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Nitrogen Mineralization as Affected by Temperature in Calcareous Soils Receiving Repeated Applications of Dairy Manure

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There are currently no tools available to help predict N mineralization for the silty soils found in southern Idaho receiving repeated manure applications. This experiment aimed to determine the effect of temperature on N mineralization from control and manured soils, develop N mineralization rate correction factors for temperature [ratio of the change in the rate coefficient of mineralization for every 10°C increase (Q_{10}) and temperature factors], and create a simple model for predicting N mineralization as a function of growing degree-days. Manured and control soils underwent a 49-d laboratory incubation at five temperatures (–14, 4, 10, 23, and 30°C); soil inorganic N concentration was determined at 0, 1, 3, 5, 7, 13, 20, 28, 35, 42, and 49 d. Net N mineralization was fitted to a zero-order model, where the rate coefficient (*k*) values for the manured soil ranged from 0.017 to 1.28 mg kg^{-1} soil d^{-1} over the five temperature treatments, whereas *k* in the control measured 0.028 to 0.53 mg kg^{-1} soil d^{-1}. The calculated Q_{10} values from –14 to 30°C were 2.7 and 2.0 for the manured and control soils respectively. At low temperatures (–14 to 4°C), the Q_{10} for manured soil was 5.1 compared with 1.5 for the control. This suggests that manure additions may lower the temperature threshold for N mineralization under near frozen soil conditions. Manure treatment effects on the temperature factor were not observed, suggesting that manure application history may not need to be considered when developing temperature factor coefficients for N mineralization models.

Abbreviations: GDD, growing degree-days; *k*, rate coefficient; Q_{10}, the ratio of the change in the rate coefficient of mineralization for every increase in temperature of 10°C; TF, temperature factor.

Core Ideas

- **Prediction of N mineralization is dependent on accurate rate correction factors and the ratio of the change of the rate coefficient of mineralization for every increase in temperature of 10°C (Q_{10}) based on temperatures observed in the region.**
- **Few studies have investigated N mineralization in soils receiving repeated applications of manures at low temperatures.**
- **This study determined that manure additions may lead to larger Q_{10} values at low temperatures and growing degree-days may aid in predicting N release from these soils.**

Dairy manure is commonly applied to crops in southern Idaho as a source of plant-available N. Repeated applications of dairy manure lead to the accumulation of organic N compounds in various stages of decomposition, creating issues for predicting N mineralization rates for soils with a previous history of repeated dairy manure applications. Several scientists have documented N release from a recent single application of dairy manure on varying soils at incubation temperatures between 22 and 25°C (Van Kessel and Reeves, 2002; Griffin et al., 2005; Gale et al., 2006). However few studies have determined the rates and amounts of N released from soils with multiple applications of dairy manure that were made months or years prior to the study.

Empirical and mechanistic models have been created to better predict N mineralization from land-applied manure and other byproducts and residues. These models allow an accurate prediction of byproduct application rates and the availability of plant nutrients as a function of local climate (Honeycutt et al., 1988; Génermont and Cellier, 1997; Chambers et al., 1999; Ni, 1999; Griffin and Honeycutt, 2000; Griffin et al., 2002; Davenport et al., 2012). The success

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of these models is reliant on accurate model inputs, such as rate coefficients, rate coefficient correction factors, and adequate Q_{10} values fitted in the temperature range observed in the region. Previous research has shown a wide variety of values measured for these inputs. Differences in the rate coefficient and response to temperature are dependent on soil texture, climatic region, soil sampling time, amendment history, and the temperature range for which the variables are measured (Stanford and Smith, 1972; Campbell et al., 1981; Bonde and Rosswall, 1987; Vigil and Kissel, 1995; Franzluebbers et al., 1996; Cabrera et al., 2005; Mallory and Griffin, 2007; Clark et al., 2009).

Some studies have shown the effect of temperature on N release and N kinetics for silty-textured soils similar to those found in southern Idaho (Campbell et al., 1981; Dessureault-Rompré et al., 2010). Campbell et al. (1984) and Dessureault-Rompré et al. (2010) determined a Q_{10} value of 2.12 for fine-textured soils and Dessureault-Rompré et al. (2010) reported an average Q_{10} of 2.85 for 20 silt textured soils. Westermann and Crothers (1980) estimated a Q_{10} of 2.3 for soil temperature ranged between 10 and 30°C for a Xerollic Calciorthid silt loam soil (referred to as Durinodic Xeric Haplacalcid or Portneuf silt loam, under current USDA NRCS soil taxonomic guidelines). For southern Idaho, soil temperatures (10 cm depth) over collected the past 20 yr ranged from −3.9 to 30.2°C with an average of 11.8°C (AgriMet Staff, 2016) indicating the need for the determination of temperature factors (TFs) across a range of temperatures and for soils receiving manure. A study conducted by Clark et al. (2009) with soils receiving the application of pig slurry determined that net N mineralization occurs even at low temperatures (−6 to 10°C), with an increased temperature sensitivity at temperatures below 2°C (Q_{10} values two orders of magnitude greater than for soils incubated above 2°C). Studies determining the effect of temperature on soils that have received repeated or long-term applications of manure are lacking.

Although Q_{10} values are often used for modeling the effect of temperature on biological processes, rate coefficient correction factors are often implemented as another tool in models for predicting N mineralization (Vigil and Kissel, 1995; Cabrera et al., 2008). Temperature factors typically range from 0 to 1 and adjust the rate coefficient compared to a standard reference temperature at which optimal mineralization occurs. In a study on soils amended with a variety of crop residues, Vigil and Kissel (1995) determined that the TF fitted to an exponential equation greatly improved the prediction capability of the CERES-MAIZE MINIMO subroutine. Temperature factor values for manured soils or silty-textured soils were not found in the literature.

Using an empirical modeling approach, previous researchers have shown that cumulative heat units or GDD can be used to predict N release from crop residues, organic fertilizers, and manures (Honeycutt et al., 1988; Griffin and Honeycutt, 2000; Griffin et al., 2002; Davenport et al., 2012). The majority of these N mineralization estimation efforts have been focused on immediate manure applications, leaving no current tools for estimating N supplied from previous or repeated applications of manure. The GDD concept may prove to be a simple tool for producers to better estimate plant-available N from applications of dairy manure.

The results from the literature indicate the importance of accurately describing the effect of temperature on N mineralization; however, the results for soils with a history of repeated manure, fall applications of manure, and silty soils are currently lacking. The objectives of this experiment were to determine the effect of temperature on N mineralization from control and manured soils (a 3-yr history of dairy manure application), develop rate correction factors for temperature (Q_{10} and TFs), and create a simple statistical model predicting N mineralization as a function of cumulative heat units (GDD) using 49-d laboratory incubations.

MATERIALS AND METHODS

Treatment Design and Soil Collection

Soils were collected from an ongoing dairy manure application study site located at the USDA ARS field station in Kimberly, ID (42°33′N; 114°21′W). The soil classification for this area is a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids). The historical 30-yr average annual precipitation (1995 to 2015) for Kimberly, ID, was 203.7 mm and the 30-yr average annual temperature was 7.7°C (AgriMet Staff, 2016). The field design is a randomized complete block design with four replications and eight treatments. The eight treatments within the ongoing manure field study include six manure treatments that vary in both the rate and frequency of dairy manure applications, one fertilizer-only treatment, and one control treatment (no nutrient source applied). The individual plots are 12.2 m in width and 18.3 m in length. Spring malt barley (*Hordeum vulgare* L.) and sugar beets (*Beta vulgaris* L.) were grown under irrigated conditions at the field site in 2013 and 2014 respectively. For the purposes of this incubation experiment, only soils from the "heavy" annual dairy manure application treatment and the control treatment were collected. For the remainder of this paper, the two soils will be referred to as the "manured soil" and "control soil".

The manured soil received annual fall applications of stockpiled dairy manure at rates of 52.0 Mg dry matter ha^{-1} on 16 Oct. 2012, 5 Nov. 2013, and 23 Oct. 2014 (874, 1478, and 776 kg N ha^{-1} respectively). A total of 3128 kg N ha^{-1} (156 Mg dry matter ha^{-1}) was applied over the 3-yr period prior to soil collection from manure application. The manure analyses methods are cited below. Prior to each planting, a preplanting soil nitrate test was performed to determine available N and determine if additional fertilizer applications were needed. On 15 March 2013, urea fertilizer (460 g N kg^{-1}) was applied at an N rate of 62 kg N ha^{-1} and diammonium phosphate fertilizer (110 g N kg^{-1} and 226 g P kg^{-1}) was applied at an N rate of 19 kg N ha^{-1} to the manured treatment to meet the malt barley industry plant nutrient requirement standards. No additional fertilizer was needed for the manured treatment plots for 2014 or 2015 crop production, as soil nutrient levels were sufficient for barley and sugar beet production. As mentioned above, the control soil did not receive manure, fertilizer, or any other N source. All treatments (controls included) were disked to a depth of 15.3 cm within 48 h of manure application.

Soils were collected from the "manure" and "control" treatments on 13 Apr. 2015 with a 5.7-cm diameter bucket soil auger (Signature Mud Auger part no. 350.20, AMS Inc. American Falls, ID). Ten subsamples were collected to a depth of 0 to 30 cm, passed through an 8-mm sieve, and combined into a single soil sample. Soil samples were stored sealed at 4°C for 24 h before incubation.

Initial Manure and Soil Characteristics

Two weeks prior to fall application in 2012, 2013, and 2014, manure was collected for laboratory analysis. Manure water content was determined gravimetrically on a 100-g subsample by drying at 105°C for 8 h; total C and N content were determined via combustion of moist manure samples with the CHN 628 analyzer (LECO, St. Joseph, MN). The initial inorganic N concentration of the manure was measured (5 g soil: 25 mL extractant) with 2 mol L^{-1} KCl extraction (Gavlek et al., 2005). The supernatant was analyzed via an automated flow injection analyzer for NO_3–N concentration via cadmium reduction (Lachat Method 12–107–04–1-B) and NH_4–N concentration via the salicylate-hypochlorite method (Lachat Method 12–107–06–2-A) (Lachat Instruments, Loveland, CO). Organic N was calculated as the difference between total N and inorganic N concentrations. The measured manure characteristics are presented in Table 1.

The initial soil characteristics are presented in Table 2. The initial inorganic N concentration of the soil and soil water content were determined immediately after collection, with subsamples of the soil being air-dried (5 d at 35°C), passed through a 2-mm sieve, and ground for total N determination. Initial soil inorganic N soil was measured (5 g soil: 25 mL extractant) via 2 mol L^{-1} KCl extraction (Mulvaney, 1996). The supernatant was analyzed with an automated flow injection analyzer as cited above. Soil gravimetric water content was determined from a 10-g subsample by drying at 105°C for 48 h. Total N (three replications per sample) was determined by dry combustion (Thermo-Finnigan Flash EA1112 CNS analyzer, CE Elantech, Lakewood, NJ). Particle size distribution was determined via the hydrometer method (Gee and Or, 2002) and no differences were observed between the manured and control soil treatments. Both soil treatments had 67 g kg^{-1} clay, 800 g kg^{-1} silt, and 133 g kg^{-1} sand on average. After collection and initial analysis, soils were stored at 4°C for less than 24 h.

Table 1. Characteristics of dairy manure that was field-applied and incorporated into manure treatment plots in the fall of 2012, 2013, and 2014. Three manure subsamples were collected directly from the manure pile within 2 wk of field application and combined into one sample.

Year	Total N	Organic N	NH_4–N	NO_3–N	C/N	Moisture content
	g kg^{-1} dry manure					g kg^{-1}
2012	16.7	13.9	2.82	0.017	17.1	500
2013	28.7	25.8	2.84	0.055	13.1	643
2014	14.7	11.1	3.62	0.097	14.7	380

Temperature Incubation Study

Nitrogen mineralization for the manured soil (a 3-yr manure history) and the control soil (unamended) was evaluated at five temperatures (–14, 4, 10, 23, and 30°C) in a 49-d laboratory incubation. For each soil treatment and temperature treatment, the original four replications from the field randomized complete block design were used. Five hundred grams of field-moist soil (415 and 424 g dry weight equivalent for the manured and control soils respectively) was placed in 17.7 by 18.8 cm polyethylene bags. The thickness of the polyethylene film was 0.044 mm. Soils were used at field-moist water content (Table 2), where the initial soil water contents (Day 0) of the manured and control soil treatments were 0.20 and 0.18 g H_2O g^{-1} dry soil respectively. Experimental units were placed in incubators and soil water content was maintained by weight by adding deionized water at each sampling period and were aerated weekly to maintain aerobic conditions. Water content was determined gravimetrically on the final day of the experiment (5-g subsample, 48 h at 105°C). The manured and control soil treatments had measured mean water contents of 0.21 g H_2O g^{-1} dry soil and 0.18 g H_2O g^{-1} dry soil, respectively. To determine N mineralized over the incubation experiment, 5-g subsamples were removed from each experimental unit at 1, 3, 5, 7, 13, 20, 28, 35, 42, and 49 d. Subsamples were extracted with 2 mol L^{-1} M KCl and analyzed colorimetrically for NO_3–N and NH_4–N as described above. The measured soil inorganic N concentration was converted to a dry weight basis via the water contents determined at Day 0. Water content was assumed to be relatively constant throughout the incubation period.

Data Analysis

The amount of N mineralized over the 49-d experiment (Net-Nmin, in mg kg^{-1} soil) for both the manured and the control soil was calculated by subtracting the initial inorganic N (NH_4–N +NO_3–N) from inorganic N values determined at time, *t*, where:

$$\text{Net-Nmin} = Inorganic\ N - Inorganic\ N_{t=0} \quad . \qquad [1]$$

To compare net N mineralized over the 49-d incubation, a generalized linear mixed model was applied via the SAS GLMMIX procedure (SAS Institute, 2013), as described by Stroup (2015). Data distribution was assumed to be normal. Treatment and temperature were established as fixed effects, and replication within temperature was established as a random effect. Mean differences were assessed via pairwise treatment comparisons within temperature regimes.

Table 2. Initial soil characteristics (± SD) for manured and control soils used in a 49-d incubation experiment.

Soil Treatment	NH_4–N	NO_3–N	Total N	Initial Water Content
	mg kg^{-1} dry soil			g H_2O g $soil^{-1}$†
Manured soil	3.9 ± 2	57.4 ± 11	1454 ± 151	0.20 ± 0.01
Control soil	2.2 ± 1	10.1 ± 2	865 ± 69	0.18 ± 0.03

† Dry weight basis.

Net N mineralized in this study was fitted to a linear (zero-order) model. Considering the wide range of temperatures and the length of the experiment, with the differences observed between the manured and control treatments taken into account, the linear model was deemed to be acceptable in fit. Rate coefficients of mineralization were determined from the zero-order model's fit and net N mineralization data versus time (in d) were fitted with SAS version 9.3 using PROC REG (SAS Institute, 2013):

$$\text{Net Nmin manure}\left(\text{mg inorganic N kg}^{-1}\text{ soil}\right) = k \times t + b, \quad [2]$$

where k is the rate coefficient of net N mineralization (mg inorganic N kg^{-1} d^{-1}), t is time (d), and b is the substrate concentration at time 0 determined through regression (Cabrera et al., 2008). Values of linear fit are presented in Table 3.

The effect of temperature on net N mineralization was evaluated via three different approaches. For the purpose of aiding computer simulation modeling, the Q_{10} and TF values were determined as rate coefficient correction factors. To provide a simple statistical model for field estimations of N mineralization, net N mineralized was regressed against cumulative heat units (Honeycutt et al., 1988; Griffin and Honeycutt, 2000; Davenport et al., 2012).

Determined k values for different temperature treatments were used to determine Q_{10} values for manured and the control soils as follows:

$$Q_{10} = \left(\frac{k_{T2}}{k_{T1}}\right)^{\frac{10}{(T2-T1)}}, \quad [3]$$

where the Q_{10} is the ratio of the change in the rate coefficient of mineralization for every increase in temperature of 10°C and T is temperature (°C) (Heumann and Bottcher, 2004; Cabrera et al., 2008).

Table 3. Linear fitting characteristics of the incubation data for temperature and soil treatments for net N (NH_4–N+NO_3–N) mineralized over 49 d.

Soil Treatment	Incubation temperature	Intercept	Zero-order rate coefficient	R^2
	°C	mg inorganic N kg^{-1} dry soil	mg inorganic N kg^{-1} dry soil d^{-1}	
Manured soil	-14	2.09 (0.5)†	0.017 (0.02)‡	0.015
	4	1.44 (0.9)‡	0.33 (0.04)	0.636
	10	3.84 (1.0)	0.33 (0.04)	0.609
	23	3.26 (1.2)	0.82 (0.05)	0.879
	30	8.22 (2.0)	1.28 (0.08)	0.854
Control soil	-14	0.63 (0.3)‡	0.028 (0.01)‡	0.176
	4	0.88 (0.5)‡	0.072 (0.02)	0.291
	10	0.93 (0.5)‡	0.099 (0.02)	0.414
	23	0.49 (0.6)‡	0.21 (0.02)	0.667
	30	0.78 (1.0)‡	0.53 (0.04)	0.803

† The SE of coefficients are represented in parentheses.

‡ The value of the parameter was not significantly different than zero (p = 0.01).

The TF was calculated as a relative rate (values from 0 to 1) with the net N mineralized at 49 d for the 30°C temperature treatment as the reference temperature (Vigil and Kissel, 1995). The TF was determined as follows:

$$TF = \frac{d49\,Net\ Nmin_{Tt}}{d49\,Net\ Nmin_{T30}}, \quad [4]$$

where the TF represented the proportion of net N mineralized at the temperature treatment (Tt) compared with net N mineralized at the 30°C temperature treatment (T30).

The TF data were fitted with SigmaPlot Dynamic Fit Wizard to exponential and linear models (Vigil and Kissel, 1995). Models were fitted with the Marquardt–Levenberg algorithm, which determined the values of the parameters by minimizing the sum of squares of the differences between the actual and fitted values through iteration.

Cumulative heat units or GDD were calculated on a 0°C base temperature (Griffin and Honeycutt, 2000). The relationship between net-N mineralized, GDD, and initial soil total N for both manured and control soil treatments was determined using PROC REG multiple regression procedure in SAS version 9.3 (SAS Institute, 2013).

RESULTS AND DISCUSSION

Net N Mineralization

Net N mineralization response to temperature in both the control and manured soil treatments are shown in Fig. 1. The mean

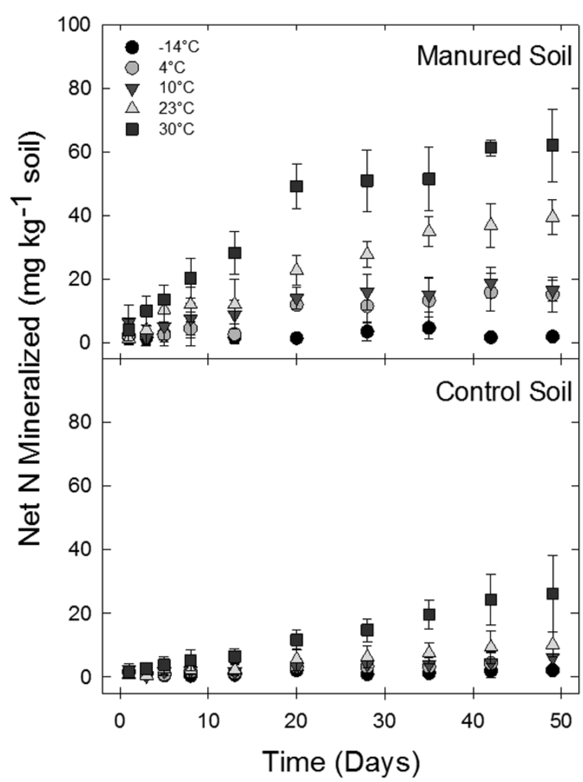

Fig. 1. Net N mineralized (mg inorganic N kg^{-1} dry soil) from manured-treated and nontreated Portneuf silt loam lab incubated at –14, 4, 10, 23, or 30°C. Data points represent treatment means; error bars represent SD.

values of net N mineralized (49 d and the supporting statistical analysis are listed in Table 4 and Table 5. Manure treatment effect, temperature effect, and the manure treatment × temperature interaction were all significant for net N mineralization at the $p = 0.05$ level (Table 5). Manure additions did not have a significant effect on net N mineralization at −14°C. Mean net N mineralization was negligible (or zero) for both treatments at −14°C, indicating the minimal occurrence of microbial activity at this low temperature. Manure additions had a significant effect on whole-study net N mineralization at the other temperatures (Table 5), with mean net N mineralized increasing by magnitudes of 4.2, 2.7, 3.9, and 2.4 at 4, 10, 23, and 30°C respectively (Table 4). The observed increase in net N mineralization between the manured and control soil by 4.2-fold was not expected at the 4°C temperature setting, as the Q_{10} function that is commonly used for N mineralization prediction models assumes that net N mineralization below 5°C is insignificant (Ellert and Bettany, 1992). This finding suggests that manure additions may lower the temperature threshold for N mineralization to occur under near frozen soil conditions. Manure additions have had a similar effect on lowering N mineralization temperature thresholds in other studies (Clark et al., 2009).

Net N mineralized as a percent of the initial soil total N was calculated by dividing the net inorganic N by the initial total soil N concentration. When the data were expressed as a percentage of initial soil total N, the manure treatment effect and temperature effect on mineralizeable total soil N were significant at the $p = 0.05$ level. (Table 4). Manure additions had no effect on percentage of mineralizable total soil N at −14, 4, or 10°C but did cause a significant increase at 23 and 30°C by 2.3-fold and 1.5-fold respectively (Table 5). Mallory and Griffin (2007) noted differences in net N mineralized between soil treatments after the 282-d incubation at 25°C in the historically manured soil and the control, with 6.8 and 5.8% net N mineralized as a percentage of soil total N for the manure and control soil respectively. Differences observed in net N mineralization as a percentage of the initial soil total N between manure-treated and control soils may be reflective of the readily mineralizable N compounds accumulated from repeated applications of manure (Mallory and Griffin, 2007), compared with recalcitrant nitrogenous compounds in the native soil organic matter (Sharifi et al., 2011).

Table 4. Net N mineralized (± SD) after 49 d of incubation for manured and control soil.

Soil treatment	Incubation temperature	Mean net N mineralized	Mean net N mineralized
	°C	mg N kg^{-1}	% of initial soil total N
Manured soil	-14	2.7 ± 0.7	0.19 ± 0.01
	4	15.2 ± 5.6	1.04 ± 0.3
	10	16.5 ± 3.2	1.13 ± 0.1
	23	39.5 ± 5.5	2.73 ± 0.4
	30	62.1 ± 11.4	4.31 ± 0.9
Control soil	-14	2.1 ± 0.5	0.26 ± 0.1
	4	3.6 ± 3.1	0.42 ± 0.4
	10	6.2 ± 3.3	0.71 ± 0.4
	23	10.2 ± 3.9	1.16 ± 0.4
	30	26.3 ± 12.0	2.97 ± 1.1

A zero-order model was fitted to net inorganic N concentrations over the 49-d incubation for each temperature regime and manure treatment. The model intercept, k value, and model fit (R^2) were determined for each temperature and treatment (Fig. 1; Table 3). Overall, the goodness of fit (R^2) for the linear model increased from 0.01 to 0.85 and 0.18 to 0.80 with increasing temperature from -14 to 30°C for manure and control soils respectively. Low R^2 values were probably a function of the lack of mineralization observed and the low overall inorganic N concentrations measured observed at low temperatures. The R^2 values were influenced by both data variation and by slope of the linear regression. Rate coefficient (k) values for the manured soil ranged from 0.017 to 1.28 mg inorganic N kg^{-1} soil d^{-1} over the five temperature treatments, whereas k values in the control measured 0.028 to 0.53 mg kg^{-1} soil d^{-1} (Table 2). In both soil treatments, N mineralization rates and net N mineralized were greatest under the 30°C temperature treatment (Fig. 1, Table 3). Net N mineralized and determined k values at 4 and 10°C temperature treatments were similar for both the control and manured soils, indicating some mineralization even at low temperatures. Likewise, Vigil and Kissel (1995) determined that N mineralized over 160 d from crop residue-amended soils and unamended soils were similar under 5 and 15°C temperature treatments. Addiscott (1983) determined minimal differences in net N mineralization from soil with a history of farmyard manure incubated at 5 and 10°C over 20 wk, indicating that the differences between treatments at these temperatures are too small to detect.

The Q_{10} and TF values

The Q_{10} values determined in this experiment are presented in Table 6. When calculated from −14 to 30°C, Q_{10} values were 2.0 for the control treatment. A Q_{10} of 2 has been commonly used as an approximation of N mineralization in unamended soils (Campbell et al., 1981; Vigil and Kissel, 1995) and is often incorporated as a constant in N modeling with the Van't Hoff function (Rodrigo et al., 1997; Cabrera et al., 2008) Campbell et al. (1984) determined a Q_{10} of 2.12 for fine-textured soils and Dessureault-Rompré et al. (2010) reported a Q_{10} range from 2.12 to 3.43 for 20 silty-textured soils, similar to the soil used in

Table 5. Reported p-values for pairwise treatment comparisons within temperature regimes, generated from a generalized linear mixed ANOVA model.

Analysis of treatment effects	Mean net N	Mean net N min
	mg N kg^{-1}	% of initial soil total N
Temperature	<0.0001	<0.0001
Manured treatment	<0.0001	0.0039
Temperature × manure treatment	0.0062	0.1800
Manured versus control, -14°C	0.9412	0.8970
Manured versus control, 4°C	0.0922	0.2535
Manured versus control, 10°C	0.0985	0.3921
Manured versus control, 23°C	0.0002	0.0054
Manured versus control, 30°C	<0.0001	0.0137

Table 6. Determined ratios of the change in the rate coefficient of mineralization for every increase in temperature of 10°C (Q_{10}), calculated with zero-order kinetics, for the manured and control soil treatments for the 49-d incubation period.

Temperature Range	Calculated Q_{10}	
	Manured Soil	Control Soil
-14 to 4°C	5.1	1.7
4–10°C	1.0	1.7
10–23°C	2.0	1.8
23–30°C	1.9	3.8
4–30°C	1.7	2.2
-14 to 30°C	2.7	2.0

this experiment. Additionally, Westermann and Crothers (1980) estimated a Q_{10} of 2.3 (10–30°C) for an unamended presumed Portneuf silt loam. The Q_{10} value was 2.7 for the −14 to 30°C temperature range for the manured soil, illustrating that Q_{10} increased from 2.0 to 2.7 in response to previous manure applications (Table 6). Fewer values are available for soils with a manure history; however, for net N mineralization from Addiscott (1983), a Q_{10} for farmyard manure-amended soil was estimated as 2.6 for a temperature range from 5 to 25°C.

Whereas the Q_{10} values in this experiment were similar to those found in the literature when calculated across all temperatures, it is interesting to note the relatively large Q_{10} value calculated for the −14 to 4°C range for the manured soil (5.1) compared with the relatively small calculated Q_{10} in the control soil (1.7). In a study analyzing the effect of low temperatures on forests soils, Schütt et al. (2014) determined that Q_{10} values calculated from −4 to 8°C were much lower for the Oa and A horizons than the substrate-rich Oi–Oe horizon counterparts. Similarly, Clark et al. (2009) determined that Q_{10} values in a soil amended with pig slurry were an order of magnitude greater at temperatures below 2°C for a temperature range from −6 to 10°C. At freezing and temperatures below 10°C, greater Q_{10} values may be observed for soils high in substrate concentrations (such as manured soils), indicating the need for varying Q_{10} values at low temperatures and the inclusion of amendment histories for modeling N mineralization.

In contrast to the determined Q_{10} values, when the TF was determined (each temperature treatment was calculated as a proportion of optimum net N mineralized at 30°C; [Eq. 4]), minimal differences were observed between the manured and control soil treatments (Fig. 2). The relationship between temperature and TF had a relatively low fit to a linear model ($R^2 = 0.74$) but fit statistics increased with quadratic and exponential fits. The best fit of the data was to the exponential model described by Vigil and Kissel (1995):

$$TF = Ae^{b \times T}, \quad [5]$$

where A and b are constants fitted during regression and T is temperature (°C). Regression of the TF and temperature with Eq. [5] led to a R^2 of 0.90, with $A = 0.126$ and $b = 0.069$. Although the coefficient values differ from those proposed by Vigil and Kissel (1995), these findings suggest that manure application

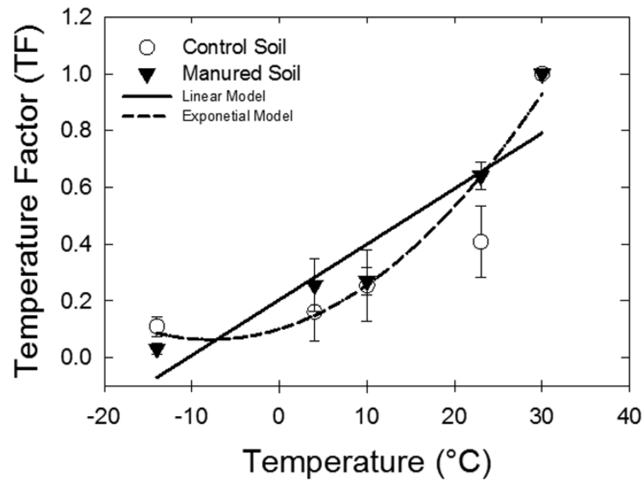

Fig. 2. The mean temperature factors (TF) and (error bars represent the SD) determined at 49 d for both the manured and control soils. The TF was calculated as the proportion of the net N mineralized for each temperature treatment from the 30°C temperature treatment and were fitted with linear, quadratic, and exponential models.

history for a field may not need to be considered when developing TF for N mineralization prediction models. Further research is needed on other soils, manure types, and manure application rates to validate the lack of manure history effects on TF.

Rate correction factors for temperature and N mineralization models are generally derived from studies conducted under mild soil temperatures or temperatures above freezing (Westermann and Crothers, 1980; Vigil and Kissel, 1995; Guñtinas et al., 2012). Several studies have challenged that assumption, illustrating that N mineralization and nitrification occurred near or below the freezing point of water (Brooks et al., 1997; Schimel et al., 2004, Clark et al., 2009). As a reference, maximum daily soil temperature at the 10 cm soil depth in Kimberly, Idaho was below 5°C for 65 d of the year on average from 1995 to 2015 (AgriMet Staff, 2016). Accounting for soil temperatures below 5°C when developing N mineralization prediction models for cooler regions like southern Idaho could help to improve N mineralization model TF estimates.

Growing Degree-Days

To aid in estimating N availability throughout the growing season without the use of computer simulation models, net N mineralization for the control and manured soils were also regressed against GDD (Fig. 3). In the literature (Griffin and Honeycutt, 2000; Griffin et al., 2002), net N mineralization from application of the manure was fitted to GDD with a single exponential model. However, the results determined in this experiment showed a linear fit with GDD (Fig. 3) and did not lend itself to exponential fits. Data were linearly fitted for both the control and manured soil treatments, with R^2 values of 0.70 and 0.85 respectively. With further studies, these regression equations may prove to be a simple tool to determine N mineralization as a function of temperature under field conditions.

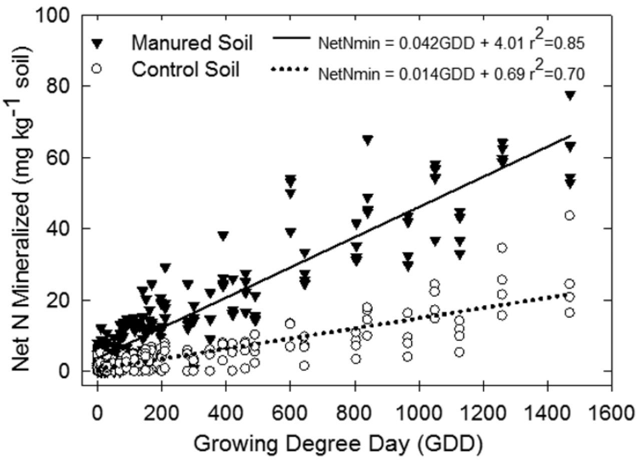

Fig. 3. Net N mineralized (all data points) as a function of growing degree-days (GDD) and corresponding regression equations from manured and control Portneuf silt loam in a 49-d incubation study.

CONCLUSIONS

Soils with a 3-yr fall application manure history and unamended control soils responded strongly to temperature treatments from −14 to 30°C in laboratory incubation experiments conducted over 49 d. Net N mineralization data were fittted to zero-order models and *k* values for the manured soil ranged from 0.017 to 1.28 mg inorganic N kg^{-1} soil d^{-1} over the five temperature treatments, whereas *k* values in the control measured 0.028 to 0.53 mg inorganic N kg^{-1} soil d^{-1}. Calculated Q_{10} values fell within reported literature values for both manured and control soils, but at low temperatures (−14 to 4°C) the Q_{10} value for the manured soil was 5.1. A simple temperature factor was created as a rate coefficient correction factor that may allow for computer simulation modeling of the silty soils found in Idaho and other regions regardless of manure history. Growing degree-days provided a good predictor of net N mineralized and was able to predict mineralization accurately for both the control and manured soil. This work may aid in future modeling of net-N mineralization with available Q_{10} and TF values for Idaho soils receiving applications of manure and with further validation may provide a simple empirical model based on GDD.

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