Net Nitrogen Mineralization from Past Years' Manure and Fertilizer Applications

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The availability of soil N changes in years following a manure application. Experimental plots were established in a southern Idaho calcareous silt loam soil to measure these changes and aid N management in manure-amended soils of the semiarid West. The study's six manure treatments included combinations of two manure rates, Man-1× (0.31 Mg total N ha^{-1}) and Man-3× (0.97 Mg total N ha^{-1}) applied in the fall either 1, 2, or 3 yr previously. Two non-manure treatments were urea fertilizer applied per soil test (Fert) and a control with no amendment. We measured net N mineralization (0–30 cm) in the plots using buried bags in 2006, 2007, and 2009 for sprinkler-irrigated crops. This resulted in (i) 2 yr of net N mineralization data for each manure rate applied 1, 2, or 3 yr before measurement, and (ii) 1 yr of data for each manure rate applied 4 or 5 yr previous to the measurement year. A 5-yr decay series for each of the two manure rates was derived from functions fitted to the net N mineralization data, expressed as a fraction of total manure N applied. The decay series (Year 1–Year 5) for the Man-1× treatment was 0.23, 0.12, 0.10, 0.09, and 0.08, while that for the Man-3× rate was 0.20, 0.08, 0.05, 0.04, and 0.03. Soil at the 30- to 60-cm depth contributed up to 28% of the total N mineralized in the 0- to 60-cm soil layer of manure-amended soils in the third year after application, with lesser amounts contributed in earlier years due to immobilization. The efficacy of N mineralization processes decreased as the manure application increased, thus using a single decay series to predict N availability across a range of manure application rates could lead to substantial estimation errors.

Abbreviations: EC, electrical conductivity.

The U.S. dairy herd includes 9 million cows that produce an estimated 20 million Mg of manure annually. Southern Idaho is a regional dairy center whose herds make up 5.6% of the U.S. total and produce approximately 1.11 million Mg manure annually. Idaho dairies typically are open-lot bedded pack operations where manure is stockpiled in a drying area. The manure is applied to cropland to supply nutrients to crops, improve soil physical properties, and increase organic C concentrations in 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 know how much N becomes available to crops from manure applications (Carter et al., 1976).

Although manure is a rich source of plant nutrients, much of the included N is in an organic form, only becoming available to crops 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 and water content, and soil characteristics (Eghball et al., 2002; Van Kessel and Reeves,

Soil Sci. Soc. Am. J. 76:1005–1015
doi:10.2136/sssaj2011.0282
Received 10 Aug. 2011.
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2002). Many laboratory studies have evaluated mineralization rates at optimal soil water contents and temperatures 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; Miller et al., 2010). Unfortunately, N mineralization rates derived from laboratory incubations generally overestimate rates measured in the field (Adams and Attiwill, 1986; Honeycutt, 1999; Sistani et al., 2008).

In situ soil N mineralization measurements better reflect the environmental factors and dynamic conditions that are specific to an individual region or management condition (Stenger et al., 1996; Hanselman et al., 2004). Methods that measure in situ net N mineralization track changes in inorganic N concentrations for small soil volumes (<750 cm^3) across time. Hanselman et al. (2004) compared several methods for measuring net N mineralization rates and found that buried bags (Eno, 1960) gave good results until the plastic film lost its integrity (>45 d). In southern Idaho irrigated soils, researchers using a polyethylene bag that differed from that of Hanselman et al. (2004) achieved good results when the bags were buried for as long as 150 d (Westermann and Crothers, 1980, 1993; Meek et al., 1994; Lentz et al., 2011).

Relatively few field studies measuring N mineralization in situ in manure-amended soils have been reported in the literature. Eghball (2000) measured N mineralization at the 0- to 15-cm depth for a soil amended annually with cattle manure. Watts et al. (2010) measured N mineralization in Alabama soils at the 0- to 20-cm depth at various landscape positions in the first year after a one-time composted dairy manure application. Hanselman et al. (2004) determined net N mineralization rates in a Florida soil at the 0- to 30-cm depth during a 180-d period after a one-time application of poultry manure. Lentz et al. (2011) measured seasonal net N mineralization rates for 3 yr after a one-time dairy manure or composted manure application. They reported that 18 to 27% of the 3-yr, cumulative, net N mineralization in manured, southern Idaho soils occurred at the 30- to 60-cm depth. Determining how a soil's net N mineralization potential changes in the years following a one-time manure application is difficult due to year-to-year climatic variation, which tends to confound the effect of time on N mineralization (Lentz et al., 2011). Our objective was to determine the effect of the year of dairy manure application on net N mineralization in a calcareous, irrigated, southern Idaho soil while minimizing the confounding effects of climate.

MATERIALS AND METHODS

We conducted the experiment at a site located 1.7 km southwest of Kimberly, ID (42°31′ N, 114°22′ W, elevation of 1190 m). The field plots were prepared in Portneuf silt loam soils. The experimental site 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, 10 yr before field plot preparations began for the current study. The Portneuf is a deep, calcareous silt loam or very fine sandy loam soil. The surface (0–15 cm) is a silt loam and contains, on average, 200 g kg^{-1} clay, 620 g kg^{-1} silt, and 180 g kg^{-1} sand, has a pH of 7.8 (H_2O-saturated paste), electrical conductivity (EC) of 0.08 S m^{-1}, and includes 5.1 g kg^{-1} organic C, and 221 mg kg^{-1} $CaCO_3$ equivalent. A silica- and $CaCO_3$–cemented horizon (20–60% cementation) occurs between the depths of 33 and 130 cm. The soil has a mean cation exchange capacity of 190 $mmol_c$ kg^{-1} and exchangeable Na percentage of 1.5. Before the study, the field site was cropped to a series of crops including alfalfa (*Medicago sativa* L.), corn (*Zea mays* L.), wheat (*Triticum aestivum* L.)–barley (*Hordeum vulgare* L.), and bean (*Phaseolus vulgaris* L.) (>12 yr).

Experimental Design

If manure is applied in 1 yr and net N mineralization is measured in the following 3 yr, the comparisons between annual measurements would be influenced not only by the time since application but also by climatic factors, which vary from year to year. To limit the direct effect of climatic factors during the year in which net N mineralization was measured, we applied manure treatments at a 1× rate (average bulk application rate of 21.7 Mg ha^{-1} dry wt. or 0.31 Mg total N ha^{-1}) and a 3× rate (average bulk application of 68.9 Mg ha^{-1} dry wt. or 0.97 Mg total N ha^{-1}) once only to a different set of field plots in the fall of 2004, 2005, and 2006. Thus, when net N mineralization was measured in 2006, the field plots included a set of two manure-rate treatments that were either 1 or 2 yr old (only the two had been included by that date). For the 2007 measurement, the field plots included a completed set of two manure-rate treatments that were either 1, 2, or 3 yr old. Finally, when net N mineralization measurements were repeated in the plots for 2009, the manure-rate treatment plots were either 3, 4, or 5 yr old. Therefore, when net N mineralization was measured in a given year, the included 2- or 3-yr application sequence of manure plots had experienced the same climatic conditions in the previous years as well as in the measurement year.

The experimental design was a randomized complete block with eight treatments and four replicates (Table 1). The experiment included six manure treatments, with the 1× (Man-1×) and 3× (Man-3×) manure rates applied once to different plots of Portneuf silt loam in 2004, 2005, and 2006. Two non-manure treatments were also included: urea fertilizer application (Fert) and a control. No N fertilizer was applied to the manure treatments, nor was any manure or fertilizer N applied to the control. The Fert treatment received urea N at recommended rates based on the inorganic N present in the root zone (0–60 cm) measured with a spring preplant soil test. The Man-1× application represented a common bulk application rate in the region. No P or K fertilizer was applied to any of the plots. The plots were 9.1 m wide by 21.3 m long.

Whenever manure treatments were applied, we obtained solid dairy cattle (*Bos taurus*) manure that had been stockpiled at a local dairy through the summer. The manure's average total C concentration (SE in parentheses) was 217 (58) g kg^{-1}, total N was 14.1 (2.6) g kg^{-1}, and the C/N ratio was 15.9 (1.5).

Table 1. Description of treatments.

Treatment name	Treatment I.D.	Added N source	Bulk application rate	Year of application†	Treatment age in season net N mineralization was measured		
					2006	2007	2009
			Mg ha^{-1} (dry wt.)		yr		
Control	Control	none	0	no application	1	1	1
Fertilizer	Fert	urea	0.29	each year	1	1	1
Man-1×							
2006	1×-06	dairy manure	17.4	2006	–	1	3
2005	1×-05	dairy manure	32.5	2005	1	2	4
2004	1×-04	dairy manure	23.0	2004	2	3	5
Man-3×							
2006	3×-06	dairy manure	56.7	2006	–	1	3
2005	3×-05	dairy manure	78.4	2005	1	2	4
2004	3×-04	dairy manure	71.7	2004	2	3	5

† Fertilizer was applied each year from 2006 to 2009, while manure was applied only once in the fall of the year shown.

Using the method described below, the net soil N mineralization was measured in all established plots during the 2006, 2007, and 2009 growing seasons. This resulted in (i) 2 yr of data for each manure treatment, 1× or 3×, and each of the three manure application times, i.e., 1, 2, or 3 yr before the measurement year, plus (ii) 1 yr of data for each manure rate applied 4 or 5 yr previous to the measurement year (Table 1). Hence, the design of this study provides unique information on the effect of the year of manure application on net N mineralization.

Field Operations

Before establishment of the experimental plots in fall 2004, the field had been used for a short-term sugarbeet (*Beta vulgaris* L. ssp. *vulgaris*) emergence study, which was tilled under on 29 May 2004, 4 wk after planting. No amendments or fertilizers were applied to the site as part of the sugarbeet emergence study. Manure was applied to designated plots on 18 Nov. 2004, 22 Dec. 2005, and 19 Oct. 2006 using a commercial spreader truck equipped with rooster-comb beaters. Two to four 0.15-m^2 trays were randomly placed in each plot before spreading to quantify the application rate. The manure collected in each tray was weighed, mixed, subsampled for C and N analysis, and then returned to the soil surface from which it had been collected. The field was disked to a depth of 0.1 m within 48 h of manure application. Urea was not applied to any plot in 2005 before planting spring barley. Barley was harvested in mid-July 2005. In fall 2005 before manure application, the surface residue was burned to destroy weedy growth that had occurred after harvest. In March 2006, soil samples were taken at the 0- to 30- and 30- to 60-cm depths in the plots and analyzed for soil N, P, and K (described below). Levels of P and K in the soils were adequate for small grains. On 13 Apr. 2006, the Fert treatment received 134 kg N ha^{-1} as urea via a hand-held spreader, while the control and manure plots received no urea. Immediately thereafter, the field was disked to the 0.1-m depth and roller-harrowed. Barley was planted in late April 2006. Barley residue and volunteer growth were burned on 13 Oct. 2006 before manure was applied to the designated plots.

On 15 Mar. 2007, soil samples were collected from the plots in 30-cm increments down to 90 cm. Based on a nutrient analysis, we applied urea to the Fert treatment on 16 Apr. 2007 at the rate of 135 kg N ha^{-1} (Moore et al., 2009) and immediately incorporated the material with a roller harrow. The field was planted with Beta 4023R sugarbeet treated with Poncho Beta [clothianidin ([C(*E*)]-*N*-[(2-chloro-5-thiazolyl)methyl]-*N*′-methyl-*N*″-nitroguanidine) + beta-cyfluthrin (cyano(4-fluoro-3-phenoxyphenyl)methyl 3-(2,2-dichloroethenyl)-2,2-dimethylcyclopropanecarboxylate)] on 20 Apr. 2007 in rows 0.56 m apart, with an in-row spacing of 55 mm, and later thinned to a population of 117,000 plants ha^{-1}. Standard commercial procedures were used to control insects, weeds, and disease. A single cultivation was performed on 26 June 2007. The sugarbeet crop was harvested on 10 Oct. 2007.

In late May 2008, the field was disked to 0.1-m depth, urea was applied to the Fert treatment at the rate of 23 kg N ha^{-1}, and the field was roller-harrowed before planting Viva Pink bean. A single cultivation was performed on 26 June 2008 and the crop was harvested on 29 Sept. 2008. In 2009, bean was again planted in the field using the same approach as in 2008.

Irrigation throughout the growing season was supplied via sprinklers to meet the crop's evapotranspiration (ET) requirements. Meteorological data required to calculate crop ET were acquired from a weather station located 5.6 km northeast of the experimental plots. A rain gauge located near the field plot measured growing-season precipitation. Mean monthly air temperature, total monthly precipitation, and irrigation during the 36-mo study are reported in Fig. 1.

Sampling and Analyses

We used a buried-bag method adapted from Westermann and Crothers (1980) and Meek et al. (1994) to measure net N mineralization in plot soils. In each plot, four 5.7-cm-diameter soil cores, 0 to 30 cm deep, were collected, composited, and passed through a 0.4-cm screen. If the soil's water content was estimated to be <17 to 20 kg kg^{-1}, distilled water was added to achieve this water content. A subsample of the composited soil was collected to determine inorganic N and the final soil water content. The

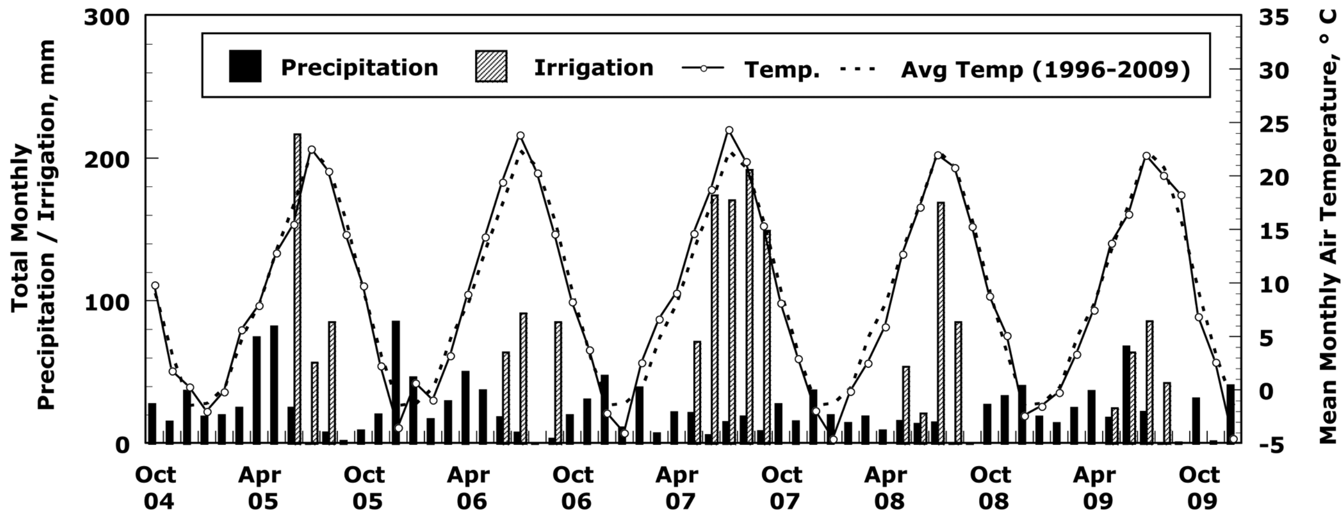

Fig. 1. Total monthly precipitation and irrigation amounts and mean monthly air temperature at the study site from fall 2004, when the first manure treatment was applied, through October 2009, the last year net N mineralization was measured.

soil's inorganic N concentration was calculated as the sum of the extractable NO_3–N and NH_4–N concentrations (mg N kg^{-1} dry soil) (analysis described below). Part of the remaining soil was placed in 10-μm-thick, 5-cm-diameter polyethylene tubes that were sealed on one end. The bag's polyethylene film was only slightly permeable to water vapor but allowed adequate O_2 and CO_2 gas exchange between the enclosed and field soils (Eno, 1960; Westermann and Crothers, 1980).

The soil was settled using a vertical shaking action, and 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. The surface soil was placed in the hole around the bag as needed to fill the cavity, thus ensuring representative soil temperatures in the bagged soil. Soil was also mounded on the soil surface atop the bag to eliminate water flow along the bag's sidewalls.

In a similar manner, buried bags were installed at 30- to 60-cm depths in a limited number of treatment plots, i.e., the control in 2006, 2007, and 2009; the Man-3× treatment from 2005 in 2006; the Man-3× treatments from 2004 and 2006 treatments in 2007; and the Man-3× treatment from 2006 in 2009. These data permitted comparison between the control and 1- and 3-yr-old, 3× manure treatments (four replicates) and presumably represented the range in subsoil net N mineralization expected from all treatments. The procedure was the same as that used for the 0- to 30-cm depth, except that two to three 30- to 60-cm soil cores were collected per plot and the buried bags were placed at the 30-to 60-cm depth. On 24 April each year (±2 d), we installed one 0- to 30-cm buried bag in each plot and one 30- to 60-cm buried bag below the 0- to 30-cm bag in selected control and Man-3× plots. The buried bag at each depth was retrieved on 15 June, at which time two sets of buried bags were installed in the same plots (with the same depth arrangement) using the procedure above. One of these two sets was retrieved on 1 August, and the other in mid-September of each year. The exceptions to this procedure occurred in 2006, which included an additional bag for the 15 September to 18 October period, and in the 2007 sugarbeet crop, when all three sets of buried bags were installed in April and the final bag was retrieved on 2 October. We determined inorganic N concentrations in soils from the initial sample and retrieved buried bags. After the samples were air dried at 35°C and crushed to pass a 2-mm screen, soil N was extracted using a 2 mol L^{-1} KCl solution (Mulvaney, 1996). The NO_3–N concentration in each extract was determined within 6 h of extraction using a Lachat Instruments automated flow injection analyzer after Cd reduction (Lachat Method 12-107-04-1-B), while the NH_4–N concentration was determined simultaneously using a salicylate–hypochlorite method (Lachat Method 12-107-06-2-A).

Field soil samples were analyzed for inorganic N using the same methods used for the analysis of the buried bag soils. Soils were extracted for bicarbonate-extractable P according to Olsen et al. (1954) and exchangeable K according to Schoenau and Karamanos (1993) except without the addition of charcoal. Extracted samples were analyzed for P and K by inductively couple plasma-optical emission spectrometry. Manure C and N concentrations were determined on a freeze-dried sample with a Thermo-Finnigan FlashEA1112 CNS analyzer.

The net N mineralization during the period between burial and retrieval was calculated by subtracting the inorganic N concentration of the initial soil from that of the soil in the retrieved bag. A positive difference indicated net N mineralization, while a negative value indicated net N immobilization during the period. We reported net N mineralization for the spring (24 April–15 June), early summer (15 June–1 August) and late summer (1 August to 17 September or 2 October) periods. The early summer and late summer values were computed by difference relative to the previously retrieved buried bag sample. The net N mineralized (termed *minN*) was reported directly (mg N kg^{-1} soil). In addition, minN values from manure treatments were reported as a percentage of the total manure N applied (minN%). This was computed for each manure treatment and measurement year as

$$\mathrm{minN\%} = \frac{(\mathrm{minN_m} - \mathrm{minN_c})10^{-4} M_{\mathrm{soil}}}{\mathrm{TN_m}} \qquad [1]$$

where $\mathrm{minN_m}$ is the net N mineralized from the manure treatment (mg N kg^{-1}), $\mathrm{minN_c}$ is the net N mineralized from the control treatment (mg N kg^{-1}), M_{soil} is the mass per unit area of a 30-cm-thick layer of soil, approximated as 4.48×10^6 kg ha^{-1}, and $\mathrm{TN_m}$ is the total N applied in the manure (kg N ha^{-1}).

To determine how growing-season net N mineralization decreased with time, we plotted the mean absolute net N mineralization values for the 1× and 3× manure rates from each of the three measurement years as a function of time after manure application. To reduce the effect of climate and other factors on the N mineralized each year, data from 2007 and 2009 were standardized to that of 2006. To do this, we subtracted the difference between the 2006 and 2007 control values from each of the 2007 amounts. The 2009 data were adjusted in a similar manner. We also plotted the net N mineralized (as a percentage of the total added manure N) as a function of the number of years since manure had been applied. These plotted data were not standardized because the values already accounted for relative differences in measurement-year control values (see Eq. [1]).

Statistical Analysis

We examined the 0- to 30-cm N mineralization data for the given reporting intervals separately via ANOVA, using PROC Mixed (SAS Institute, 2009). The statistical model included treatment as the fixed effect and block as the random effect. Pairwise comparisons of treatment means were performed using the Tukey option (SAS Institute, 2009). We also included several more powerful single-degree-of-freedom orthogonal contrasts in the analysis. These included four class comparisons, where a class represents a combination of treatments: (i) no manure vs. manure (1× + 3×) treatments, where the non-manure class is control + Fert; (ii) Man-1× vs. Man-3× treatments across all years; and (iii) young manure vs. older manure treatments across both 1× and 3× rates (i.e., manure treatments of Year 1 vs. Year 2 in 2006, or manure treatments of Year 1 vs. those of Years 2 and 3 in 2007, or manure treatments of Year 3 vs. Years 4 and 5 in 2009).

The 30- to 60-cm data were evaluated using ANOVA to determine the effect of the manure treatment age on net N mineralization. This used PROC Mixed and Fisher's protected least significant difference for pairwise comparisons of treatment means (SAS Institute, 2009). All analyses were conducted using a $P = 0.05$ significance level.

Power or exponential functions describing the effect of year of manure application on minN and minN% were calculated from treatment means using an iterative method that selected the best fit based on minimizing the sum of squares of the residuals (SPSS Inc., 1997).

RESULTS AND DISCUSSION

Late summer air temperatures at the experimental plots generally followed normal values for the period fall 2004 through fall 2009 (Fig. 1). Spring and early summer temperatures varied during the period, however, being normal or cooler in 2005, 2008, and 2009 and warmer than normal in 2006 and 2007. The 2007 growing season was warmest of the 5 yr, with the 2007 February through July temperatures being 1.5°C warmer than the 1996 to 2009 mean. The increased early summer heat units coupled with abundant irrigation water supplies and the delay of hard frost until after October contributed to record-breaking 2007 sugarbeet yields in southern Idaho. Annual precipitation varied considerably across the years, with 2005 and 2006 being 1.41 and 1.18 times wetter than normal (264 mm yr^{-1}), respectively, and 2007 being 34% drier than normal.

The mean preseason plot soil N concentration in 2006 was relatively low, 7.0 mg kg^{-1} (Table 2), and was approximately one-quarter that in 2007 and one-half that in 2009 (Table 2). This probably resulted from the unusually dry fall the area experienced in 2005 and cooler than normal early spring temperatures in 2006 (Fig. 1). These conditions substantially reduced microbiological activity and N mineralization in the fall and early spring before sampling.

Table 2. Initial soil N for all treatments at the 0- to 30-cm depth in 2006, 2007, and 2009. Values are reported directly as milligrams N per kilogram soil for each measurement period and for treatment classes included in orthogonal contrast tests.

Treatment	Initial soil N		
	25 Apr. 2006	26 Apr. 2007	21 Apr. 2009
	mg N kg^{-1} soil (dry wt.)		
Control	4.4	12.6 b†	11.3 c
Fertilizer	8.4	33.6 a	16.3 abc
1× Manure, 2006	–	31.8 a	15.3 ab
1× Manure, 2005	8.2	17.9 b	13.8 bc
1× Manure, 2004	5.4	14.1 b	12.3 bc
3× Manure, 2006	–	45.9 a	20.6 a
3× Manure, 2005	9.3	27.8 ab	19.6 ab
3× Manure, 2004	6.6	28.7 ab	17.4 ab
	Contrasts‡		
No manure	6.4	23.1	13.8 b
vs. manure	7.4	27.7	16.5 a
1× Manure	6.8	21.3 b	13.8 b
vs. 3× manure	8.0	34.1 a	19.2 a
Manure Year 1	8.8 a	–	–
vs. manure Year 2	6.0 b	–	–
Manure Year 1	–	38.3 a	–
vs. manure Years 2 and 3	–	22.2 b	–
Manure Year 3	–	–	17.9 a
vs. manure Years 4 and 5	–	–	15.8 b

† For a given year, treatment means or means for individual contrasts followed by the same lowercase letter are not significantly different ($P <$ 0.05). No letter is shown if the effect was not significant in the ANOVA.

‡ No manure = control + fertilizer treatments; manure = 1× manure + 3× manure treatments; Years 1, 2, 3, 4, and 5 = fall manure applied 1, 2, 3, 4, and 5 yr in the past, respectively.

Table 3. Treatment effects on net N mineralization at the 0- to 30-cm depth during the 2006, 2007, and 2009 measurement periods and summed across each growing season (bolded and italic), where net N mineralization is given directly or relative to the total manure N applied. Shown are *P* values for treatment effects and single-degree-of-freedom orthogonal contrasts derived from an ANOVA.

	P value												
	2006					2007				2009			
Source of variation	26 Apr.–14 June	15 June–1 Aug.	2 Aug.–18 Sept.	18 Sept.–18 Oct.	*26 Apr.–18 Oct.*	25 Apr.–15 June	15 June–1 Aug.	1 Aug.–2 Oct.	*25 Apr.–2 Oct.*	25 Apr.–15 June	15 June–1 Aug.	1 Aug.–17 Sept.	*25 Apr.–17 Sept.*
	Net N mineralized, mg N kg^{-1} soil												
Treatment	***	**	*	0.07	***	0.1	**	***	***	***	0.1	0.45	***
Contrasts†													
No manure vs. manure	0.46	0.53	0.99	0.29	***0.42***	0.17	**	**	***	**	0.98	0.28	***0.08***
1× vs. 3× manure	***	*	*	0.15	***	0.40	**	0.41	**	0.18	0.19	0.79	***0.10***
In terms of treatment age													
Manure, Year 1 vs. 2	***	***	0.24	0.07	**								
Manure, Year 1 vs. 2 and 3						0.17	**	*	***				
Manure, Year 3 vs. 4 and 5										**	0.63	*	*
	Net N mineralized, % of manure N applied												
Treatment (manure only)	*	***	0.27	0.64	*	0.11	0.24	0.06	***	*	0.06	0.13	*
Contrasts†													
1× vs. 3× manure	0.67	0.20	0.11	0.80	***0.30***	*	0.63	*	**	*	*.	0.26	*
In terms of treatment age													
Manure, Year 1 vs. 2	**	***	0.77	0.14	**								
Manure, Year 1 vs. 2 and 3						*	**	*	***				
Manure, Year 3 vs. 4 and 5										**	0.40	*	*

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.
† No manure = control + fertilizer treatments; manure = 1× manure + 3× manure treatments; Years 1, 2, 3, 4, and 5 = fall manure applied 1, 2, 3, 4, and 5 yr in the past, respectively.

Net Nitrogen Mineralization in the 0- to 30-cm Soil

Significant Treatments and Contrasts

Treatment effects on the absolute net N mineralization response in the 0- to 30-cm depth of soil were highly significant for most measurement periods and for the cumulative net N mineralized for the 2006, 2007, and 2009 growing seasons (Table 3). The contrast tests further established that (i) the net N mineralization from non-manure treatments taken as a group differed from that of the manured treatments for early and late summer periods and the growing season in 2007 and for the spring period in 2009; (ii) Man-1× commonly differed from Man-3× treatments in 2006 and 2007 but not in 2009; and (iii) N mineralized from the manure treatments differed depending on the year of application. When the net N mineralization response was analyzed as a percentage of the manure N applied, the results were generally similar except that treatment effects for individual periods within each growing season were less often significant. Furthermore, when N mineralization was analyzed in terms of the percentage of manure N applied, differences between the Man-1× and Man-3× treatments (contrast tests) for the monitored periods in 2007 and 2009 were more often significant than was the case when absolute values were examined.

Net Nitrogen Mineralization

We considered first the effect of treatments on the absolute net N mineralization response. The non-manure treatments (control and Fert) generally produced similar net N mineralization amounts during measurement periods and growing seasons (Table 4). The exceptions were the 26 April to 14 June 2006 spring period and the 2006 growing season, where the Fert values were nearly fourfold greater than the controls. The fertilizer N stimulated N mineralization in spring 2006, probably by stimulating microbial activity (Westerman and Kurtz, 1973; Ma et al., 1999). We did not observe this fertilizer priming effect in subsequent years (Table 4) when preseason soil N exceeded that in 2006, >8.4 mg kg^{-1} (Table 2), or in an earlier study on this soil when preseason soil N exceeded 9 mg kg^{-1} (Lentz et al., 2011).

The season-long net N mineralization for the control treatment was greater in 2007 and 2009 than 2006 (Table 4), probably due to differences in temperature, moisture, and crop conditions, which influenced microbial activity. In addition, the pattern of net N mineralization produced by all treatments across the measurement periods differed for 2006 relative to 2007 and 2009. In 2006, net N mineralization peaked during spring, followed by immobilization in early summer, whereas in subsequent measurement years net N mineralization amounts were more evenly distributed throughout the growing season. We attribute the 2006 spring mineralization maximum to the combined effect of abundant precipitation (1.4 times the average value) and warmer-than-normal temperatures in spring 2006 (Fig. 1). In contrast, spring precipitation in 2007 and 2009 was below normal (Fig. 1).

For 2006 and 2007 the net N mineralized during the growing season for the Man-1× treatment in Year 1 (treatment age = 1 yr) averaged 26.1 mg kg^{-1} [(19.3 + 32.8)/2], or 2.0 times the average control value, and 51.1 mg kg^{-1} for Man-3×, or nearly 4.0 times that of the control average. These net N mineralization values for the Year 1 manure treatments were similar to those reported by Lentz et al. (2011) for similar treatments in 2003, i.e., 32.6 (Man-1×) and 48.7 mg kg^{-1} (Man-3×). Net N mineralized during the growing season for manure treatments in Years 2 and 3 was reduced an average of 38% compared with Year 1 manure treatments (Table 4).

Nitrogen Recovery From Applied Manure Nitrogen

The advantage of reporting the net N mineralization values ($minN_m$) for a given measurement period or growing season as percentages of the total manure N applied (minN%) is that the findings are more robust, less sensitive to the variations in manure quality or the amount applied to plots in any given year. Results reported in these terms are more widely applicable, in general. The mean net N mineralization

Table 4. Treatment effects on net N mineralized at the 0- to 30-cm depth for measurement periods and summed across each of three growing seasons (bold and italic).

Source	Net soil N mineralized: 2006 Treatment age	2006 26 Apr.– 14 June	2006 15 June– 1 Aug.	2006 2 Aug.– 18 Sept.	2006 18 Sept.– 18 Oct.	2006 *26 Apr.– 18 Oct.*	2007 Treatment age	2007 25 Apr.– 15 June	2007 15 June– 1 Aug.	2007 1 Aug.– 2 Oct.	2007 *25 Apr.– 2 Oct.*	2009 Treatment age	2009 21 Apr.– 15 June	2009 15 June– 1 Aug.	2009 1 Aug.– 17 Sept.	2009 *25 Apr.– 17 Sept.*
	yr	mg N kg^{-1} soil					yr	mg N kg^{-1} soil				yr	mg N kg^{-1} soil			
Control	1	11.4 b†	−0.6 a	3.7 ab	−3.2	***11.4 c***	1	3.8	6.8 bc	3.9 b	***14.6 c***	1	7.2b	6.5	4.1	***17.8 b***
Fertilizer	1	39.0 a	−3.3 ab	8.9 ab	−1.8	***42.8 b***	1	8.0	6.9 bc	4.7 b	***19.6 bc***	1	8.2ab	14.2	4.3	***26.7 b***
1× Manure, 2006	–	–	–	–	–	–	1	8.5	12.5 a	11.8 a	***32.8 ab***	3	10.3ab	7.8	7.1	***25.2 b***
1× Manure, 2005	1	20.2 b	−1.3 ab	2.1 b	−1.7	***19.3 bc***	2	6.7	8.0 bc	9.0 ab	***23.7 bc***	4	8.8b	10.7	4.1	***23.6 b***
1× Manure, 2004	2	17.6 b	−0.3 a	4.1 ab	−3.0	***18.4 bc***	3	6.0	8.0 abc	8.5 ab	***22.5 bc***	5	8.4b	9.3	5.8	***23.5 b***
3× Manure, 2006	–	–	–	–	–	–	1	8.8	17.6 a	14.9 a	***41.4 a***	3	12.0a	11.7	9.2	***32.9 a***
3× Manure, 2005	1	51.4 a	−4.3 b	13.5 a	0.2	***60.8 a***	2	7.2	12.9 ab	8.3 ab	***28.5 bc***	4	8.9b	11.0	3.7	***23.6 b***
3× Manure, 2004	2	21.7 b	−0.4 a	5.6 ab	−2.1	***24.8 bc***	3	8.1	10.4 abc	10.6 ab	***29.1 b***	5	9.3b	10.7	5.3	***25.3 b***
							Contrasts‡									
No manure	1 & 2	25.2	−2.0 b	6.3	−2.5	***27.0***	1, 2, & 3	5.9 b	6.9 b	4.3 b	***17.1 b***	3, 4, & 5	7.7b	10.4	4.2	***22.3***
vs. manure	1 & 2	27.7	−1.6 a	6.3	−1.7	***30.7***	1, 2, & 3	7.6 a	11.6 a	10.5 a	***29.7 a***	3, 4, & 5	9.6a	10.2	5.9	***25.7***
1× manure	1 & 2	18.9 b	−0.8 a	3.1 b	−2.4	***18.8***	1, 2, & 3	7.1	9.5 b	9.7	***26.3 b***	3, 4, & 5	9.2	9.3	5.6	***24.1 b***
vs. 3× manure	1 & 2	36.6 a	−2.4 b	9.6 a	−1.0	***42.8***	1, 2, & 3	8.0	13.6 a	11.3	***32.9 a***	3, 4, & 5	10.1	11.1	6.1	***27.3 a***
Manure, Year 1	1	35.8 a	−2.8 b	7.8	−0.8	***40.0***	–	–	–	–	–	–	–	–	–	–
vs. manure, Year 2	2	19.7 b	−0.4 a	4.9	−2.6	***21.6***	–	–	–	–	–	–	–	–	–	–
Manure, Year 1	–	–	–	–	–	–	1	8.7	15.1 a	13.3 a	***37.1 a***	–	–	–	–	–
vs. manure, Years 2 and 3	–	–	–	–	–	–	2 & 3	7.0	9.8 b	9.1 b	***26.0 b***	–	–	–	–	–
Manure, Year 3	–	–	–	–	–	–	–	–	–	–	–	3	11.1a	9.8	8.2 a	***29.1 a***
vs. manure, Years 4 and 5	–	–	–	–	–	–	–	–	–	–	–	4 & 5	8.9ba	10.4	4.7 b	***24.0 b***

† Treatment means or means for individual orthogonal contrast pairs followed by the same lowercase letter are not significantly different ($P < 0.05$). No letter is shown if the effect was not significant in the ANOVA.

‡ No manure = control + fertilizer treatments; manure = 1× manure + 3× manure treatments; Years 1, 2, 3, 4, and 5 = fall manure applied 1, 2, 3, 4, and 5 yr in the past, respectively.

Table 5. Treatment effects on net N mineralized, given as a percentage of the N applied in manure, at the 0- to 30-cm depth for measurement periods and summed across each of three growing season (bold and italic).

Source	2006 Treatment age	2006 26 Apr.–14 June	2006 15 June–1 Aug.	2006 2 Aug.–18 Sept.	2006 18 Sept.–18 Oct.	2006 ***26 Apr.–18 Oct.***	2007 Treatment age	2007 25 Apr.–15 June	2007 15 June–1 Aug.	2007 1 Aug.–2 Oct.	2007 ***25 Apr.–2 Oct.***	2009 Treatment age	2009 21 Apr.–15 June	2009 15 June–1 Aug.	2009 1 Aug.–17 Sept.	2009 ***25 Apr.–17 Sept.***
	yr	%					yr	%				yr	%			
1× Manure, 2006	–	–	–	–	–	**–**	1	8.7	10.4	14.4	***33.3 a‡***	3	5.7 a	2.4	5.4	***13.4 a***
1× Manure, 2005	1	14.5 ab†	−1.2 b	−2.7	2.5	***13.1 ab***	2	4.7	2.1	8.4	***15.1 b***	4	2.6 ab	6.9	0.0	***9.5 ab***
1× Manure, 2004	2	6.9 b	0.3 a	0.4	0.3	***7.9 b***	3	2.5	1.3	5.2	***8.8 b***	5	1.4 ab	3.2	1.8	***6.2 ab***
3× Manure, 2006	–	–	–	–	–	**–**	1	2.8	6.1	6.2	***15.1 b***	3	2.7 ab	2.9	2.9	***8.5 ab***
3× Manure, 2005	1	20.8 a	−1.9 b	5.1	1.7	***25.7 a***	2	1.8	3.2	2.3	***7.2 b***	4	0.9 b	2.3	−0.2	***3.0 ab***
3× Manure, 2004	2	3.7 b	0.1 b	0.6	0.4	***4.8 b***	3	1.5	1.3	2.4	***5.2 b***	5	0.8 b	1.5	0.4	***2.7 b***
							Contrasts‡									
1× manure	1 & 2	10.7	−0.4	−1.2	1.4	***10.5***	1, 2, & 3	5.2 a	4.6	9.3 a	***19.1 a***	3, 4, & 5	3.2 a	4.1 a	2.4	***9.7 a***
vs. 3× manure	1 & 2	12.2	−0.9	2.9	1.1	***15.3***	1, 2, & 3	2.1 b	3.5	3.6 b	***9.2 b***	3, 4, & 5	1.5 b	2.2 b	1.0	***4.7 b***
Manure, Year 1	1	17.6 a	−1.6 b	1.2	2.1	***19.4 a***	–	–	–	–	**–**	–	–	–	–	**–**
vs. manure, Year 2	2	5.3 b	0.2 a	0.5	0.3	***6.3 b***	–	–	–	–	**–**	–	–	–	–	**–**
Manure, Year 1	–	–	–	–	–	**–**	1	5.7 a	8.3 a	10.3 a	***24.3 a***	–	–	–	–	**–**
vs. manure, Years 2 and 3	–	–	–	–	–	**–**	2 & 3	2.6 b	1.9 b	4.6 b	***9.1 b***	–	–	–	–	**–**
Manure, Year 3	–	–	–	–	–	**–**	–	–	–	–	**–**	3	4.2 a	2.6	4.2 a	***11.0 a***
vs. manure, Years 4 and 5	–	–	–	–	–	**–**	–	–	–	–	**–**	4 & 5	1.4 b	3.5	0.5 b	***5.4 b***

† Treatment means or means for individual orthogonal contrast pairs followed by the same lowercase letter are not significantly different ($P < 0.05$). No letter is shown if the effect was not significant in the ANOVA.

‡ Manure = 1× manure + 3× manure treatments; Years 1, 2, 3, 4, and 5 = fall manure applied 1, 2, 3, 4, and 5 yr in the past, respectively.

amount for all manure treatments was 12.9% in the 2006 growing season, 14.2% in 2007, and 7.2% in 2009 (Table 5). Thus, the manure continued to supply inorganic N 3 to 5 yr after being applied.

The percentage of total manure N mineralized during the growing season generally differed with the manure application rate, the exception being in 2006. Class comparisons showed that the 2006 Man-1× and Man-3× values were not significantly different. When averaged across application year, the proportion of manure N mineralized during the 2007 and 2009 growing seasons for the Man-1× application class was twice that of the Man-3× class (Table 5). This indicates that the net N mineralized was not strictly a function of the quantity of manure applied and suggests that smaller rather than larger manure applications were more effective at supplying inorganic N on a per unit mass basis. A similar phenomenon was observed by Motavalli et al. (1989) in the first year after a dairy manure application, i.e., the percentage N recovery from the applied manure N decreased with increasing manure applications. The current study shows that the effect persists for multiple years. It is not clear why the efficacy of N mineralization processes decreased as the manure application increased. It may be caused by the manure itself, e.g., manure effects on soil EC, pH, nutrient concentrations, and water distribution, and their subsequent impact on soil microbial activity, or by differences in application efficiency, such as the degree of mixing and distribution of applied manure in the soil. Incorporation of the 3× manure rate was observed to be less uniform than that of the 1× rate.

Effect of Application Year

After the one-time manure application, the growing-season net N mineralization decreased with time, although the pattern of this decrease varied depending on whether the net N mineralization was reported in absolute (Fig. 2a) or relative (Fig. 2b) terms. The absolute net N mineralization declined as an exponential or power function in time, with the fitted curve for the Man-3× starting at a greater value for Year 1 and declining more steeply than Man-1× during the first 3 yr after manure application (Fig. 2a). After the third year, the curves are much closer but offset such that the predicted (or fitted) Man-3× values consistently exceed those of Man-1× by approximately 3 mg N kg^{-1}.

The fitted curves in Fig. 2b describe the effect of application time on the net N mineralization given as a percentage of the total manure N applied. They indicate that a greater proportion of the total manure N became available in Man-1× than in Man-3× treatments. The slopes of Man-1× and Man-3× fitted curves at Year

5 suggest that net N mineralization might either continue to slowly decline or possibly plateau in subsequent years. For both sets of curves (Fig. 2a and 2b), the smaller R^2 values associated with Man-1× indicate that other factors besides manure age had a substantial impact on net N mineralization soon after application. These may well be related to differences in manure characteristics that influence short-term mineralization and immobilization rates (Liang et al., 1996; Griffin et al., 2005; Mallory and Griffin, 2007), particularly in the first year after manure application (Gallet et al., 2003; von Lützow et al., 2006; Wen et al., 2003).

From the functions describing the change in relative net N mineralization (Fig. 2b), we derived a 5-yr decay series for each of the two manure rates applied in this study. These decay series represent the fraction of total manure N applied that would be available for crop use in Years 1 through 5 after a single manure application. The decay series was 0.23, 0.12, 0.10, 0.09, and 0.08 for the Man-1× and 0.20, 0.08, 0.05, 0.04, and 0.03 for the Man-3×. Our decay rates in the first 3 yr after manure application were 0 to 50% lower than those predicted from limited field data for warm southern California valleys (Pratt et al., 1973). Research done under cool-winter climates may be more relevant. Our series may be compared with a 3-yr decay series of 0.21, 0.09, and 0.03 reported by Klausner et al. (1994) for New York, which was derived from the mean of two dairy manure rates, 250 and 700 kg total N ha^{-1} compared with our 310 and 970 kg total N ha^{-1}. The Year 1 and 2 values of Klausner et al. (1994) are quite similar to ours, but their Year 3 value was less. Note that Klausner et al. (1994) derived net N mineralization (i) using the two spring manure applications from which NH_3 volatilization was encouraged, and (ii) from N uptake data, which is a function of crop growth and influenced by other factors such as root distribution, soil water availability, and leaching. Eghball (2000) also estimated decay values from crop N uptake data: 0.39 and 0.18 for the first and second years after a 378 kg total N ha^{-1} cattle manure application to Nebraska soils. The greater values of Eghball (2000) may have resulted in part from the manure's relatively low C/N ratio, 9.9, and abundant NH_4–N content, 1263 mg kg^{-1} (Mallory and Griffin, 2007).

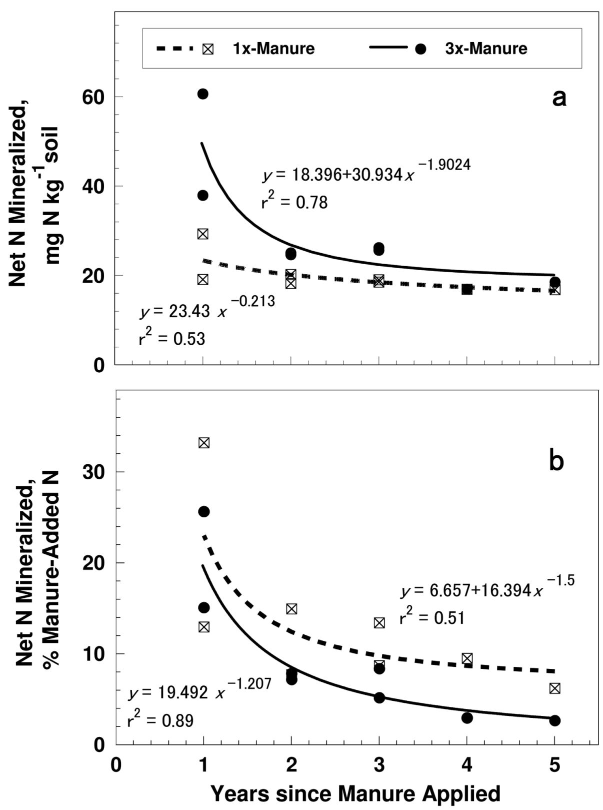

Fig. 2. The effect of the age of applied manure on the net N mineralized at the 0- to 30-cm depth during the growing season, as measured in 2006, 2007, and 2009. Net N mineralization is presented as (a) standardized relative to the N mineralized in 2006, and (b) relative to the total amount of manure N applied.

The current study did not address the case where multiple manure applications were made annually. Pratt et al. (1973) indicated that N availability from consecutive annual manure applications could be estimated using a single decay relationship by summing overlapping decay curves from the individual applications. Previous manure applications have been shown to reduce the availability of added N in soils (Mallory and Griffin, 2007), however, suggesting that the decay curve for a site having multiple manure applications may shift relative to that for a one-time application.

Net Nitrogen Mineralization in the 30- to 60-cm depth

Net N mineralization in absolute terms at the 30- to 60-cm depth was similar among the control and 1- and 3-yr-old Man-3× treatments for all measurement periods (Table 6). The contrast test indicated, however, that net N mineralization during the early summer was more strongly affected by N

Table 6. The effect of control and manure treatment age on net N mineralized from 3× manure applications at the 30- to 60-cm depth for measurement periods and summed across the growing season (bold and italic). The effect of treatment combinations included in contrast tests are also shown.

Treatment†	Spring	Early summer	Late summer	*Entire growing season*
	——— mg N kg^{-1} soil (dry wt.) ———			
Manure, Year 1	4.4	−3.3	−0.5	***0.6***
Manure, Year 3	3.0	0.9	4.6	***8.5***
Control	2.5	0.6	1.1	***4.2***
Contrasts				
Manure, Year 1	4.4	−3.3b‡	−0.6	***0.6b***
Manure, Year 3 + control	2.8	0.8a	2.8	***6.4a***
Source of variation, *P* value				
Treatment	0.85	0.09	0.11	***0.07***
Contrast				
Manure, Year 1 vs. manure, Year 3 + control	0.18	*	0.10	*

* Significant at $P < 0.05$.

† Year 1 and Year 3, 3× manure fall applied 1 or 3 yr in the past, respectively.

‡ For a given time period, treatment means or means for individual orthogonal contrast pairs followed by the same lowercase letter are not significantly different ($P < 0.05$). No letter is shown if the effect was not significant in the ANOVA.

immobilization for the 1-yr-old Man-3× treatment than for the combined 3-yr-old Man-3× and control treatment class (Table 6). As a result, during the growing season, the 1-yr-old Man-3× treatment produced only about 1/10th the net mineralized N as that produced by the control and older manure treatment class (Table 6). We hypothesize that the fresh manure contained more soluble, readily metabolized organics than did the 3-yr-old manure or controls. When this soluble C was leached into the C-poor soils at 30- to 60-cm depth, it was metabolized and much of the available inorganic N was immobilized by microorganisms. In the older manure and control plots, less soluble C leached into the deeper soils and immobilization processes were inhibited.

Net N mineralization at the 30- to 60-cm depth for the 1-yr-old Man-3× treatment ranged from 4.4 in spring to −3.3 mg kg^{-1} in early summer (Table 6). This differed from measurements reported by Lentz et al. (2011) for a similar manure treatment and soil, where the net N mineralization at the 30- to 60-cm depth ranged from −34 mg kg^{-1} in early summer to 43 mg kg^{-1} in late summer. Apparently soil microorganisms were less active in subsoils of the current study than in the earlier study. In the current study, the mean soil N concentration in the Man-3× subsoil in the spring following the fall manure application was 12 mg kg^{-1} (data not shown). In the earlier study, however, the initial soil N in the corresponding Man-3× subsoils was 79 mg kg^{-1} (Lentz et al., 2011). Hence, the low-N subsoil in the current study may have lacked the N necessary to support substantial microbial mineralization of the manure-derived soil organic matter that was leached from the amended surface soil (Fierer et al., 2003).

The net N mineralized in the 30- to 60-cm soil during the growing season for the 1-yr-old Man-3× treatment was −1.7% of the total manure N applied compared with 2.4% for the 3-yr-old Man-3× treatment (data not shown). Therefore, the contribution of the 30- to 60-cm soil layer to the overall net N mineralization in the entire uppermost 60 cm of the profile during the growing season was −9% for the first year after application and 28% for the third year (data not shown). This confirms an earlier observation made by Lentz et al. (2011) that the 30- to 60-cm depth plays a substantial role in both the immobilization and mineralization of N in these soils.

CONCLUSIONS

Growers in semiarid, irrigated regions can better estimate the quantity of N available to crops grown in fields treated with stock-piled dairy manure using our study's findings. A decay series was derived for each of two one-time manure application rates, 1× (24.3 Mg ha^{-1} dry wt.) and 3× (68.9 Mg ha^{-1}). The fraction of applied manure N that became available from net N mineralization in the years after application differed between the two manure rates, revealing that N mineralization efficiency varied inversely with the manure application rate. Uncertainties related to net N mineralization prediction were greatest for the lesser application rate, particularly in the first year after application. These differences may be related to variations in manure characteristics, such as C, N, or labile, soluble organic C concentrations that affect short-term manure mineralization and immobilization dynamics. At greater application rates, variations in manure characteristics have a lesser relative effect, which may partially explain the greater uncertainties associated with first year 1× manure application relative to the 3× application rate. A single decay series describing the fraction of applied manure N that becomes available to crops in succeeding years is often used to predict N availability. Our results indicate, however, that a single decay series would not accurately predict N availability across a range of manure application rates.

ACKNOWLEDGMENTS

We thank Dr. Amber Moore and Dr. David Tarkalson for their helpful comments on an initial draft of the manuscript, and Mr. Larry Freeborn, Ms. Paula Jolley, and James B. Nava for their technical support and able assistance in the laboratory and field.

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