg ha^{-1}) to ensure this micronutrient was not limiting. The entire field was then sprayed with preemergence herbicide and all materials were immediately incorporated with a roller harrow. The field was then bedded in preparation for sugarbeet planting in the spring.

The field was pre-irrigated in late April to ensure adequate moisture for the shallow-seeded sugarbeet crop, but subsequent rainfall delayed planting until 21 May 2003. Beets were planted in rows 0.56-m apart with an in-row spacing of 75 mm. They were thinned later, resulting in a 150-mm in-row spacing between plants. Insects were controlled with labeled rates of Temik applied at planting. Postemergent weed control was achieved using conventional postemergent herbicides in addition to a single cultivation on 7 July 2003, and hand weeding. Irrigation through the growing season was supplied via sprinkler every 3 to 7 d to meet the crop's evapotranspiration (ET) requirements. The beet crop was harvested on 20 Oct. 2003.

The plots were prepared on 24 Oct. 2003 with a roller harrow and winter wheat was planted using a rate of 123 kg seed ha^{-1}. No N fertilizer was applied to any of the experimental plots for the 2003/2004 winter wheat or the subsequent 2005 spring barley crop, hence the 2004 and 2005 small grain yields resulted entirely from residual soil N and that mineralized from the soil, crop residues, and the N-source treatments. Weed control in the small grains was accomplished using conventional postemergent herbicides. We irrigated the wheat (2004) and barley (2005) to meet ET requirements using the same procedure employed for sugarbeets. Wheat was harvested on 1 Aug. 2004. Plots were disked to a depth of 0.07 m in late fall 2004.

All plots were plowed to a depth of 0.2 m on 15 Mar. 2005, roller harrowed, and planted to spring barley using a rate of 112 kg seed ha^{-1}. Barley was harvested on 8 July 2005.

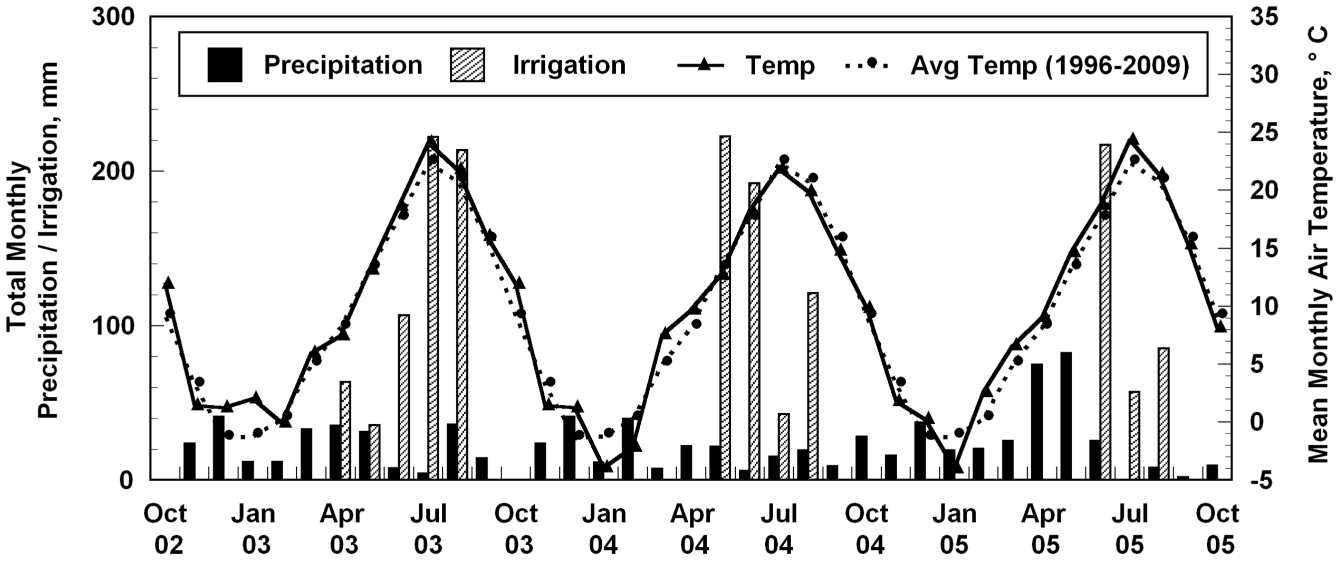

Fig. 1. Total monthly precipitation and irrigation amounts, and mean monthly air temperature at study site from October 2002 through October 2005.

SAMPLING AND ANALYSES

Meteorological measurements required to calculate crop ET were provided by a weather station located 5.6 km northeast of the experimental plots. A rain gauge located near the field plot measured growing season precipitation. Crop ET was estimated from the maximum reference ET calculated using the Kimberly–Penman ET model (Wright et al., 1998), adjusted with the appropriate daily crop coefficient. Mean monthly temperature, precipitation, and irrigation amounts during the study were reported in Fig. 1.

The study employed a buried bag method adapted from Westermann and Crothers (1980) and Meek et al. (1994) to measure

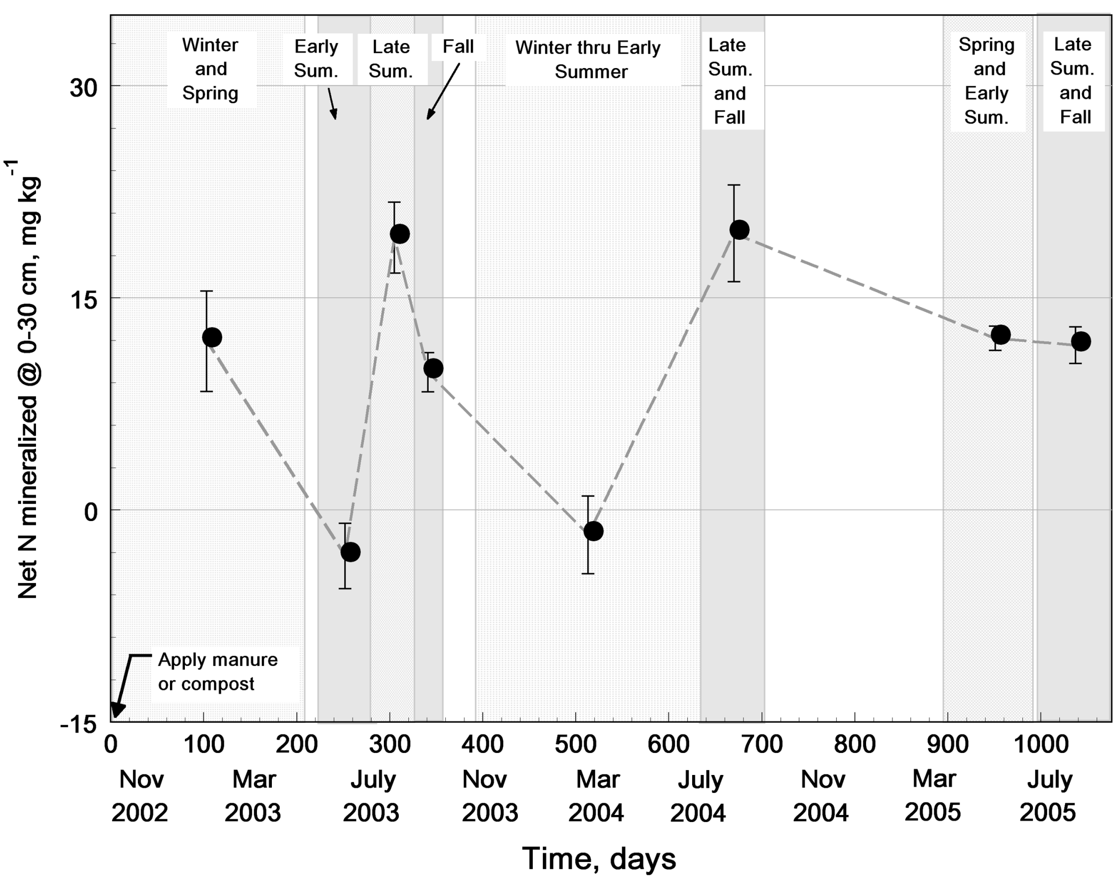

Fig. 2. The net N mineralized at 0- to 30-cm soil depths for defined periods from October 2002 through October 2005. Values are averaged across all N-source treatments for both whole and eroded soils (excluding Manure 3). Each leg of the error bars represents one standard error of the mean (*n* = 48). Back panels in the figure identify the measurement interval used for each data point.

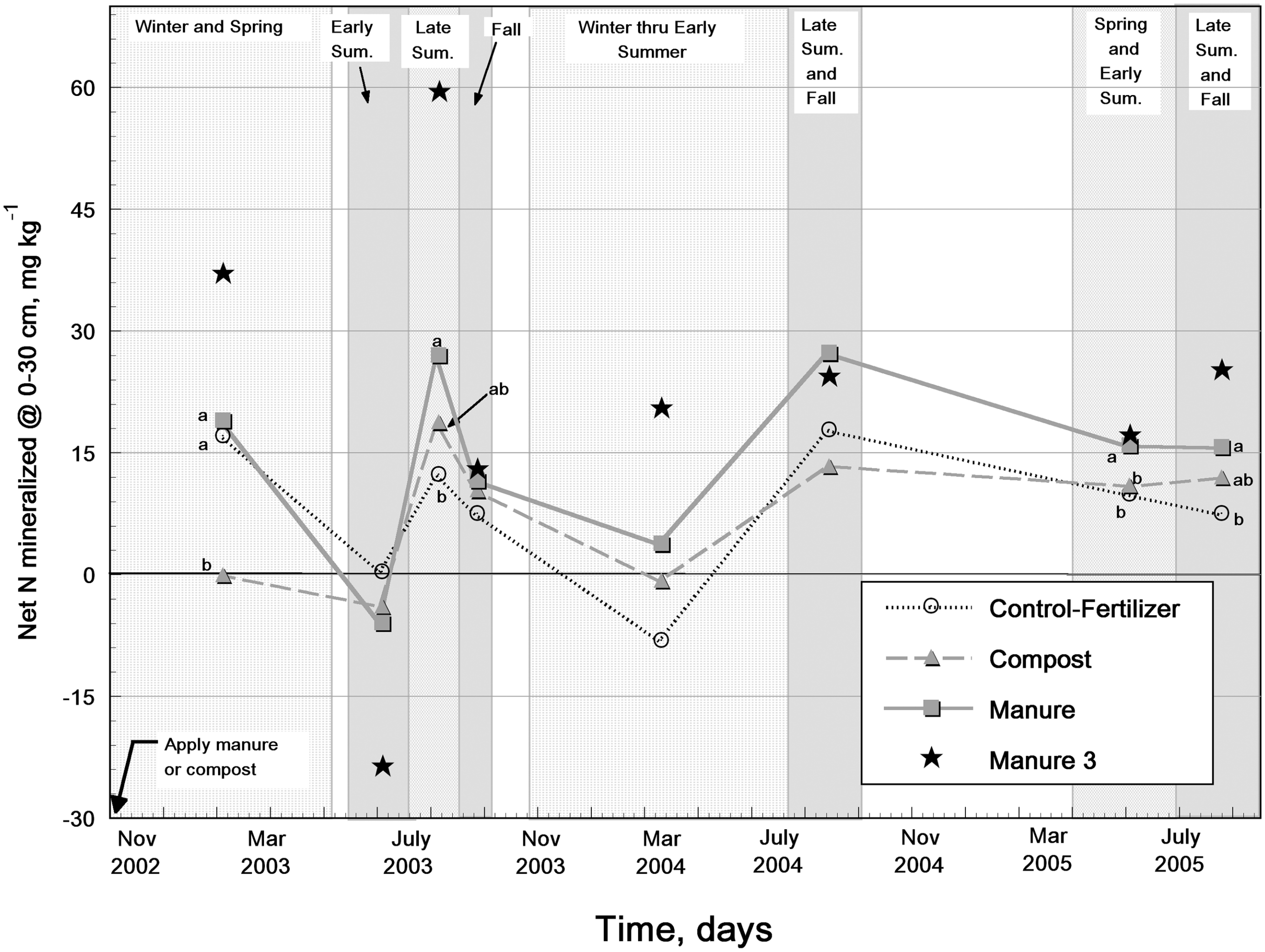

Fig. 3. The net N mineralized for treatment classes, averaged across soil erosion levels, at 0 to 30-cm soil depths for defined periods during October 2002 through October 2005. Means of treatment classes are significantly different if labeled with different lowercase letters (orthogonal contrasts). Back panels in the figure identify the measurement interval used for each data point.

net N mineralization in plot soils from November 2002 through October 2005 (with the exception of the 2004–2005 winter). Before bag installation 10 0- to 30-cm soil samples were collected from a range of treatment plots. These were dried in a microwave oven to estimate soil water content. For a typical installation, experience indicated that substantial variation in soil water content was uncommon between plots. For example, gravimetric soil water determinations (oven dried) on subsamples from a full set of initial bagged soils produced a mean of 21 ± 3.3%. Three to four soil cores, 0- to 30-cm deep were taken from prepared beds in each plot with a 5.7-cm diam. bucket auger, composited, and passed through a 0.4-cm screen. In the field, if the average gravimetric soil water content was estimated to be less than about 20%, distilled water was added to achieve this water content. A subsample was collected from the composited soil to later determine inorganic N and gravimetric soil water content. Mixed soil was filled with vertical shaking into tube-shaped polyethylene bags 10-μm thick and 5 cm in diameter (Wagner Corp., Salt Lake City, UT). The open end was then sealed, resulting in a 30-cm long soil column that was inserted into one of the sample holes created previously. Soil was used to fill gaps between the cylindrical bags and the surrounding soil wall. At the surface, soil was packed into a 1-to-2 cm cap to cover the bag and prevent irrigation water flowing into the hole.

We expected the greatest impact of amendments on net N mineralization to be in surface soil. However buried bags were also installed at 30- to 60-cm depths in two whole-soil treatments: control and manure 2; and three eroded soil treatments: control, manure 1, and manure 3 to evaluate treatment effects at depth. Manure treatments only were selected for 30- to 60-cm measurement because resources were limited and the manure included a wider range of application rates than compost. The procedure was the same as that used for the 0- to 30-cm depth, except that two to three soil cores were collected per plot, and bags were placed in plots from two of the four blocks.

The intervals over which net N mineralization was measured or reported each year differed somewhat because of the crop planted (Fig. 3 and 4). Buried bags were installed or retrieved, depending on the year, within a week of the dates used to define the start or end of the seasonal periods: winter, 14 November; spring, 1 April; early summer, 20 May; and late summer, 21 July; and the fall measurement interval was defined as the period between 9 September through 1 October. The one exception to this rule was the first set, which was installed 15 Nov. 2002 and retrieved in mid-spring, 12 May 2003, to allow beet planting. The installation of the next bags was deferred until the rain-delayed planting operation was complete. Specific dates for other buried bag sets were: three sets installed 27 May 2003, with one

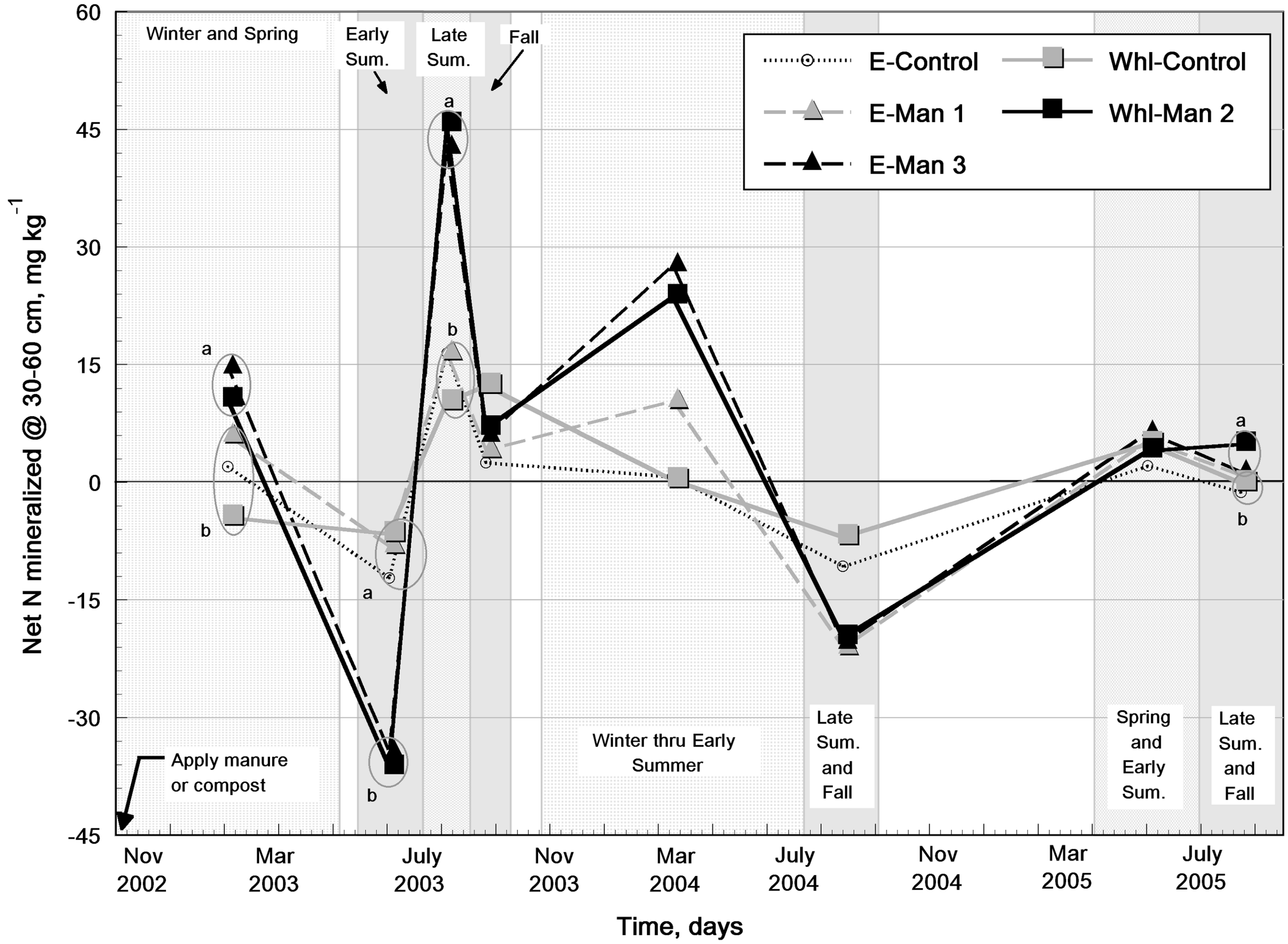

Fig. 4. Net N mineralized at 30 to 60-cm soil depths for defined periods during October 2002 through October 2005. Means of treatment classes identified by circles (no/low amendment treatments vs. high rate treatments) are significantly different if labeled with different lowercase letters. Back panels in the figure identify the measurement interval used for each data point. (E = eroded; Whl = whole soil; Man 1 = manure 1, etc.)

each retrieved on 28 July 2003; 9 Sept. 2003 and 7 Oct. 2003; two sets installed 13 Nov. 2003 with one each retrieved on 14 July 2004 and 23 Sept. 2004; and two sets installed on 7 Apr. 2005 with one each retrieved on 14 July 2005 and 26 Sept. 2005.

An appropriate number of buried bags were installed in new locations in each plot at the beginning of a sampling sequence (fall, spring, or early summer, depending on the year) and destructively sampled over the sequential periods. Gravimetric water content and inorganic N (NO_3–N, NH_4–N) in initial soil and retrieved buried bags was determined. After soil samples were air dried at 35°C, then crushed to pass a 2-mm screen, the soil N in them was extracted using a 2 M KCl solution. Within 6 h of extraction an automated flow injection analyzer (Lachat Instruments, Loveland, CO) was used to measure extract NO_3–N concentration after cadmium reduction (Method 12-107-04-1-B) and NH_4–N concentration using a salicylate-hypochlorite method (Method 12-107-06-2-A). The soil sample's inorganic N concentration was determined as the sum of the NO_3–N and NH_4–N concentrations (mg N kg^{-1} dry soil).

The soil net N mineralization during the period between burial and retrieval of the bagged soil was computed as the difference in inorganic N concentration (retrieved minus initial). The bags' polyethylene film is impermeable to liquid water, only slightly permeable to water vapor (Eno, 1960), allowed gas exchange between the enclosed and field soils (Eno, 1960; Westermann and Crothers, 1980), and excluded plant roots (any bag penetrated by roots was excluded from analysis). Hence the net N mineralization value incorporated net effects of N mineralization, denitrification, and immobilization in the enclosed soil and was not influenced by N losses from leaching or plant uptake during the measurement period. A positive difference indicated net N mineralization and a negative value indicated net N immobilization during the period. Because bag soil water contents were moderate and changed little during burial, it was assumed that N immobilization and not denitrification accounted for the greatest N losses.

The net N mineralization values were reported directly as mg N kg^{-1} soil (minN). Annual net N mineralization was computed by summing minN over the included periods. We also calculated annual net N mineralization (fall to fall, except spring to fall in 2005) for compost or manure treatments as a percentage of the total compost/manure N applied (minN%). This was computed using:

$$\text{minN\%} = [(\text{minN}_m - \text{minN}_c) \times 10^{-4} \times \text{BD}_{soil}]/\text{TN}_m$$

where $minN_m$ = minN of the manure treatment; $minN_c$ = minN of the control treatment; BD_{soil} = mass of a 30-cm thick layer of soil, 4.48×10^6 kg ha^{-1}; and TN_m = total N applied in the manure or compost treatments (kg ha^{-1}). Finally, the 3-yr, cumulative net N mineralization amounts were computed by summing minN over all monitored periods from fall 2002 through fall 2005. This amount does not include the period 23 Sept. 2004 to 7 Apr. 2005, which was not monitored.

Crop N uptake in sugarbeet was measured three times during 2003 by sampling total biomass of plant tops (leaves) and roots from a 1.5-m long row. The season-long N uptake for winter wheat (2004) and spring barley (2005) was determined when the crop reached the soft-dough stage by hand clipping aboveground biomass (10 mm above soil surface) from 4 m of row. The shredded sugarbeet roots and other aboveground plant tissue were dried at 65°C for dry matter determination. A subsample of the dried tissue was ground in a Thomas Wiley mill (Swedesboro, NJ) to pass an 865-μm screen and its total N concentration determined on a Thermo-Finnigan FlashEA1112 CNS analyzer (CE Elantech, Lakewood, NJ).

Sugarbeet yields were determined on 14 Oct. 2003 from two samples in each plot, each consisting of two adjacent 7.6-m long rows. Beet root subsamples collected for each of the two plot samples were analyzed for soil and crown tare, as well as quality factors such as brei nitrate, brei conductivity, and sugar concentration by the Amalgamated Sugar Company laboratory (Paul, ID). Beet subsample values were used to calculate the reported means, based on four replicates. Wheat and barley grain yields were measured with a small plot combine by harvesting a 1.5-m by 12-m area within each plot. Protein content of wheat and barley grain was determined using NIR (Perten Instruments, Chatham, IL) calibrated with total N analyzed by combustion (Leco Corporation, St. Joseph, MI). The grain N content was calculated from the yield and protein determinations using a factor of 5.7 for the conversion of protein to total N. Small grain yield and protein content were reported on a 12% moisture basis. The apparent N recovery (Crop NR) by crops was computed with the formula:

$$\text{Crop NR} = (100)\,(\text{Treatment N uptake} - \text{Control N uptake})\,(\text{total N applied in amendment})^{-1}$$

STATISTICAL ANALYSIS

The 0- to 30-cm net N mineralization data for a given reporting interval were analyzed via ANOVA, PROC Mixed (SAS Institute, 2008). Data from each year and measurement period were analyzed separately and included only those treatments that were common to both soil types, that is, the manure 3 treatment was excluded from the analysis (for 0- to 30-cm depths). The statistical model included N source (control, fertilizer, compost 1, compost 2, manure 1, manure 2), erosion status (whole vs. eroded), and the interaction as fixed effects, while col_blk, block(col_blk), soil type*col_blk, and treatment*block(col_blk) were included as random effects. The col_blk class was required to account for whole or eroded soil types that were laid out in strips across the two sets of aligned treatment blocks. For all fixed effects found significant, treatment means were separated using the Tukey option (SAS Institute, 2008). We also included several more powerful single degree-of-freedom orthogonal contrasts in the ANOVA analysis. These tested the effect of soil erosion status across all compost and manure treatments, excluding the control and fertilizer treatments; compared control and fertilizer as a class vs. either compost or manure treatments across both soil types; and tested for differences between compost vs. manure classes, across all treatment levels and soil types.

The net N mineralization at 30- to 60-cm depths was measured for select treatments in only two of four replicate plots. Therefore the treatments were grouped into a no/low amendment (whole-control, eroded-control, and eroded-manure 1) and high amendment (whole-manure 2, eroded-manure 3) classes, and an ANOVA, PROC Mixed (SAS Institute, 2008), conducted to test for amendment class effects. The statistical model included amendment level (no/low vs. high) as the fixed effect and amendment level*replicate and replicate as random effects. Data from each year and measurement period were analyzed separately.

Other response variables such as crop yield, biomass, and N uptake, and quality factors for sugarbeet (brei nitrate, brei conductivity) and small grain protein concentration were analyzed using the same model employed for the 0- to 30-cm N-mineralization data. All analyses were conducted using a $P = 0.05$ significance level.

RESULTS

Meterological data show that 2003 was warmer than 2004 and 2005 (Fig. 1), and warmest of all years during the 1996–2009 period. In particular, the winter and summer months in 2003 were 2°C. warmer on average than the same period in 2004–2005. Annual precipitation in 2003 (249 mm) and 2004 (232 mm) was close to the 1996–2009 mean (252 mm), while 2005 (373 mm) was a wetter than average year, mainly due to an exceptionally wet spring (Fig. 1). Soil inorganic N present in freshly filled buried bags (Table 3) indicates at the start of the study (November 2002) that initial soil N levels among N-source treatments were similar and relatively high (68–97 mg kg^{-1}). Nor did initial soil N concentrations differ between whole and eroded soils in fall 2002 ($P = 0.51$) or spring 2003 ($P = 0.20$).

Net Nitrogen Mineralization

0- to 30-cm Soil Depth. Nitrogen source influenced the net N mineralized in 2003, particularly in early and late summer periods, as well as the 3-yr cumulative net N mineralization (Table 4). While soil erosion status and erosion N-source interaction effects were generally not significant in the overall analysis, the orthogonal contrasts were more definitive. These single degree-of-freedom tests established that, when compost and manure treatments were considered together as a class, net N mineralization in whole and eroded soil did differ. Net N mineralization for manure treatments differed from control and fertilizer plots at some period during each year, whereas no differences between compost and control/fertilizer treatments were observed after 2003.

In general the 0-to-30-cm net N mineralization data showed a distinct pattern of seasonal variation, with values typically in moderately positive territory during winter and spring, decreasing and sometimes negative during early summer, increasing in late summer, and decreasing again in Fall (Fig. 2). Relative to the control in 2003, the manure 2 treatment increased N immobilization (negative net N mineralization) during the early summer shortly

Table 3. Soil N (mg kg^{-1}) on the date buried bag sets were installed, for N-source treatments averaged across soil erosion types (0–30-cm depths), or N-source erosion/classes (30–60-cm depths). The manure 3 treatment was not present in both whole and eroded soil types, thus it was not included in mean separations.

Source of variation	15 Nov. 2002	27 May 2003	13 Nov. 2003	7 Apr. 2005
	Soil N, mg kg^{-1}			
Nitrogen source†	0- to 30-cm depth			
Control	68.8	11.8c‡	26.1b	9.1b
Fertilizer	80.3	23.7bc	26.3b	9.3b
C1	76.6	27.4bc	30.0ab	9.7b
C2	91.3	37.7b	24.9b	12.3ab
M1	82.7	34.1b	30.6ab	15.4a
M2	68.2	55.7a	33.9a	16.6a
M3 (Eroded only)	96.5	106.7	37.7	21.3
Erosion/N source†	30- to 60-cm depth			
Eroded control	15.0	24.9	13.4	4.2
Eroded M1	21.0	37.6	18.0	9.1
Eroded M3	20.2	79.4	17.4	19.5
Whole Control	33.6	22.7	15.9	5.3
Whole M2	33.0	83.2	23.1	17.2
Class comparison§	30- to 60-cm depth			
Low	23.2	28.4b	16.4	6.2b
High	26.5	79.1a	21.0	18.3a

† C1 = compost 1; C2 = compost 2; M1 = manure 1; M2 = manure 2; M3 = manure 3.

‡ Within a given period and depth series, treatment means followed by the same lowercase letter are not significantly different ($P < 0.05$). Means of treatment classes§ are not significantly different if labeled with the same uppercase letters. Not displayed if effect was not significant in the ANOVA.

§ Class: Low = eroded control + whole control + eroded M1; High = eroded M3 + whole M2.

after soil warm up, and increased net N mineralization values during the late summer when the soil was warmest (Table 5). In contrast, while individual compost treatments typically had lower net N mineralization values than the control in early summer and greater values in late summer, differences were not statistically significant at $P = 0.05$ (Table 5). The effect of manure on net N mineralization during the late-summer and fall period declined with time, from 38.3 mg kg^{-1} in 2003, to 27.2 mg kg^{-1} in 2004, and 15.6 mg kg^{-1} in 2005. The effect of compost over time was similar, the same time series being 29.1, 13.8, and 11.9 mg kg^{-1}.

The 3-yr, cumulative, net N mineralization at 0- to 30-cm trended upward with increased organic additions although differences for individual treatments were not always significant (Table 5). Orthogonal contrasts (Table 4) showed that manure 1 and 2 as a N-source class produced an average 1.85× more 3-yr, cumulative net mineralized N than either the compost or control/fertilizer classes (Table 5). The net N mineralization values for compost treatments differed from noncompost treatments during the first winter-spring period after compost application, when compost treatments, as a class, produced significantly less net N mineralization than either the controls or manure treatments (Fig. 3).

30- to 60-cm Soil Depth. Net N mineralization responses for the 30- to 60-cm soil depth showed a similar pattern to that of the surface soil, except that greater N was immobilized there early in the 2003–2004 growing seasons (Fig. 4). The magnitude of the responses measured in the subsoil were substantial and somewhat unexpected given that (i) manure was not incorporated into soil at depths below 20 cm and (ii) microbial activity in subsoil was inhibited relative to surface soil owing to cooler temperatures during the growing season. Of the total cumulative net N mineralized in both soil layers during 3 yr, the 30- to 60-cm soil layer contributed the following amounts: whole control = 13.0%; eroded control = 0%; eroded manure 1 = 18.6%; whole manure 2 = 24.6%; and eroded manure 3 = 27.7%. The eroded-manure 3 and whole-manure 2 treatments, when combined as a high amendment class, resulted in a 5.5-fold greater cumulative net N mineralization than the no/low amendment treatment class in the 30- to 60-cm layer (Table 5).

The Proportion of Total Applied Organic Nitrogen Mineralized Annually. The net N mineralized each year in excess of the control value was assumed to be derived from organic N added with compost or manure amendments.

***0 to 30 cm*:** The N mineralized as a percent of total N applied (minN%) was not affected by erosion status in any year ($P > 0.5$), while orthogonal contrasts showed that when averaged over both amendment levels (1, 2) manure minN% exceeded that of compost in 2003 ($P = 0.02$) and 2004 ($P = 0.04$) but not in 2005 ($P = 0.09$). Compost treatment minN% in 2003 was –4.3% of the total N applied, compared to 4.2% in 2004 and 4.8% in 2005. The negative first year value indicates that compost produced greater immobilization than mineralization during 2003. For manure treatments, 17.4% of the total added N was mineralized in 2003 (winter 2002 to fall 2003), compared to 17.0% in 2004 (winter 2003 to fall 2004), and 11.4% in 2005 (spring 2005 to fall 2005).

***30 to 60 cm*:** Of the total N added as manure an additional 8.4% was mineralized in the 30- to 60-cm soil in 2003, followed by 4.2% in 2004, and 3.1% in 2005.

Thus in the 0- to 60-cm soil layer of manured plots 25.8% of total added N was mineralized in 2003, 21.2% in 2004, and 14.5% in 2005.

The Effect of Soil Erosion Status on Net Nitrogen Mineralization

Soil erosion status influenced net N mineralization differently in the 0- to 30-cm soils depending on the seasonal period and year. Note the significant N source × erosion status interaction observed for the late summer and fall 2003, and orthogonal contrast tests showing that erosion status influenced net N mineralization for compost and manure treatments as a class for individual periods in 2003 and 2004, as well as the 3-yr cumulative values (Table 4). During early summer 2003 eroded soils responded to increasing compost/manure application rate with increased N immobilization; while whole soils had little response (Fig. 5A). During late summer 2003 eroded soils responded to increased compost/manure application rates with increased net N mineralization rates; while the response of whole soils was more variable (Fig. 5B).

The effect of soil erosion status on net N mineralization in manure and compost amended soils varied with year. During the peak N mineralization period of late summer and fall 2003, compost and manure amendments at their highest rates stimulated N mineralization more in eroded soils than in whole soils (Fig. 6A), whereas in 2004 and 2005, the opposite was true (Fig. 6B, C). When averaged across both levels of compost and manure treatments, net N mineralization in whole soils

Table 4. The influence of N source and soil erosion status on net N mineralization at 0- to 30-cm depths during each measurement period and for summed sequences (shaded columns) for years 2003 to 2005. Table gives *P* values for main effects and interaction terms, and single degree-of-freedom orthogonal comparisons derived from an ANOVA.

Source of variation	*P* values: 2003 Winter–Spring 2002–03	2003 Early summer 2003	2003 Late summer 2003	2003 Fall 2003	2003 Winter thru early summer 2002–2003	2003 Late summer and fall 2003	2003 Spring thru fall 2003	2003 Winter 2002 thru fall 2003	2004 Winter through early summer 2003–2004	2004 Late summer and fall 2004	2004 Winter 2003 through fall 2004	2005 Spring and early summer 2005	2005 Late summer and fall 2005	2005 Spring through fall 2005	3-yr Cumulative Winter 2002 through fall 2005
N Source (N)†	0.18	*	*	0.73	0.25	**	**	**	0.16	0.34	0.15	0.14	0.16	**	*
Erosion status (Soil)	0.49	0.24	0.25	0.56	0.21	0.21	0.7	0.69	0.30	0.20	0.85	0.32	0.34	0.22	0.23
N × Soil	0.98	0.09	0.08	0.10	0.49	*	0.16	0.16	0.93	0.97	0.38	0.30	0.60	0.18	0.72
Orthogonal Contrasts															
COMP + MAN‡: Whole vs. Eroded	0.27	***	**	0.95	*	**	0.97	0.21	0.07	*	0.95	0.26	0.11	*	*
Cntrl+Fert vs. COMP	*	0.31	0.15	0.38	*	0.07	0.07	0.22	0.22	0.70	0.68	0.66	0.16	0.08	0.88
Cntrl+Fert vs. MAN	0.83	0.14	**	0.23	0.66	**	***	0.15	*	0.37	*	*	*	***	*
COMP vs. MAN	*	0.61	0.08	0.73	0.10	0.08	*	**	0.41	0.15	*	*	0.25	**	**

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

† This factor includes control, fertilizer, compost 1, compost 2, manure 1, and manure 2 treatments.

‡ Cntrl = control; Fert = fertilizer; MAN = manure 1 and manure 2 treatments; COMP = compost 1 and compost 2 treatments.

was greater than that of eroded soils in both 2004 (26.5 vs. 14.4 mg kg^{-1}) and 2005 (30.5 vs. 23.7 mg kg^{-1}).

In absolute terms, the average 3-yr, cumulative net N mineralized from the combined manure and compost treatments for whole soils, 97.6 mg kg^{-1}, was nearly 1.3 times greater than the 76.5 mg kg^{-1} for eroded soils. However, the organic amendments increased net N mineralization to a greater degree in eroded than whole soils The manure and compost treatments on eroded soils produced on average 1.77 times more net N mineralization than the control, while the relative increase for whole soils was only 1.55 times.

2003 Sugarbeet Biomass, Nitrogen Uptake, and Yield

The analysis of 2003 sugarbeet crop biomass and N uptake data produced results similar to those of net N mineralization (Table 6). Contrast tests showed that manure 1 and 2 treatments as a class significantly increased biomass and N uptake of beet tops and roots relative to the control treatment and compost class (Tables 6 and 7). Manure influenced beet top growth and N uptake early in the season, 30 July 2003, when it increased top biomass accumulation at least 1.5-fold and N uptake at least 1.7-fold relative to control or the compost treatment class (Table 7). Manure's effect on beet roots was strongest at season's end, 13 Oct. 2003, where it had increased root biomass accumulation at least 1.5-fold and N uptake at least 1.4-fold relative to control or compost treatment classes. Compost as individual treatments or as a treatment class had little significant effect on accumulated biomass or N uptake.

At harvest the relationship of accumulated whole plant biomass or N uptake (Table 7) to the net N mineralized during winter 2002 thru fall 2003 described a classic yield curve (not shown). The curve showed that beet biomass and N uptake peaked when year-long, 2003 net mineralized N approached 56 mg kg^{-1}, and declined when mineralized N exceeded that amount.

Orthogonal contrasts showed that erosion status influenced cumulative beet root biomass of compost and manure treatments as a class early in the season, 30 July 2003 (Table 6). Biomass accumulation in beets grown on compost-and-manure amended, eroded soils was 30% less than similarly amended whole soils (data not shown). Presumably this resulted because mean net N mineralization rates during winter 2002 through early summer 2003 were less for eroded (–2.7 mg kg^{-1}) than for whole soils (19.7 mg kg^{-1}).

Beet root N uptake was influenced by N-source × erosion-status interactions on 11 Sept. and 13 Oct. 2003 sampling dates (Table 6). Earlier in the growing season, N uptake by beet roots in whole-manure and eroded-manure treatments was variable (Fig. 7A), whereas by season's end, N uptake of eroded-manure treatments exceeded that of whole-manure (Fig. 7B).

Nitrogen source effects on 2003 sugarbeet yield and quality were minimal and no soil erosion status or interaction effects were observed. The manure and compost treatments did not differ significantly from the control with respect to any of the six yield and quality parameters listed in Table 8. Fertilizer and manure 1 treatments produced the greatest mean values for field beet root yields, averaging 60.75 Mg ha^{-1}, clean beet yields, 55.0 Mg ha^{-1}, and estimated recoverable sugar, 7.03 Mg ha^{-1}. However, these values were not significantly different from the control.

Small Grains Biomass, Nitrogen Uptake, and Yield

Since no N was added to any plots in 2004 and 2005, wheat and barley growth and yields were dependent on soil N carried over from the previous year and mineralized N. Contrast tests showed that, before planting wheat and barley, the initial, 0- to 30-cm soil N levels in manure 1 and manure 2 soils on average were greater than for fertilizer and control soils ($P < 0.001$). For winter wheat in November 2003 initial soil N amounts for the two classes were 32.3 vs. 26.2 mg kg^{-1} and for spring barley in April 2005, 16.0 vs. 9.2 mg kg^{-1}. A similar relationship was found for the amounts of net N mineralized during winter through early summer 2004 (wheat) and spring and early summer 2005 (barley) periods (Table 5). As a result, manure 1 and 2 treatments as a class increased 2004 wheat biomass, grain yield, and N uptake 1.5- to 1.8-fold relative to the control or compost treatment class (Table 9). Similarly, manure treatments increased 2005 barley biomass, grain yield, and N uptake 2.2- to 2.9-fold relative to the control or compost treatment class (Table 9). In 2005 orthogonal contrasts indicated that soil erosion status influenced barley yield and protein concentration of manure and compost treatments as a class ($P < 0.01$). The mean barley grain yield for manure compost-treated whole soils (4.39 Mg ha^{-1}) was 1.3 times greater than the related yield for eroded soils (3.36 Mg ha^{-1}). However, the barley grain protein concentration for manure compost-treated, eroded soils (7.84%) was 1.07 times greater than the related concentration for whole soils (7.35%).

The apparent N recovery by crops in 2003 was greatest for fertilizer, followed by manure and compost treatment classes (Table 10). A similar relationship was observed for the 3-yr cumulative amounts where average N recovery by manure amended crops was 5.5 times that of compost amended crops. The effects of soil erosion status proved significant only with respect to the cumulative 3-yr values, where the 3-yr N recovery in eroded manure and compost-amended soils was nearly twice that of similarly treated whole soils.

DISCUSSION

The temporal pattern of net N mineralization resulting from compost and manure additions to these soils (Fig. 3 and 4) emphasizes the cyclic nature of the associated microbially mediated processes. Two aspects of the pattern are notable. The first is the immobilization event (negative net N mineralization) that occurred shortly after the fall manure-amended soil

Table 5. Net N mineralized for N-source treatments averaged across soil erosion status (0–30-cm depths), or treatments/classes (30–60-cm depths) during portions of the annual cycle from winter 2002 through fall 2005. The manure 3 treatment was not present in both whole and eroded soil types, thus it was not included in mean separations.

Source of variation	2003								2004			2005			3-y Cum.
	Winter–Spring 2002–2003	Early summer 2003	Late summer 2003	Fall 2003	Winter through early summer 2002–2003	Late summer and fall 2003	Spring through fall 2003	Winter 2002 through fall 2003	Winter through early summer 2003–2004	Late summer and fall 2004	Winter 2003 through fall 2004	Spring and early summer 2005	Late summer and fall 2005	Spring through fall 2005	Winter 2002 through fall 2005
	mg kg^{-1}														
Nitrogen source†	0- to 30-cm depth														
Control	9.2	4.9a	9.0b	6.8	14	15.7b	20.6ab	29.8	–8.2	16.1b	6.8	10.6	5.8	16.4b	53.0b
Fertilizer	2.5	–4.4ab	15.4b	8.0	20.6	23.4b	19.1b	44	–8.2	19.3b	11.1	9	9.0	18.1b	73.1ab
C1	-1.0	1.6ab	13.1b	10.0	0.6	23.1b	24.7ab	23.6	–3.9	14.3b	10.4	10.4	11.2	21.6ab	55.7b
C2	0.8	–9.5ab	24.3ab	10.7	-8.8	35.1ab	25.5ab	26.3	2.3	13.2b	15.4	11.3	12.7	24.0ab	65.7ab
M1	15.2	2.1ab	16.7b	13.8	17.3	30.5ab	32.6a	47.8	10.2	17.5b	27.7	14.5	16.9	31.4a	106.9ab
M2	22.6	–14.2b	37.0a	9.1	8.37	46.1a	31.9a	54.5	–2.7	36.9a	34.2	17	14.3	31.3a	120.1a
M3 (eroded only)	36.9	–23.8	59.3	12.8	13.1	72.5	48.7	85.6	20.3	24.2	44.5	17	25.0	42.1	172.1
Erosion/N-Source †	30- to 60-cm depth														
Eroded control	2.0	–12.3	16.5	2.5	–10.3	18.9	6.7	8.7	0.7	–10.7	–10	2.2	–1.3	0.8	–0.4
Eroded M1	6.0	–8.1	16.6	4.1	–2.1	20.7	12.7	18.6	10.4	–21.0	–10.6	5.3	0.9	6.2	14.2
Eroded M3	14.7	–34.4	42.7	6.0	–19.7	48.8	14.3	29	27.7	–20.4	7.3	6.4	1.3	7.8	44.2
Whole control	–4.5	–6.6	10.2	12.3	–11.1	22.5	15.9	11.3	0.3	–7.0	–6.7	4.9	–0.1	4.8	9.4
Whole M2	10.5	–36.4	45.6	6.9	–25.9	52.4	16	26.5	23.6	–19.8	3.8	4	4.8	8.74	39.1
Class comparison†	30- to 60-cm depth														
Low	0.9	–9.0B	14.4B	6.3	–8.5	20.7B	11.7	12.6	3.8	–12.9	–9.0B	4.1	–0.2B	4.0	7.4B
High	11.9	–35.4A	43.7A	6.5	–23.7	50.5A	15.2	26.4	25.7	–19.7	6.9A	5.1	3.1A	8.4	40.8A

† C1 = compost 1; C2 = compost 2; M1 = manure 1; M2 = manure 2; M3 = manure 3; Class: Low = eroded control + whole control + eroded M1; High = eroded M3 + whole M2.

‡ For a given period and depth series, treatment means followed by the same letter are not significantly different ($P < 0.05$). Letters are not displayed if the effect was not significant in the ANOVA.

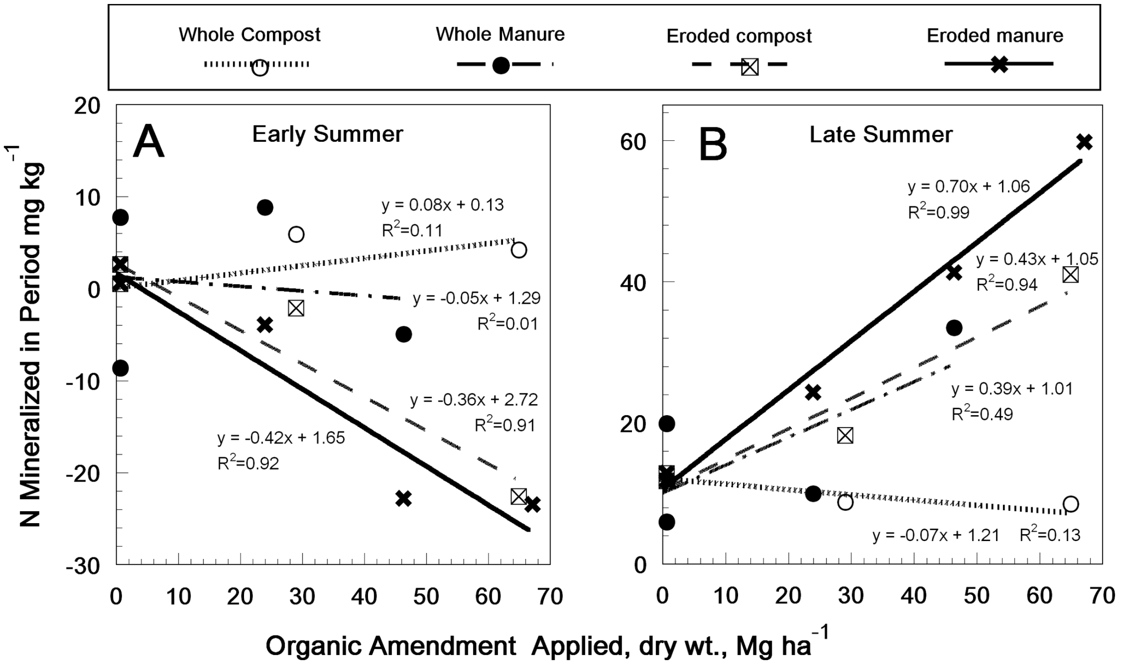

Fig. 5. The effect of compost and manure application rates on net N mineralized in whole and uneroded soils (0–30 cm) for (A) early and (B) late summer periods in 2003. (The fertilizer treatment data was included as one with zero organics applied.)

warmed in early summer. The second is the mineralization peak that followed in late summer. Because soil in the sealed buried bags was not rewetted during irrigation or rainfall we conclude that N was being immobilized in microbial biomass rather than lost through denitrification. This cyclic pattern typically has not been observed in longer-term laboratory incubations (Chae and Tabatabai, 1986; Hadas et al., 1996; Carpenter-Boggs et al., 2000; Hanselman et al., 2004; Griffin et al., 2005); although Burger and Venterea (2008) did observe immediate microbial N immobilization after adding liquid dairy manure to incubated soil. In addition Azeez and Van Averbeke (2010) reported strong immobilization of N in laboratory-incubated, manure-amended soils 30 d after manure incorporation and incubation at 23°C, followed by a peak in N mineralization at Day 40.

Far fewer are the field studies documenting temporal changes in N mineralization. A similar cyclic pattern was observed in an

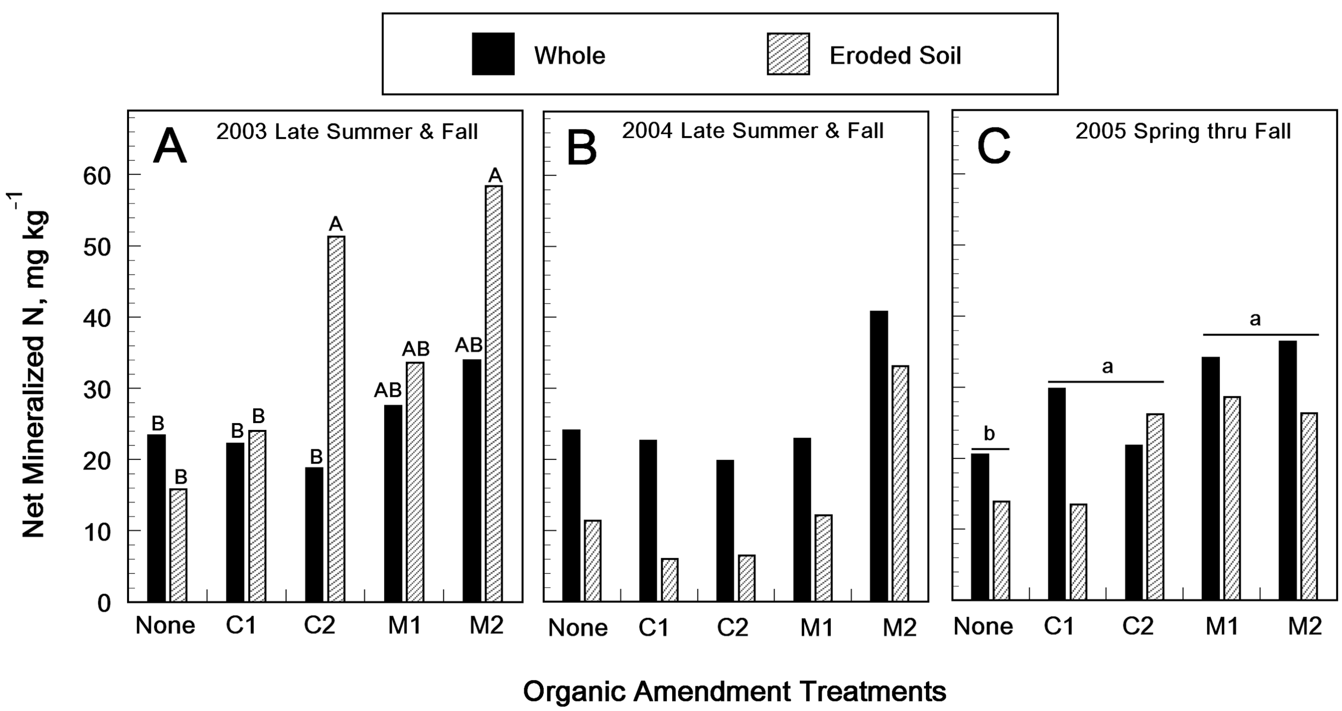

Fig. 6. The influence of amendment application rate on net N mineralized in 0- to 30-cm soil during the late summer thru fall periods in (A) 2003 and (B) 2004, and spring through fall period in (C). Column values with the same uppercase letter are not significantly different (*P* < 0.05) and treatment classes none, compost, manure with the same lowercase letter are not significantly different (*P* < 0.05). (Letter C = compost and M = manure and the number indicates application rate.)

Table 6. The influence of N source and soil erosion status on biomass accumulation and N uptake in 2003 sugarbeet plant components. Table gives *P* values for main effects and interaction terms, and single degree-of-freedom orthogonal comparisons derived from an ANOVA.

Source of variation	*P* values																	
	Biomass, dry wt., Mg ha^{-1}									Nitrogen uptake, kg ha^{-1}								
	Tops			Roots			Whole plant			Tops			Roots			Whole plant		
	30 July	11 Sept.	13 Oct.	30 July	11 Sept.	13 Oct.	30 July	11 Sept.	13 Oct.	30 July	11 Sept.	13 Oct.	30 July	11 Sept.	13 Oct.	30 July	11 Sept.	13 Oct.
Nitrogen source (N)†	*	0.35	*	0.52	0.80	0.08	0.08	0.65	*	*	0.56	*	0.07	0.43	***	*	0.41	***
Erosion status (Soil)	0.24	0.42	0.38	0.31	0.55	0.30	0.28	0.40	0.27	0.23	0.49	0.42	0.23	0.96	0.35	0.21	0.59	0.35
N × Soil	0.89	0.68	0.71	0.51	0.13	0.71	0.87	0.25	0.73	0.78	0.78	0.88	0.62	*	*	0.80	0.65	0.41
Contrasts‡																		
COMP + MAN: Whole vs. Eroded	0.08	0.22	0.65	*	0.31	0.22	*	0.15	0.24	0.12	0.39	0.67	*	0.73	0.95	0.07	0.45	0.76
Cntrl vs. COMP	0.89	0.31	0.10	0.86	0.51	0.81	0.98	0.37	0.58	0.47	0.52	0.12	0.71	0.86	0.95	0.74	0.59	0.21
Cntrl vs. MAN	**	0.52	**	0.19	0.21	*	*	0.21	**	**	0.35	**	**	0.11	***	**	0.12	***
COMP vs. MAN	**	0.64	0.08	0.08	0.45	**	**	0.64	**	**	0.72	0.11	**	0.09	***	**	0.20	***

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† This factor includes control, fertilizer, compost 1, compost 2, manure 1, and manure 2 treatments.
‡ Treatment classes: Cntrl = control; MAN = manure 1 and manure 2; COMP = compost 1 and compost 2.

in situ field study with manure-amended soils (Monaco et al., 2010), and in two that examined nonamended field soils (Meek et al., 1994; Stenger et al., 1996). Our results showing greater N immobilization in late spring and early summer with manure addition agree with the results of these field studies. Note that field studies that observed this seasonal cycle measured N mineralization in a soil layer ≥30-cm soil deep, whereas those that did not, were generally focused on the ≤20-cm depth (Adams and Attiwill, 1986; Eghball, 2000; Hanselman et al., 2004; Watts et al., 2010). The observation that temporal net N mineralization patterns may vary as a function of soil depth and the strong cyclic pattern observed for 30- to 60-cm soils in the current study (Fig. 4), leads us to hypothesize that a substantial portion of N immobilization in soils may be driven by soluble organics that are leached from the soil and manure amendments. The soluble organics may provide both a source of C and N as added support for microbial activity. This also suggests that surface soil layers with less soluble organic C may realize net N mineralization while deeper soils that receive leached soluble organic C simultaneously undergo net immobilization. A buried bag was installed in plots on November 2002 and removed in May 2003, and a set of three bags were installed in late May 2003 with one bag being retrieved in July, September, and October. Since the bags are sealed leaching processes could not modify their N contents. Thus the translocation of soluble organics must have occurred between November 2002 and May 2003. Soil N measurements made in November 2002 and May 2003 provide evidence for such leaching events because they indicated that substantial quantities of N moved downward in the profile during the period (Table 3).

In southern Idaho N uptake by sugarbeet is greatest between late June and early August (Carter and Traveller, 1981). This period coincides with the period when maximum N amounts are made available via manure mineralization (Fig. 3). This likely explains why sugarbeet yield and quality were similar between fertilizer and the manure 1 treatment. However, beet sugar content and recoverable sugar values trended downward and brei nitrate and conductivity trended upward with increasing

Table 7. Accumulated biomass and N uptake in sugar beet plant components at three times during the 2003 growing season. Data have been averaged across erosion status (whole and eroded). The manure 3 treatment was present only in the eroded soil thus was not included in either the two-factor analysis or mean separations shown below.

Treatment	Biomass			N Uptake		
	30 July	11 Sept.	13 Oct.	30 July	11 Sept.	13 Oct.
	Mg ha^{-1}			kg ha^{-1}		
Tops						
Control	1.67b†	3.89	3.21b	52.0ab	108.0	90.7b
Fertilizer	2.02ab	5.26	4.80a	69.0ab	132.4	141.0a
Compost 1	1.49b	4.26	3.99ab	48.4b	105.5	113.3ab
Compost 2	1.93ab	4.78	3.91ab	63.3ab	136.4	108.5ab
Manure 1	2.71a	4.67	4.91ab	92.3a	137.7	125.3ab
Manure 2	2.36ab	3.89	4.66ab	85.7ab	116.1	130.0ab
Manure 3 (eroded only)	2.91	5.32	4.49	111.8	157.1	125.7
Roots						
Control	1.41	9.43	12.5	15.9	83.1	109.0b
Fertilizer	1.55	10.6	13.6	21.2	95.0	140.1a
Compost 1	1.35	10.1	11.9	16.7	88.6	104.1b
Compost 2	1.39	10.6	12.7	17.7	83.5	114.8b
Manure 1	1.86	11.7	14.4	26.9	119.8	152.6a
Manure 2	1.69	10.7	14.6	24.3	102.7	164.5a
Manure 3 (eroded only)	1.53	10.86	14.13	26.5	129.5	155.5
Tops and roots						
Control	3.09	13.3	15.7b	68.0b	191.1	199.7c
Fertilizer	3.57	15.8	18.4ab	90.2ab	227.4	281.1a
Compost 1	2.83	14.4	15.9ab	65.1b	194.1	217.4c
Compost 2	3.32	15.4	16.6ab	81.0ab	220.0	223.3bc
Manure 1	4.57	16.4	18.9ab	119a	257.6	277.9ab
Manure 2	4.06	14.6	19.2a	110a	218.8	294.5a
Manure 3 (eroded only)	4.44	16.17	18.62	138.3	286.6	281.3

† Within a given plant component and sample date, N-source treatment means followed by the same letter are not significantly different ($P < 0.05$). Letters are not displayed if the effect was not significant in the ANOVA (Table 5).

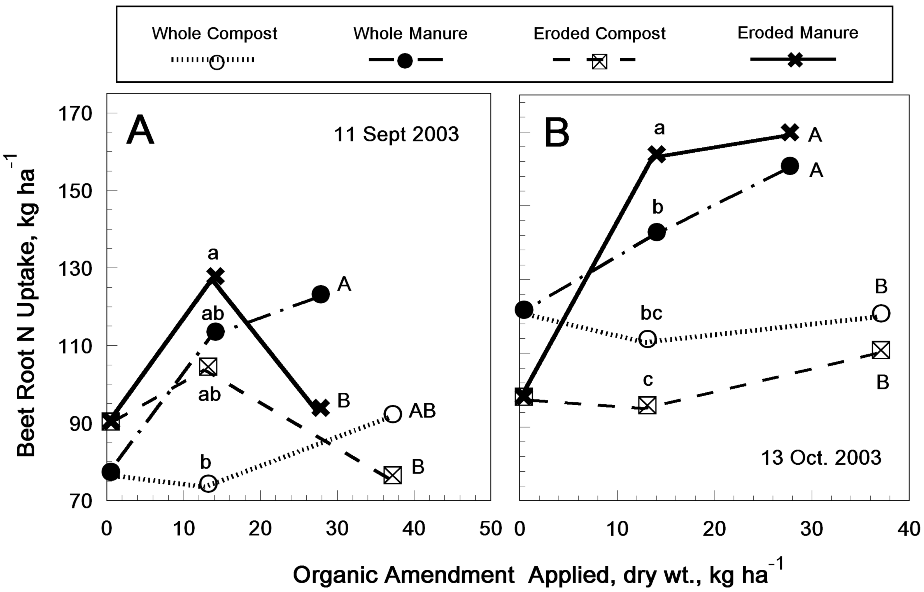

Fig. 7. The effect of compost and manure application rates on N uptake in sugarbeet roots on (A) 11 Sept. 2003 and (B) 13 Oct. 2003. Mean values for a given amendment rate are significantly different if labeled with different letters (*P* < 0.05).

manure application rates (Table 8), symptomatic of excessive soil N (Carter and Traveller, 1981). It was not entirely clear why yields for manure 2 were less than those for both the fertilizer and manure 1 treatments (Table 8). It may have resulted from reduced N availability in the early summer due to relatively greater N immobilization in manure 2 than in manure 1 (Table 5) (See discussion below). This conjecture is supported by the observation on 30 July 2003 that beet-top biomass for manure 2 was only 87% of that of manure 1 (Table 7).

The period of maximum uptake for winter and spring grain corresponds to late spring and the first 2 wk of early summer (Nielsen and Jensen, 1986; Westermann and Crothers, 1993). The winter wheat could not benefit from the amendment N mineralized in late summer due to the asynchrony between N supply and demand. The N mineralized in late summer and fall 2004 should have been available to the 2005 spring barley crop; but this N does not appear in the soil sampled on 7 Apr. 2005. The unusually warm temperatures and greater rainfall in the spring 2005 may have encouraged an early flush of microbial activity in the soils, resulting in temporary immobilization of the soil N.

The substantial increase in net N mineralization in the 30- to 60-cm soil layer as a result of manure application (Fig. 4) indicate that readily metabolized C was moving from the zone of manure incorporation to greater soil depths. This C is likely dissolved organic carbon (DOC) leached from the manure (Gallet et al., 2003), or fine manure particulates moving downward via mass flow in soil macropores. In the current study, microbes populating the 30- to 60-cm soil layer (apparently) responded vigorously to the fresh organic carbon inputs. However, it is also possible that bacteria present in the manure itself were transported downward with the DOC (Gallet et al., 2003), and may have contributed to the increased microbial activity in the 30- to 60-cm depth of manure-amended soils.

The percent of organic N applied, which was mineralized during November 2002 to October 2003, −4.3% for compost and 17.4% for manure, was lower than the amounts we assumed would be available. Eghball (200) reported a 11.8% value for fall-applied compost, measured from mid-June through October.

Table 8. Nitrogen-source effects on 2003 sugarbeet yield and quality parameters. Data have been averaged across erosion status (whole and eroded). The manure 3 treatment was not present in both whole and eroded soil types and so it was not included in the two-factor analysis or mean separations.

	Field beet root yield†	Clean beet root yield†	Sugar	Est. recov. sugar†	Brei nitrate	Brei conductivity
	Mg ha^{-1}		%	Mg ha^{-1}	mg kg^{-1}	dS m^{-1}
Treatment						
Control	57.4ab‡	51.5ab	15.5	6.48ab	706	1.04
Fertilizer	60.8a	54.9a	16.0	7.09a	598	1.04
Compost 1	57.5ab	51.5ab	15.7	6.46ab	619	1.10
Compost 2	56.3ab	50.7ab	15.9	6.55ab	628	1.03
Manure 1	60.7a	55.1a	15.7	6.97a	640	1.08
Manure 2	49.6b	44.9b	15.3	5.48b	648	1.11
Manure 3 (Eroded only)	53.9	49.5	15.1	5.74	801	1.25

† Clean yield = yield minus soil and crown tare; Est. recov. sugar = estimated amount of sugar extractable from beets per unit area.

‡ For a given yield or quality parameter, N-source treatment means followed by the same letter are not significantly different (*P* < 0.05). Letters are not displayed if the effect was not significant in the ANOVA.

Table 9. Accumulated aboveground biomass, grain yield, grain protein, and N uptake at maturity for wheat in 2004 and barley in 2005. The manure 3 treatment was not present in both whole and eroded soil types and so it was not included in the two-factor analysis or mean separations.

	2004 Winter wheat				2005 Spring barley			
	Biomass†	Grain yield‡	N uptake	Grain protein‡	Biomass†	Grain yield‡	N uptake	Grain protein‡
	Mg ha^{-1}		kg ha^{-1}	%	Mg ha^{-1}		kg ha^{-1}	%
N Source†								
Control	11.1bc§	3.99	75.0b	8.1	3.4b	2.30b	28.1c	7.75
Fertilizer	10.7bc	4.23	78.0b	8.2	4.1b	2.51b	34.1bc	7.64
Compost 1	10.4c	4.49	80.3b	9.1	3.8b	2.55b	31.7bc	7.69
Compost 2	11.1bc	4.86	82.9b	9.1	4.3b	2.78b	37.7bc	7.60
Manure 1	15.3ab	5.72	121.8a	8.9	6.7a	4.40a	54.9b	7.62
Manure 2	17.8a	6.77	154.5a	9.3	8.9a	5.76a	83.4a	7.44
Manure 3 (Eroded only)	22.2	7.8	184.2	10.4	10.9	7.17	111.2	7.80
Contrast								
Control	11.1b	4.0b	75.0b	8.1	3.4b	2.3b	28.1b	7.8
COMP†	10.8b	4.7b	81.6b	9.1	4.8b	2.7b	41.0b	7.6
MAN†	16.6a	6.2a	138.2a	9.1	9.2a	5.1a	81.6a	7.5
COMP + MAN¶ : Whole vs. Eroded								
Whole	13.9	5.7	117.1	9.1	6.6a	4.4a	56.0	7.3b
Eroded	13.3	5.3	102.6	5.27	5.27b	3.36b	47.8	7.8a

† Data have been averaged across erosion status (whole and eroded); Cntrl = control; Fert = fertilizer; treatments.

‡ Grain yield and protein given on a 12% moisture basis.

§ Within a given parameter, N-source or treatment-class means followed by the same lowercase letter are not significantly different ($P < 0.05$). Not displayed if effect was not significant in the ANOVA.

¶ Data have been averaged across compost 1 and 2 (COMP) and manure 1 and 2 (MAN).

The difference between our result and Eghball's likely is due to the differences in (i) measurement period, (ii) soil water due to their rain-fed crop and use of uncapped microcylinder, and (iii) compost composition and handling. The first year value obtained for manure is similar to the 17.6% obtained by Motavalli et al. (1989) for injected dairy manure in southern Wisconsin and 21% obtained by Klausner et al. (1994) for dairy manure in New York State. Both cited studies estimated N availability from N uptake in corn. In contrast, our second year value is two times greater and our third year value is four times greater than values obtained in New York by Klausner et al. (1994).

Of the amendment N applied, the amount mineralized in manure plots, on average, was 1.85 times greater than that in compost treatments over the 3 yr (Table 5). Eghball (2000) reported N mineralized from field-applied manure to be two times that of composted manure. The compost's lower C/N ratio and slightly lower NDF suggests that composted manure contained more recalcitrant organic compounds than manure. These recalcitrant organics degrade at one-quarter the rate of organics present in stockpiled dairy manure (Castellanos and Pratt, 1981). Thus for any given period, manure net N mineralization rates tended to exceed control values to a greater extent than compost mineralization exceeded controls (Table 5). Another important contributor to this difference occurred immediately after application during the winter–spring (2002–2003) period, when compost treatments produced a mean net N mineralization of −0.12 mg kg^{-1} compared to 18.9 for manure and 14 for the control (Fig. 3). Thus net N mineralization of compost lagged behind that of manure. This difference in initial activity between the compost and manure may be related to the types of soluble organic matter immediately released to the soil solution after amendment incorporation (Marschner and Kalbitz, 2003). Water soluble organics from composted manure include less simple carbohydrate-C and more complex protein-C and phenolic-C compounds than those from manure; and the latter are more readily adsorbed onto soil sorbtive surfaces (Liang et al., 1996), thereby hindering its degradation by soil microbes.

Organic additions produced a greater net N mineralization in eroded soils than in whole soils (relative to respective controls) suggesting that less manure needs be applied to eroded soils than whole soils to produce the same increase in net mineralized N (Table 5). On the other hand, the manure-amended, eroded soils had greater N immobilized during early summer 2003 than whole soils (Fig. 5A). Depending on the initial

Table 10. Effect of N-source and soil erosion status on apparent recovery of applied N for each year and the 3-yr cumulative amount.

	2003	2004	2005	3-yr Cumulative
	%			
Nitrogen source				
Fertilizer	98.3a†	3.6ab	7.3a	109.2a
Compost‡	3.5c	1.1b	1.0b	5.6c
Manure‡	14.6b	10.1a	6.3a	31.0b
Contrast				
Compost + Manure: Whole vs. Eroded				
Whole§	6.3	2.5	3.6	12.4b
Eroded§	11.8	8.7	3.7	24.1a

† For a given time or erosion status comparison, treatment means followed by the same lowercase letter are not significantly different ($P < 0.05$). Not displayed if effect was not significant in the ANOVA.

‡ Values are averaged across compost 1 and 2, or manure 1 and 2 application levels.

§ Values are averaged across all compost and manure N-source levels.

concentration of inorganic N in the soil, the rate of manure applied, and the crop's N requirement, this greater net N immobilization in eroded soil may limit crop growth early in the season.

Greater N mineralization fluctuations for eroded soil during early and late summer (e.g., Fig. 4) are curious and suggest greater microbial activity. This result may be counter-intuitive considering that whole soils, with their higher organic C, more neutral pH, and lower salt content, represent a more favorable environment for microbial growth than eroded soil. Apparently the lack of easily metabolizable C in eroded soils was more limiting to microbial growth than the above listed soil environmental conditions. The initial input of organic C with the amendments produced a rapid flush of microbial activity that exceeded that in whole soils, but over time the supplies of easily metabolizable C declined in eroded soils and microbial activity decreased. This could explain why net N mineralization in eroded soil was greater than that of whole soil in 2003, but less in 2004 and 2005 (Fig. 6).

CONCLUSIONS

To use nutrients available in southern Idaho soils optimally, it is important to consider the effect of whole vs. eroded soils on the net N mineralization of the organics added, account for the additional net N mineralized in the 30- to 60-cm soil layer, and to select crops whose N requirements coincide with both the amount and timing of the N released. In the first year after manure application eroded soils can achieve a greater increase in net N mineralization than whole soils; however, this relationship is reversed in the subsequent second and third years after application. Organic amendments are generally considered to have little effect on soil N availability and microbial activity below the depth of incorporation. This study indicates that as much as 27% of the net N mineralization in the 0- to 60-cm soil is produced in the 30- to 60-cm layer. The speed with which the crop root system develops may be important for fully using the sizeable amounts of N mineralized in the 30- to 60-cm soil layer. For example, a small grain crop's N demand appears to peak before the period of maximum net N mineralization for manure-amended soils. However, a winter wheat crop may more efficiently use mineralized manure N than spring grain because the wheat's germination and growth in the fall (i) increases crop N uptake in late fall and early spring, and(ii) may extend the plant's s rooting depth in time to use the N mineralized in the subsoils. Other crops like corn experience two periods of high N uptake, one in early July and one in late August (Dharmakeerthi et al., 2006). The late-season N requirement coincides with a net N mineralization peak from a manure amendment, whereas the early-season peak N requirement may more closely coincide with a manure-induced period of N immobilization (Fig. 3). In this case, more inorganic N may be needed to meet corn N needs during the early summer.

A better understanding of the amount of N mineralized and its availability to crops in subsequent years after a one-time manure application would allow farmers to more accurately match crop N requirements with available N and maximize yield and quality. In this current experiment N-mineralization data for three consecutive years was not easily compared because measurement periods and climatic conditions varied from year to year, which confounded results. Further experimentation is needed to address this topic.

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