Using Growing Degree Days to Predict Nitrogen Availability from Livestock Manures

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ABSTRACT

Predictive tools are needed to better match N release from manure with crop demand. Growing degree days (GDD) have been successfully used to predict N release from crop residues and other amendments. A 112-d incubation experiment was conducted at 10, 17, and 24°C to evaluate GDD (0°C base temperature) predictions of N transformations from beef (*Bos taurus*), dairy, poultry (*Gallus gallus*), and swine (*Sus scrofa*) manure. Manure was incorporated at rates estimated to provide 150 kg N ha^{-1} (or 75 mg N kg^{-1} soil). Soil NO_3 and NH_4 concentrations were determined at weekly or biweekly intervals. The rate of NO_3 accumulation increased with increasing temperature, and could be predicted across temperature regimes using GDD. This predictive ability could be generalized across dairy, poultry, and swine manures using an exponential equation, $NO_3 = 54.10[1 - exp(-0.006GDD)]$, while N was immobilized by incorporation of beef manure. The disappearance of NH_4 was a linear function of time and of GDD. A single predictive equation was sufficient for dairy, poultry, and swine manures, in the form NH_4 (as percentage of input) $= 0.703 - 0.0021GDD$ ($R^2 = 0.66$), with soil NH_4 reaching zero at $\approx$350 GDD. These laboratory data indicate that GDD can be used for predicting NO_3 accumulation and NH_4 disappearance from a range of livestock manures. If successfully extended to the field, this predictive capability may allow for improved management of N from animal manures.

IMPROVED ability to predict the availability of N from organic sources, including livestock manures, plant residues, and industrial byproducts, would serve two complimentary purposes. First, at the farm level, supplemental fertilizer N application to crops could be restricted to those situations where a crop yield response is most likely, increasing productivity and avoiding unnecessary expense where a response is unlikely. Second, environmental loss of mineral N as NO_3 could be re-duced by both eliminating unneeded application and better matching mineral N supply with crop demand.

Season-long mineralization constants for the organic N component of manure are broadly based on the recalcitrance of the organic N fraction. Mineralization constants for composted manures are commonly 5 to 10% yr^{-1} (Hadas and Portnoy, 1994). Conversely, Bitzer and Sims (1988) found that an average of 66% of the organic N in poultry manures was mineralized in the first year. Cabrera et al. (1994) confirmed this rapid mineralization from poultry manures, estimating that 35 to 50% of organic N could be mineralized within 14 d of incorporation into soil. Estimated mineralization constants for dairy and beef manures usually fall between these extremes (e.g., 16–21% by Klausner et al., 1994). These estimated mineralization constants are useful in calculating N-based application rates. However, they do not provide sufficient detail to make supplemental N application decisions during the growing season.

Estimating the amount of mineral N available from manure during the growing season is further complicated by the presence of both mineral N (usually NH_4) and organic N fractions. Ammonium is subject both to rapid nitrification to NO_3 and to volatile loss as NH_3, while organic N requires an initial mineralization step to be utilized by plants. Because both nitrification and mineralization are microbially mediated in soil, they are influenced not only by substrate characteristics, but also by soil climate, including temperature, soil water status, and aeration.

In past research, thermal units or GDD have been used successfully to predict cumulative N mineralization through a growing season for carbonaceous wastes, biosolids, and plant residues of varying composition (Honeycutt et al., 1988, 1991; Honeycutt and Potaro, 1990), recognizing that the thermal unit relationship with mineralization is modified by soil water status (Doel et al., 1990). For livestock manures, a general relationship between N mineralization and temperature was demon-

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Abbreviations: GDD, growing degree days; ICP, inductively coupled plasma emission spectroscopy; PAN, plant-available N.

Table 1. Chemical composition of animal manures used in incubation experiment.

Manure	Dry matter	C	Total N	NH₄-N	Organic N†	PAN‡	P	K	CN	Manure application rate§
				g kg⁻¹ DM#						g fresh manure kg⁻¹ dry soil
Beef	174	443.4	14.94	0.0	14.94	3.74	4.02	8.05	29.7	54.1
Dairy	161	232.5	21.12	11.80	9.32	15.06	4.35	10.56	11.0	34.9
Poultry	394	349.4	54.82	22.59	32.23	41.93	23.60	32.23	6.4	4.5
Swine	235	390.9	50.64	30.64	20.00	40.64	24.69	23.40	7.7	7.8

† Organic N = total N − NH₄-N.
‡ Plant–available N = NH₄-N + f(organic N); f = 0.25, 0.35, 0.60, and 0.50 for beef, dairy, poultry, and swine manures, respectively.
§ Application rate to supply equivalent of 150 kg PAN ha⁻¹.
# DM is dry matter.

strated by Paul and Beauchamp (1994), and established temperature functions (e.g., $Q_{10} \approx 2$) have been used to predict NO_3 accumulation in the field (Cabrera and Kissel, 1988). Sims (1986) and Hadas et al. (1983) conducted laboratory incubations of soil amended with poultry manure at temperatures ranging from 0 to 35°C, finding that more N was mineralized at higher temperatures for a defined time period. Sims (1986) also clearly demonstrated that the rate and extent of manure N mineralized from the organic fraction varied among manures, even from the same animal species. While the general effect of increased temperature has been demonstrated, the predictive ability of GDD has not been evaluated for different livestock manures. This study was conducted to evaluate (i) the impact of temperature on N transformations for beef, dairy, poultry, and swine manures and (ii) the utility of GDD for predicting cumulative NO_3 availability, disappearance of manure NH_4, and mineralization of manure organic N.

MATERIALS AND METHODS

Soil and Manure Materials

Soil used for the laboratory incubation was collected from the USDA-ARS research site in Newport ME, in November 1998. The sandy loam soil (coarse-loamy, mixed, frigid Typic Haplorthod) has a particle-size distribution of 610, 290, and 100 g kg⁻¹ for sand, silt, and clay fractions, respectively, as measured by the pipette method (Gee and Bauder, 1986). Soil was collected from the Ap horizon (0–20 cm) in a field previously cropped to potato (*Solanum tuberosum* L.), sieved (2 mm), and stored at 4°C until the incubation was initiated. Field moisture level (≈0.19 kg kg⁻¹, determined gravimetrically) was maintained through the storage period. Selected soil properties include: soil pH = 5.8 (1:1, soil/water); cation-exchange capacity = 3.4 cmol kg⁻¹; P = 16.5 kg ha⁻¹; K = 303 kg ha⁻¹; Mg = 169 kg ha⁻¹; and Ca = 1130 kg ha⁻¹, as determined using a modified Morgan extraction (pH 4.8, 0.62 M NH₄OH + 1.25 M CH₃COOH) and inductively coupled plasma emission spectroscopy (ICP). Beef, dairy, swine, and poultry manures were collected from local commercial farms, transported in 20-L plastic buckets, and stored at 4°C until incubation was initiated. Manure analyses at the beginning of incubation (t = 0) are shown in Table 1. Total C was determined by thermal conductivity detection following combustion at 1650°C on a CE Instruments NA2500 Elemental Analyzer (ThermaQuest Italia S.p.A., Rodano, Italy). Total N was measured by total Kjeldahl digestion (Wall and Gehrke, 1975). Manure P and K contents were measured by dry combustion, followed by digestion in HCl and ICP.

Incubation Experiment

Four hundred-fifty grams of field moist soil (360 g oven-dry equivalent) was weighed into individual 2-L glass jars. Triplicate jars for each manure treatment (beef, dairy, poultry, and swine) and the unamended control were preincubated for 14 d at 10, 17, and 24°C. Manures were then homogenized in a small food processor and incorporated into soil at a rate equivalent to 150 kg plant-available N ha⁻¹ (PAN), according to the following:

$$\text{Estimated PAN} = NH_4\text{-N} + fN_{organic} \qquad [1]$$

where f is the proportion of organic N fraction expected to mineralize within the first growing season. Coefficient f equals 0.25, 0.35, 0.60, and 0.50 for beef, dairy, poultry, and swine manures, respectively, from Klausner (1997) and Bitzer and Sims (1988). Soil water in all jars was maintained at 0.19 kg kg⁻¹ (80% of field capacity) by adding deionized water twice weekly for the first 4 wk, and once weekly thereafter. Jars were placed in incubators (10, 17, and 24°C) corresponding with their preincubation temperature and loosely capped with metal canning lids. To provide adequate aeration, lids were removed for 1 h daily during the first 4 wk and every 2 to 3 d thereafter.

Five-gram subsamples were removed from each jar at 0, 7, 14, 21, 28, 42, 56, 70, 84, and 112 d. Inorganic N (N_i: NO_3-N and NH_4-N) was determined colorimetrically on a Lachat Autoanalyzer (Lachat Instruments, Mequon, WI) following extraction of 3.5 g soil in 35 mL of 2 M KCl for 1 h on an orbital shaker. Gravimetric soil water was determined on each sampling date by drying 1.5 g of soil at 105°C for 24 h.

Cumulative nitrification (N_{cum}) for manure-amended soil, measured as soil NO_3-N concentration at time, t, was similar to Sims (1986) in correcting for unamended soil and initial soil NO_3

N_{cum} (mg kg⁻¹ soil)

$$= (NO_3\text{-N})_{manure} - (NO_3\text{-N})_{control} - (NO_3\text{-N})_{t=0} \qquad [2]$$

Soil concentration of manure-derived NH_4 at time, t, was defined similarly as

N_{amm} (mg kg⁻¹ soil)

$$= (NH_4\text{-N})_{manure} - (NH_4\text{-N})_{control} - (NH_4\text{-N})_{t=0} \qquad [3]$$

The amount of N mineralized from the manure organic N fraction at time, t, was calculated in several ways, taking the general form

N_{org} (mg kg⁻¹ soil)

$$= (N_i\text{-N})_{manure} - (N_i\text{-N})_{control} - (NH_4)_{t=0} \qquad [4]$$

with $(NH_4)_{t=0}$ being either manure NH_4 or soil NH_4 concentration and N_i equal to the sum of NO_3-N and NH_4-N. This

calculation accounts for both indigenous soil N mineralized and manure NH_4 nitrified, both of which subsequently enter the cumulative NO_3 pool, N_{cum}.

Cumulative nitrification and organic N mineralization were fit to single exponential equations

$$N_{cum} \text{ or } N_{org} = N_0[1 - \exp(-k\text{Day})] \qquad [5]$$

$$N_{cum} \text{ or } N_{org} = N_0[1 - \exp(-k\text{GDD})] \qquad [6]$$

as used by Deans et al. (1986). These equations were used to estimate nitrified or mineralizable N (N_0) and the associated rate constant, k, with time (Eq. [5]) and GDD (Eq. [6]), respectively. The disappearance of manure NH_4 was fit to linear functions

$$N_{amm} = N_A + b\text{Day} \qquad [7]$$

$$N_{amm} = N_A + b\text{GDD} \qquad [8]$$

All equations were fit using all data points, although only mean values (of three observations each) are shown in the figures below. Equations were calculated using linear regression or nonlinear curve fitting via a Marquardt iteration (SYSTAT, Version 8.0; SPSS Corp., Chicago, IL). Regression equations were deemed significantly different if the 95% confidence intervals around the parameters (the rate constant, k, for example) did not overlap.

RESULTS AND DISCUSSION

Net Nitrification

Manure-derived NO_3 accumulation (N_{cum}) was estimated by subtracting NO_3 concentration of unamended soil from NO_3 concentration of amended soil. This assumed that the manure amendment did not stimulate mineralization of indigenous soil organic N. It further recognized that the nitrified N could originate from two sources, manure NH_4 and manure organic N. Using dairy manure as an example, soil NO_3–N concentration reached levels of 50 to 70 mg kg^{-1} during the 112-d incubation and was clearly influenced by incubation temperature (Fig. 1A). Results were similar for soil amended with either poultry or swine manure (data not shown). The potential amount of N nitrified, defined as N_0 in the first-order exponential model (Eq. [5]), was not significantly different between temperature regimes, averaging 56.7 mg kg^{-1} soil amended with dairy manure. However, the rate constant, k, was significantly higher at 24°C ($k = 0.174$ d^{-1}) than at 10°C ($k = 0.052$ d^{-1}), indicating a faster rate of N accumulation with increasing temperature. This more rapid accumulation of NO_3 as temperature increases has been demonstrated by Honeycutt et al. (1991, 1993) for added plant residues, fertilizer, and papermill sludge. Organic N from different soils or from soil with different cropping histories also mineralized more rapidly as temperature increased (Stanford et al., 1973; Campbell et al., 1981; Addiscott, 1983; Gale and Gilmour, 1986). Sims (1986) measured net N mineralization from poultry manures from 0 to 40°C, and found both higher inorganic N accumulation and faster mineralization rates as temperature increased.

When dairy manure N_{cum} was expressed as a function of GDD, rather than time, no significant difference
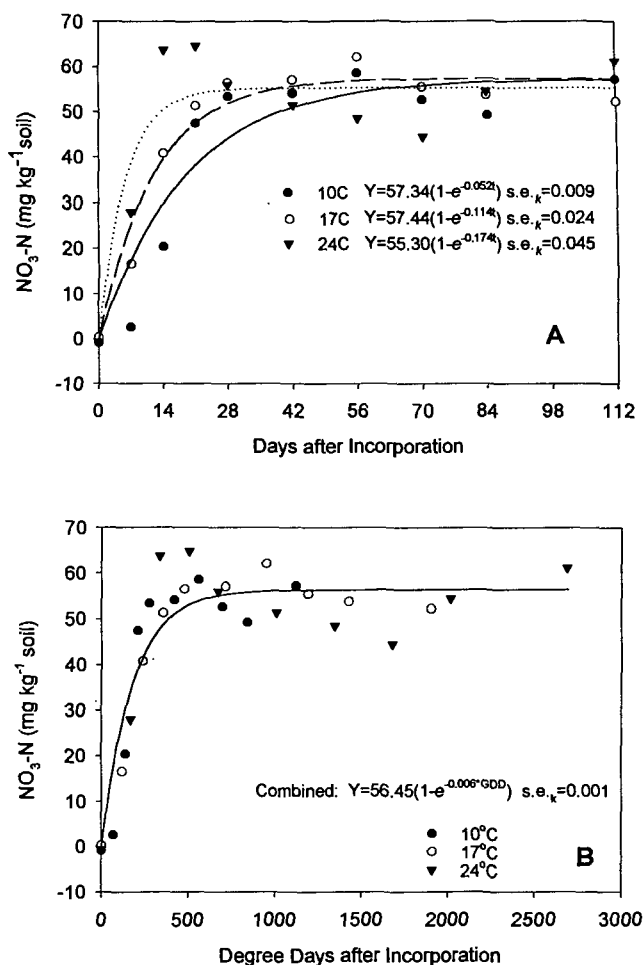

Fig. 1. Effect of temperature on NO_3 accumulation in soil amended with dairy manure as a single exponential function of (A) time and (B) growing degree days (GDD). Data points are mean of three observations; t is time in days after incorporation, and s.e.$_k$ is the standard error of regression parameter k.

among temperature regimes was found for either N_0 or k (Fig. 1B). As a result, N_{cum} can be predicted using GDD across all temperature regimes. This extends the approach taken by Honeycutt et al. (1991, 1993) and Honeycutt and Potaro (1990) in using GDD to predict net N mineralization. Specifically, using dairy manure as an example, N_{cum} can be predicted using GDD even though it differs from previous work in a fundamental way; the NO_3 is accumulated from nitrification of both manure NH_4 and mineralized manure organic N. The utility of the GDD approach in predicting these processes separately is discussed below.

To be useful in assessing N availability during the growing season, the GDD relationship would ideally be generalizable across manure types. In this incubation study, GDD could successfully predict N_{cum} for dairy, poultry, and swine manures using a single exponential regression, $\{N_{cum} = 54.10[1 - \exp(-0.006\text{GDD})]\}$, as shown in Fig. 2. The R^2 value for this regression, although not completely analogous to R^2 in linear models, was 0.75 when the equation was fit using all data points, and 0.85 when only mean values were used. The potential N nitrified (54.10 mg kg^{-1}) was only 75% of the
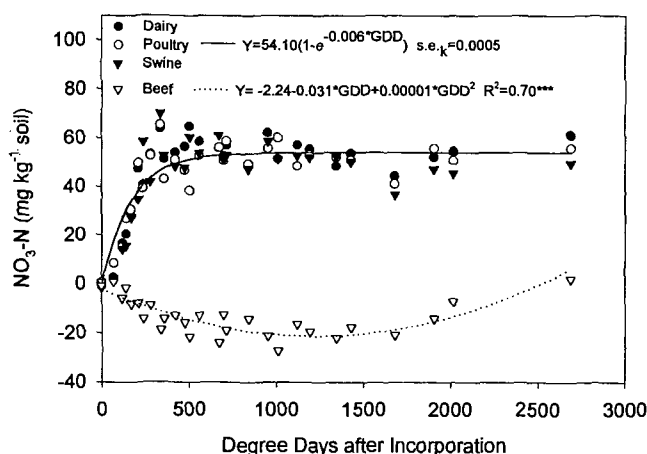
Fig. 2. Nitrate accumulation in soil amended with beef, dairy, poultry, and swine manure as a function of growing degree days (GDD). Data points are mean of three observations; t is time in GDD after incorporation, and s.e.$_k$ is the standard error of regression parameter k.

75 mg kg^{-1} estimated by the PAN approach (the equivalent of 150 kg PAN ha^{-1}). This is very similar to the overestimation by the PAN approach (Eq. [1]) reported by Bitzer and Sims (1988).

Amendment with beef manure caused net N immobilization through the 112-d incubation, with lower NO_3 concentration in amended soil than in unamended soil, even at the highest temperature. Net nitrification from this amendment could be described using a simple quadratic model ($R^2 = 0.70$; Fig. 2). This amendment contained no appreciable inorganic N at the time of incorporation and had a significantly higher C/N ratio than the other amendments (Table 1).

Ammonium Disappearance

As mentioned above, nitrification processes in manure-amended soil act on two primary pools of NH_4, namely (i) NH_4 originally present in the manure and (ii) NH_4 arising from mineralization of manure organic N. Because some manures contain high concentrations of NH_4 (i.e., 50–80% of total N), the ability to predict the disappearance of NH_4 after application would be valuable. For the amendments used here, we recognize that NH_4 disappearance might have occurred via nitrification or microbial immobilization. However, we have no clear method of discerning the amount of N transformed via each pathway, so instead we evaluated net NH_4 disappearance. It is also clear that N transformations were occurring even during the short period between manure incorporation and the subsequent sampling and extraction at $t = 0$ (≈ 2 h later). This is most easily demonstrated by soils amended with beef manure, where NH_4-N concentration averaged 36.7 mg kg^{-1} soil at the $t = 0$ extraction, even though this amendment contained no appreciable inorganic N (Table 1).

Dairy manure-amended soil is again used to illustrate the impact of temperature on NH_4 disappearance, and the effectiveness of GDD in predicting NH_4 disappearance. The disappearance of NH_4 within each temperature regime could be described using simple linear func-
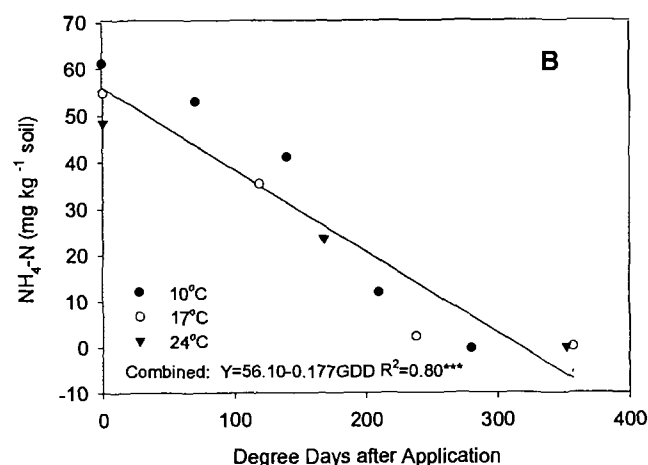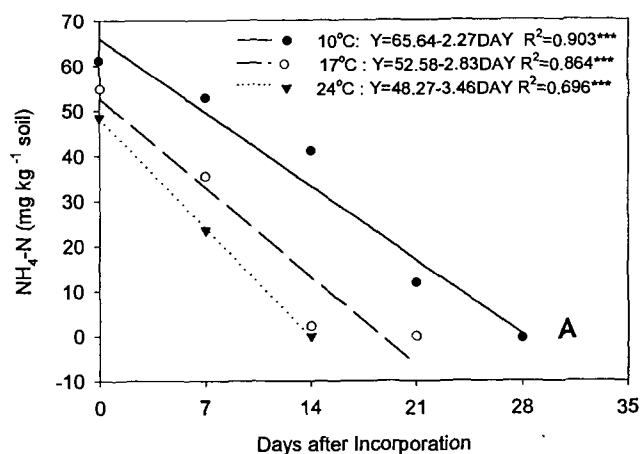

Fig. 3. Effect of temperature on disappearance of NH_4 in soil amended with dairy manure as a linear function of (A) time and (B) growing degree days (GDD). Data points are mean of three observations.

tions (Fig. 3A). The decline in NH_4 through the first 28 d of the incubation was very similar to that shown by Schmidt et al. (1992), where soil NH_4 from injected dairy manure fell to zero even at high application rates. Both Addiscott (1983) and Zanner and Bloom (1995), in evaluating nitrification of NH_4-containing fertilizers in soils of varying cropping history, also noted linear reductions in NH_4 with time, with more rapid reductions at higher temperatures. Research by Grundmann et al. (1995) suggests that the nitrification rate would be maximized under conditions similar to those we used at 24°C. The differences in NH_4 at $t = 0$ due to incubation temperature are also clear in Fig. 3A. This may reflect very rapid microbial immobilization. It could also indicate very rapid nitrification; however, if this is the case then the lack of a corresponding increase in NO_3 at $t = 0$ with increasing temperature would suggest that this NO_3 must also be rapidly denitrified and lost.

Disappearance of dairy manure NH_4 within all three temperature regimes was a linear function of GDD, with soil NH_4 reaching zero at ≈ 350 GDD (Fig. 3B). Unlike NO_3 accumulation, the disappearance of NH_4 could not be generalized across all manure treatments
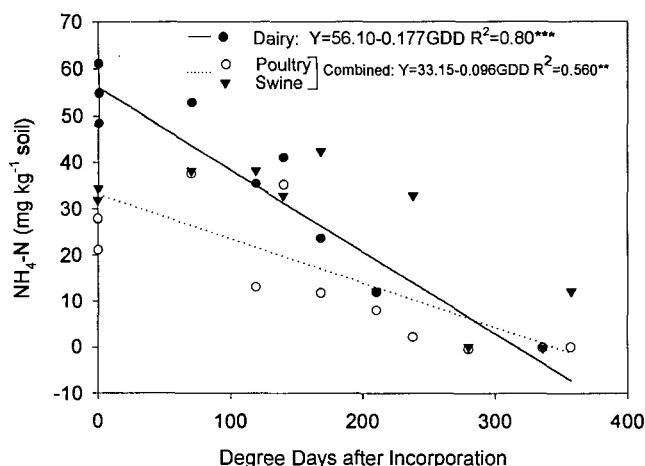
Fig. 4. Ammonium disappearance in soil amended with dairy, poultry, and swine manure as a function of growing degree days (GDD). Poultry and swine treatments are represented by combined regression. Data points are mean of three observations.

Fig. 6. Organic N mineralized from swine manure at different temperatures, as a function of growing degree days. Data points are mean of three observations.

(Fig. 4). A single regression equation could predict disappearance in the poultry and swine treatments, but the slope and intercept of this equation differed significantly from those predicting NH_4 disappearance following dairy manure application. The dairy manure treatment had higher initial NH_4 concentration and a more rapid rate of NH_4 disappearance. These differences in NH_4 disappearance could be accounted for by differences in NH_4 application rate, with substantially more NH_4-N applied from dairy manure (79 mg kg^{-1}) than from either poultry (41 mg kg^{-1} soil) or swine (57 mg kg^{-1} soil) manure (Table 1). When expressed as a proportion of manure NH_4-N input, the disappearance of NH_4 during the early part of the incubation was closely tied to GDD (Fig. 5).

An average of 30% of NH_4 input was not accounted for at $t = 0$. A number of previous reports suggest that this is a result of microbial immobilization of manure NH_4. Flowers and Arnold (1983) and Sorensen et al. (1996) found that 28 and 36%, respectively, of manure NH_4 was immobilized. A substantially greater immobili-
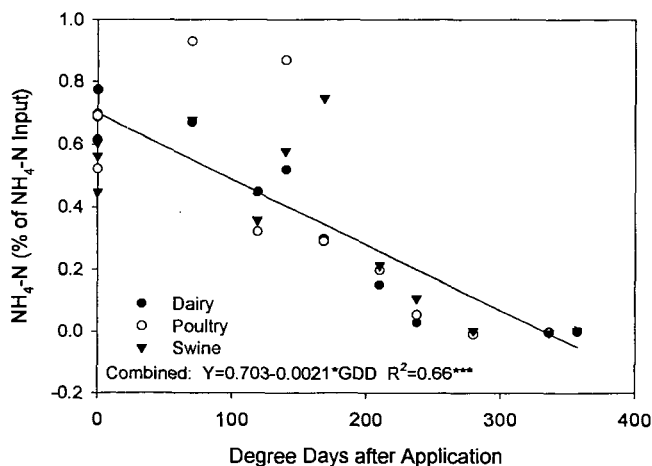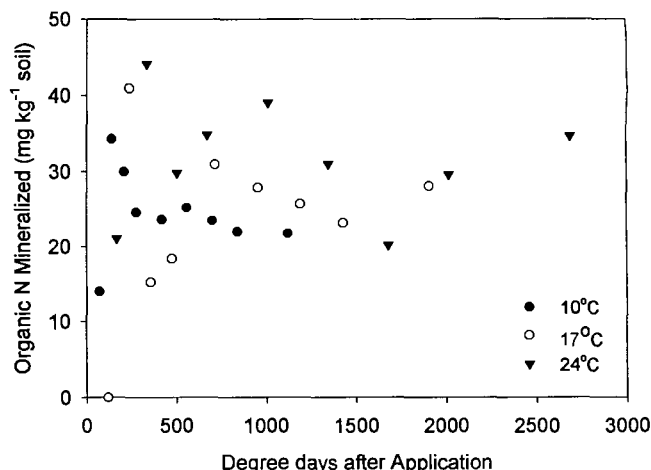

Fig. 5. Disappearance of manure NH_4, as a percentage of manure NH_4 input, from soil amended with dairy, poultry, and swine manure, as a function of growing degree days (GDD). Data points are mean of three observations.

zation (or loss) of 65% of manure inorganic N at $t = 0$ was noted by Bitzer and Sims (1988). Additionally, manure NH_4 immobilization is generally greater than that for fertilizer NH_4 sources (Paul and Beauchamp, 1993, 1995). Again, previously described differences in NH_4 with temperature at $t = 0$ (Fig. 3A), in the absence of corresponding differences in NO_3 (Fig. 1A), are consistent with rapid microbial immobilization.

Manure Organic Nitrogen Mineralization

Unlike NO_3 accumulation and NH_4 disappearance, which were measured directly in this incubation, estimation of net mineralization of manure organic N (N_{org}) is a calculated value. We evaluated several approaches for calculating N_{org}. Two approaches take the form of Eq. [4]. The first, as used by Gordillo and Cabrera (1997) and Sims and Wolf (1994), subtracted the initial NH_4 content of the manure from N_i, under the assumption that all of the NH_4 in the manure is eventually nitrified and enters the NO_3 pool. Because the amount of manure-derived NH_4 extracted from the soil at $t = 0$ was always less than 100% (averaging $\approx$70% for dairy, poultry, and swine manures; Fig. 5), this approach can consistently yield negative values for N_{org}, especially during the early phase of the incubation. The second approach, taken from Sims (1986), subtracts the soil NH_4 at $t = 0$ from N_i to account for manure-derived NH_4 recovered in the initial extraction. While probably more realistic than the first approach, there is a problem in that NH_4 at $t = 0$ was clearly influenced by preincubation temperature, as shown in Fig 3A for dairy manure. It is conceivable that higher preincubation temperatures resulted in greater population or activity of immobilizing microbes, which responded rapidly to manure addition.

The third approach tries to account for the fact that NH_4 concentration changes with time, until reaching zero (usually within 28 d). Weekly changes in soil NO_3 (ΔNO_3) and NH_4 (ΔNH_4) were calculated for $t = 0$ to 28 d. If $\Delta NO_3 > \Delta NH_4$, then (presumably) the difference for that time interval can be attributed to N mineralized from manure organic N by the equation
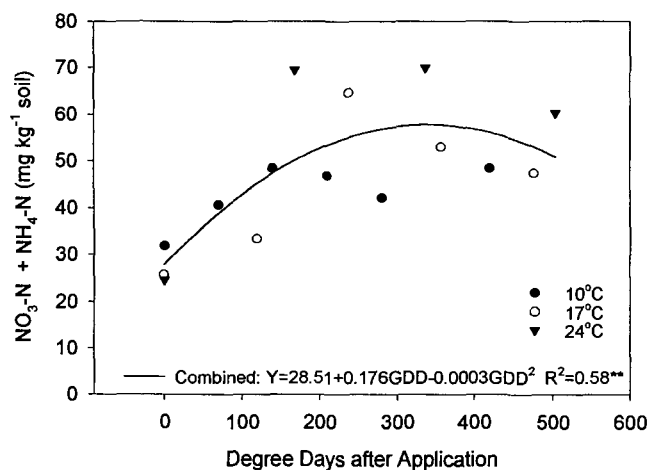
Fig. 7. Changes in inorganic N content (NO₃ + NH₄) in soil amended with swine manure between 0 and 600 growing degree days (GDD). Data points are mean of three observations.

$$\text{Apparent } N_{org} = \Delta NO_3 - \Delta NH_4 \qquad [7]$$

As the incubation proceeds, N_{org} for a specific time interval is essentially equal to ΔNO_3 because NH_4 concentration becomes very small or zero.

Net mineralization could not be predicted from GDD using either approach based on Eq. [4]. An example of the lack of relationship (using data for poultry manure, corrected for soil NH_4-N at $t = 0$, as in Sims, 1986) is shown in Fig. 6. Two things are apparent in this example. First, N_{org} stabilizes at around 28 mg N kg^{-1} soil (equal to 48% of manure organic N input) as the incubation proceeds. And second, the distribution of N_{org} during the initial phase of the incubation ($\approx$0–1000 GDD) is essentially random. This may be compounded by the fact that soil N_i follows a quadratic trend (increasing, then decreasing) during this initial phase, as shown in Fig. 7, when NO_3 is accumulating rapidly but some manure NH_4 is still present. As Eq. [4] subtracts a constant value from N_i, this would mean that cumulative N_{org} increases quickly, but then declines as the incubation proceeds. Although this is possible, nearly all similar research in this area indicates that mineralization follows an increasing (e.g., exponential) function with time or GDD.

The alternative approach developed here, evaluating the difference between NO_3 evolution and NH_4 disappearance, was no more successful in estimating N_{org} than the approaches detailed above. It is clear that, during the first 14 d of the incubation, NO_3 is accumulating more quickly than NH_4 is disappearing for each manure at each temperature (Table 2). If this is interpreted as manure organic N being rapidly mineralized, it is supported by recent research by Cabrera et al. (1994) and Gordillo and Cabrera (1997), who demonstrated that more than one-half of the organic N in some manures may be mineralized in the first days or weeks after incorporation into soil.

The reason that the GDD approach could not predict N_{org}, while predicting both NO_3 accumulation and NH_4 disappearance, is not clear. As mentioned above, N_{org} is a calculated value that has been used successfully

Table 2. Difference between nitrate (NO₃) accumulation and ammonium (NH₄) disappearance for weekly intervals to Day 28.

Manure Type	Week	ΔNO_3N† − ΔNH_4N†		
		10°C	17°C	24°C
		mg kg^{-1} soil		
Dairy	1	−4.80	−3.21	8.94
	2	6.01	12.33	12.26
	3	−2.06	−12.96	0.48
	4	−6.45	4.94	−8.88
Poultry	1	14.13	−0.58	21.84
	2	28.62	40.84	23.11
	3	−4.39	−25.67	−14.26
	4	−5.41	3.16	4.96
Swine	1	8.83	7.67	36.63
	2	7.67	36.99	0.42
	3	−1.52	−11.67	−9.55
	4	−4.71	−5.65	0.67

† $\Delta NO_3-N = NO_3-N_{t=1wk} - NO_3-N_t$ and $\Delta NH_4-N = NH_4-N_{t+1wk} - NH_4-N_t$.

to evaluate mineralization of many organic N sources. Likewise, long-term aerobic incubation of amended soils with periodic sampling of N_i have been used extensively. Even so, the calculation of N_{org} and the incubation method are fundamentally unable to discern gross N transformations because of the number of N pools and the number of processes involved. The use of ^{15}N-labeled manure may overcome some of these limitations, although uniform labeling of both organic and inorganic N fractions (e.g., Sorensen et al., 1994) would do so only partially. Alternatively, the application of a small amount of highly enriched $^{15}NH_4$ with manure slurries, as reported by Paul and Beauchamp (1995), allows the NH_4 pool to be traced, which is especially important during the rapid transformation immediately after application. Use of ^{15}N tracers should consequently be investigated before discounting the utility of GDD in predicting manure organic N mineralization.

CONCLUSIONS

The accumulation of NO_3 and disappearance of NH_4 from livestock manures was measured in a 112-d laboratory incubation at 10, 17, and 24°C. We were able to account for differences in incubation temperature and predict N_{cum} and N_{amm} through this period using GDD in single exponential and linear models, respectively. We were further able to predict these N transformations across animal manures that had widely different initial NH_4-N and organic N concentrations and application rates, if the manure contained appreciable NH_4. This predictive ability, which has now been demonstrated for numerous soil amendments and crop residues, is useful not only for estimating N availability from manures during the season, but also in improving the synchrony between N supply and crop N demand.

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