Nitrogen mineralization in selected Montana soils
by Raymond George Gavlak

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Crop and Soil Science
Montana State University

Abstract:
Mineral nitrogen (N) production from cultivated soils has decreased with the reduction in soil organic matter. The ability to predict seasonal contributions of mineral N to the soil N pool would increase the precision of fertilizer N recommendations. The objectives of the study were to quantify and model N mineralization of selected Montana soils by field and laboratory incubation techniques and compare the levels of mineral N predicted by the two models.

Soil A horizons containing 1.8, 2.4, 2.6, and 4.4% OM were incubated in the laboratory at 0, 14 and 28°C for 12 weeks. Results indicated that mineral N production was linear with time.

Laboratory data was combined with a soil temperature predictive equation. The resulting computer model predicted that soils containing 1.8, 2.4, 2.6, and 4.4% OM mineralized an average of 20.4 kg N ha^-1 per percent OM over a 61 day period and 39, 49, 53, and 84 kg N ha^-1 total mineral N, respectively.

Field experiments were established on a coarse-loamy, mixed Borollic Calciorthid near East Helena, Montana. Soil was sampled to 30 cm, mixed by 10 cm increments, placed in polyethylene bags and returned to the original sample holes at three sites in 1983 and four sites in 1984« Triplicate bags were removed from each site and soil temperature was monitored at 10, 20, and 50 cm on a weekly basis. Bags were frozen on dry ice then air dried and analyzed for nitrate and ammonium N.

Stepwise multiple linear regression was used to analyze field data. An index of early season mineral N content and time were the most important independent variables predicting growing season mineral N production (R^2=0.83) in the upper 30 cm of soil. Measurement of early season mineral N content to 30 cm and an estimate of time (weeks) allows an accurate prediction of field N mineralization.

One of the soils used in the laboratory experiment was sampled from a site included in the field study, and allowed for a comparison of the laboratory and field models. The laboratory and field models predicted 46.7 and 42.2 kg N ha-'*, respectively. The addition of temporal soil water content should improve the model. Examination of the model on different soils is needed to validate the model.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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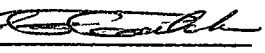
Signature 

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ABSTRACT

Mineral nitrogen (N) production from cultivated soils has decreased with the reduction in soil organic matter. The ability to predict seasonal contributions of mineral N to the soil N pool would increase the precision of fertilizer N recommendations. The objectives of the study were to quantify and model N mineralization of selected Montana soils by field and laboratory incubation techniques and compare the levels of mineral N predicted by the two models.

Soil A horizons containing 1.8, 2.4, 2.6, and 4.4% OM were incubated in the laboratory at 0, 14 and 28°C for 12 weeks. Results indicated that mineral N production was linear with time.

Laboratory data was combined with a soil temperature predictive equation. The resulting computer model predicted that soils containing 1.8, 2.4, 2.6, and 4.4% OM mineralized an average of 20.4 kg N ha^{-1} per percent OM over a 61 day period and 39, 49, 53, and 84 kg N ha^{-1} total mineral N, respectively.

Field experiments were established on a coarse-loamy, mixed Borollic Calciorthid near East Helena, Montana. Soil was sampled to 30 cm, mixed by 10 cm increments, placed in polyethylene bags and returned to the original sample holes at three sites in 1983 and four sites in 1984. Triplicate bags were removed from each site and soil temperature was monitored at 10, 20, and 50 cm on a weekly basis. Bags were frozen on dry ice then air dried and analyzed for nitrate and ammonium N.

Stepwise multiple linear regression was used to analyze field data. An index of early season mineral N content and time were the most important independent variables predicting growing season mineral N production (R^2=0.83) in the upper 30 cm of soil. Measurement of early season mineral N content to 30 cm and an estimate of time (weeks) allows an accurate prediction of field N mineralization.

One of the soils used in the laboratory experiment was sampled from a site included in the field study, and allowed for a comparison of the laboratory and field models. The laboratory and field models predicted 46.7 and 42.2 kg N ha^{-1}, respectively. The addition of temporal soil water content should improve the model. Examination of the model on different soils is needed to validate the model.

CHAPTER I

GENERAL INTRODUCTION

Organic matter (OM) is an extremely important soil component that contributes to over-all soil cation exchange capacity (CEC), enhances water relations and helps maintain good soil structure, particularly in fine-textured soils. Soil OM is the reservoir for supplying nearly all of the nitrogen (N) and some of the phosphorus, sulfur, and other crop nutrients. Conversion of organically associated N to plant available inorganic forms is called mineralization. Soil microorganisms control the multi-stage process of N mineralization.

Grassland or prairie soils usually contain more OM than cultivated soils. Early grain farmers in Montana and other Great Plains states began cultivating these virgin prairie soils and found them quite fertile. The practice of crop-fallow allowed the accumulation of a full growing season's mineralized N (fallow-year) for the following crop. This worked well as many of the virgin soils contained between 5 and 10 percent OM. "Mining" this soil N for over half a century caused a continual reduction in absolute OM content and recently, much less fallow-year accumulated N. Consequently, the remaining OM, to a large extent, is a stable component of humus. The less stable OM components which include plant residues have been utilized by microbes and converted to mineral N.

The need to fine-tune crop production inputs is apparent as farm

commodity prices continually fail to provide sufficient profit margin to alleviate the burden of escalating production costs. Nitrogen fertilizer is one of the major inputs, some of which is contributed from soil OM. By assessing a soil's ability to provide N, we may increase the precision of accurately supplying crop N requirements.

The objectives of the study were to quantify N mineralization of Montana soils by laboratory and field incubation techniques with development of predictive models from field and laboratory data. Predicted N mineralization levels from models would be compared.

The following chapters provide substantial evidence that N mineralization can be quantified and most importantly, be predicted. Chapter II contains a review of pertinent literature relating to the methods used. Chapters III and IV form the core of the dissertation and elaborate on the laboratory and field methodology used in this modeling study. Chapter V summarizes the results of the research accomplished. Considerable data have been placed in the Appendix and these Appendix tables are cited in the body of the text.

CHAPTER II

LITERATURE REVIEW

Researchers have been interested in the availability of N from soil organic matter (OM) for decades. Early work by Stanford and Hanway (1955) described the advantages of a new method of estimating N mineralization. They used a laboratory incubation method which allowed multiple measurements of nitrate production with the same soil sample over time. Soil samples were mixed with expanded vermiculite prior to incubation then leached with water. Excess water was removed by suction then the samples were placed in a 35°C incubator for two weeks. The process was repeated at two week intervals. Leachate nitrate was quantified colorimetrically using phenoldisulfonic acid. Their new leaching method resulted in a 56% increase in nitrate production over the previous method of incubation and extraction in bottles. Increased precision was due to enhanced aeration and better control of soil water content. Most importantly the work produced a rapid method of assessing a soils' ability to supply mineral N.

Legg et al. (1971) modified the above procedure by excluding the expanded vermiculite and included leaching with 0.01M $CaCl_2$ followed by the addition of a minus N nutrient solution. The study lasted 40 weeks to determine the long term mineralization of ^{15}N tagged and total N from pots maintained under continuous oat (Avena sativa L.) cropping. Long periods of continuous cropping depressed initial N mineralization

rates (all plant material returned to pots after seed harvest), however, later incubation periods had relatively constant mineralization rates. Differing rates seemed to be related to excess carbonaceous material which dissipated in the longer, continuously cropped soils.

The incubation method of Legg et al. (1971) was used by Stanford and Smith (1972) to assess the N mineralization potential of 39 widely differing soils over a 30 week period at 35°C. The method was modified by adding quartz sand equal to the weight of soil to enhance leachate percolation. Additionally, soil water content was established in leaching tubes with 80 kPa suction following each successive leaching. Net N mineralization was linearly related to the square root of time in most soils. Cumulative N mineralization obeyed first order kinetics where equation (2) is obtained from the integration of equation (1).

$$-\frac{dN}{dt} = kN \qquad (1)$$

The amount of mineralizable N was denoted as N and k is the rate constant. Integration of equation (1) produced

$$\log (N_o - N_t) = \log N_o - \frac{k}{2.303}(t) \qquad (2)$$

where N_o = N mineralization potential (ug g^{-1}), N_t = cumulative N mineralized in time t (weeks), and k = mineralization rate constant ($weeks^{-1}$).

One of the most important factors controlling the production of mineral N nitrogen is temperature. All of the studies reviewed have a

similar incubation temperature of 35°C. Tyler et al. (1959) incubated four California soils with six levels of ammonium fertilizer at 23.9, 7.2, and 2.8°C to quantify the effect of temperature on nitrification. Nitrification proceeded at a moderate rate when incubated at 7.2°C. They concluded that fall application of ammonical fertilizers could be hazardous (in areas where the soil does not freeze) when attempting to minimize leaching losses because of continuing nitrification. Additionally, the overall Q_{10} approached 2.1 between 7.2 and 23.9°C

Stanford et al. (1973) incubated 11 of the original 39 soils used in their 1972 study at 5, 15, and 25°C over a 24 week period to assess the temperature-mineralization relationship. Q_{10} values were near 2 when the 5°C temperature was omitted from the regression of log k on 1/T (T in degrees Kelvin).

Laboratory incubations provide insight into the capacity of soils to supply mineral N under relatively optimal conditions. A field incubation technique was first reported by Eno (1960). His method allowed soil samples (secured in polyethylene bags and buried for 6 weeks under 10 cm soil) to experience field temperature fluctuations. Mineral N determination was made on soil samples following 6 weeks of field incubation. The polyethylene used was permeable to oxygen and carbon dioxide but impermeable to water and nitrate. Nitrate production was closely related to changes in soil temperature, however, a time lag effect was observed between temperature change and mineralization.

Westermann and Crothers (1980) used the buried bag technique to evaluate N mineralization under irrigated cropped and fallow field

conditions and estimate N uptake during crop maturation. They took several random soil cores to 45 cm, screened the soil then filled precut lengths of polyethylene tubing. The sealed bags (tubes) were then placed into the original sample holes. Periodic quantification of mineral N contained in the bags and field soil samples revealed a highly significant linear relationship (r=0.95). Nitrogen uptake in the cropped sites was determined as the difference between mineral N in the bags and that in the surrounding soil. Estimates generally agreed with results of N uptake determined by plant tissue analysis.

Smith et al. (1977) combined laboratory incubation results with field N mineralization measurements and adjusted for both soil water content and soil temperature in estimating mineral N production of eight Oklahoma soils. Their "calculation" method assumed a Q_{10} of 2, and mineralization rate constants calculated from the k (0.054 $weeks^{-1}$) reported by Stanford and Smith (1972). "Calculated" amounts agreed favorably to amounts measured in the field, with differences frequently less than 10 ug g^{-1}.

CHAPTER III

NITROGEN MINERALIZATION MODEL OF SURFACE SOILS FROM LABORATORY INCUBATIONS

Introduction

Nitrogen mineralization is the general process by which organic forms of N in the soil are converted to inorganic plant available forms. The rate that mineralization of organic N occurs in soils is dependent on a number of factors including supply of substrate, population of microorganisms, temperature, pH, aeration, and soil water content. The N mineralization process is actually a multi-stage, microbially mediated set of intricate reactions. Simplified, these reactions fall into three categories, aminization, ammonification, and nitrification. Aminization is the final reaction in a series of reactions conducted by heterotrophic organisms (require organic carbon sources for energy), primarily bacteria and fungi, which decompose OM to the point that proteins are converted to amines, carbon dioxide and energy. The amines are then converted to ammonium by heterotrophic organisms. Under ideal conditions much of the ammonium will be oxidized to nitrite primarily by the autotrophic bacteria (energy from oxidation of inorganic salts) Nitrosomonas, this nitrite is then converted to nitrate primarily by Nitrobacter.

Conditions favoring mineralization of OM are similar to conditions optimal for crop growth. The C:N ratio must be in a range near ten or

the ammonium produced during aminization will be utilized by the heterotrophic population decomposing OM. Additionally, aeration must be maintained because molecular oxygen is required by the Nitrobacteria. The soil pH can range widely from 5.5 to 10.0, however, the optimum is near 8.0. Temperature for maximum N mineralization is near 35°C. Soil water is directly related to the level of aeration within a particular soil. Soil water contents near field capacity are considered optimal with decreasing mineralization occuring at decreasing water contents (Cassman and Munns, 1980).

The experiment was designed to determine the effect of temperature and OM on the production of mineral N. This study attempted to optimize all of the important factors required for maximum N mineralization. This chapter summarizes results conducted on upper Missouri River Basin surface soils to index N mineralized as a function of soil temperature and OM content.

Materials and Methods

Surface horizons of five different soils (Table 1) were collected in 1983, dried at 36°C, disaggregated and sieved through a 2 mm screen. Subsurface horizons were treated similarly, chemical and physical data for these horizons are shown in Appendix Table 16. Subsamples of each A horizon were analyzed for OM content with a modified Walkley-Black procedure (Sims and Haby, 1970), and total N digestion by semi-micro Kjeldahl similar to Bremner (1965) with the colorimetric portion of the Kjeldahl procedure on a Technicon Auto Analyzer II (Technicon Ind. Method No. 154-71W, Ammonia in water and seawater. Feb., 1973).

Soils were leached with 0.01M $CaCl_2$ by the method of Stanford and Smith (1972) except that post-leaching soil water potential was brought to 18 kPa, which is in the critical soil water range for assessing N mineralization (Cassman and Munns, 1980). Leachates were analyzed for nitrate by cadmium reduction (Technicon Ind. Method No. 100-70W, Nitrate and nitrite in water and wastewater. Sept., 1973), nitrite similarly, though without the cadmium column, and ammonium on an Auto Analyzer II system. Mineral nitrogen is the sum of nitrate, nitrite, and ammonium.

Table 1. Physical and chemical characteristics of five Montana soil A horizons.

Series	Classification	Total C	Total N	C:N	pH
		- - - % - - -			
Bridger	fine, mixed Argic Cryoboroll	5.80	0.48	12.1	7.0
Bozeman	fine, silty, mixed Pachic Agriboroll	2.50	0.22	11.6	7.8
Williams	fine-loamy, mixed Typic Argiboroll	1.51	0.15	10.1	6.6
Scobey	fine, montmorillonitic Aridic Argiboroll	1.39	0.16	8.7	7.7
Sappington-Amesha	coarse-loamy, mixed Borollic Calciorthid	1.04	0.11	9.5	8.3

Selected soils varied in their historical management. The Bridger soil is the only uncultivated soil and is found in a relatively high elevation (1500 m) prairie setting. Of the four cultivated soils, only the Bozeman soil has a history of small grain/alfalfa rotation and is found at elevations near 1400 m. Scobey, Williams and Sappington-Amesha soils have been alternately crop-fallowed for many years and are

located in semi-arid areas at 1075, 585 and 1200 m elevation, respectively.

The indexing model is a first attempt at approximating the relative magnitude of N mineralization of four cultivated soils with varying OM contents. Soil N mineralization data were generated in the laboratory under optimal soil water conditions (near field capacity) with temperature (0, 14, 28°C) strictly controlled. Laboratory incubation data are summarized by soil horizon and temperature in Appendix Tables 17, 18, and 19.

Cumulative net N mineralization at each temperature and OM level was averaged over the 12 week incubation period (84 days). Simple linear regression of mean cumulative net N mineralization on temperature at each OM level provided an equation for 1.8%, 2.4%, 2.6%, and 4.4% OM with r^2=0.99 (Table 2).

Table 2. Linear equations for mean daily N mineralization by organic matter content.

Series	OM	Cum. net N min. day^{-1} 0°c	14°C	Equation where kg N min. ha^{-1} day^{-1}
	%	kg ha^{-1}		
Bozeman	4.4	0.992	1.330	= 0.0238 T°C + 0.992
Williams	2.6	0.385	0.936	= 0.0393 T°C + 0.385
Scobey	2.4	0.450	0.799	= 0.0249 T°C + 0.450
S. Am.	1.8	0.252	0.549	= 0.0244 T°C + 0.252

A predictive equation was employed (Meikle and Treadway, 1979) to estimate field soil temperature. The equation was developed from 10 cm depth soil temperature data collected over a minimum three year period at 114 locations in the United States and is shown by the expression:

$$\text{Temperature } (^{\circ}F) = 30.5 - (0.401)X + (9.39 \times 10^{-3})X^2 - (4.17 \times 10^{-5})X^3 + (3.22 \times 10^{-8})X^4 \quad (1)$$

where X is the Julian calendar day (Jan. 1 = 1, Dec. 31 = 365). Partial regression coefficients for Moccasin, Montana were selected (R^2 = 0.937).

Starting date for estimating field N mineralization was selected as May 15 (Julian day 136). Cumulative N mineralization at each OM content was determined. Ten cm soil temperatures from the polynomial expression did not exceed 14.03 °C, therefore, only the 0° and 14°C laboratory N mineralization data were included in the model.

Results and Discussion

Selected soils reflect different cropping histories ranging from virgin grassland (Bridger) to small grain/alfalfa rotation (Bozeman) to many years of crop/fallow grain production (Scobey, Sappington-Amesha, Williams). Nitrogen mineralization was greatest in the Bridger soil (10% OM) and least in the Sappington Amesha soil (1.8%) OM across all temperatures (Fig. 1).

Net soil N mineralization data are contrasted at the initial and final leaching date for the Bozeman, Scobey, Sappington-Amesha and Williams soils. Results at the 2 week period of the incubation

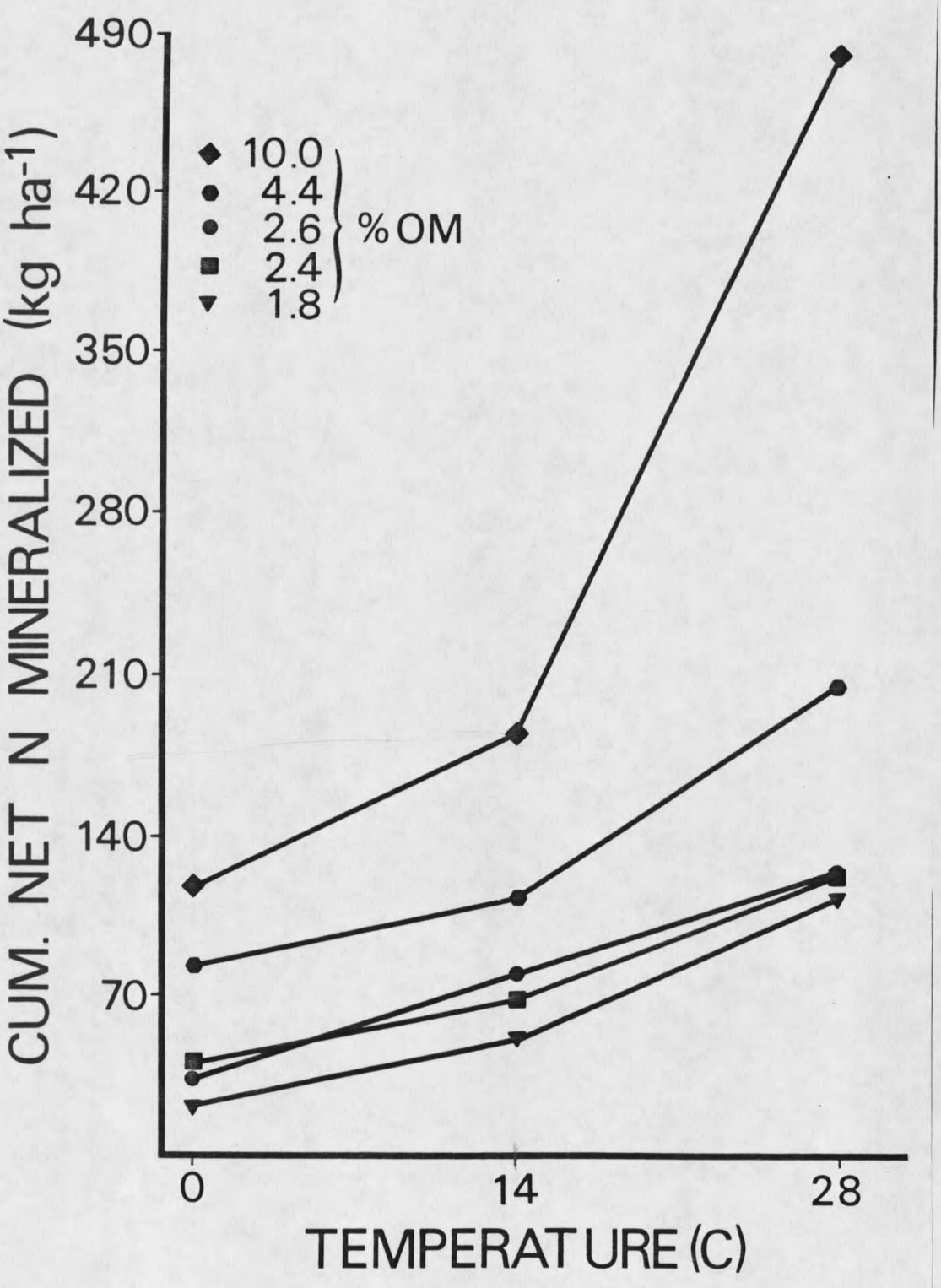

Figure 1. Total cumulative net N mineralization of five soils by laboratory incubation at three temperatures.

(Fig. 2) indicate the significant (P = 0.05, 2 S.D.) effect of temperature and OM content on the amount of N mineralized. Soil N mineralization was not significantly different at 0° and 14° C at 12 weeks (Fig. 3) , however, the Bozeman soil did produce significantly more N at 28° C. The lack of overall statistical differences in N mineralized by twelve weeks indicates that the duration of the laboratory incubation was sufficient to remove most of the "easily mineralizable" N. Readily convertible organic materials in these soils probably had been consumed at 12 weeks and only the humus component remained as substrate.

Increased N mineralization with temperature is expected, however, the amount of mineralized N produced by all soils at 0°C was surprisingly large (Fig. 4). The samples were kept at 0°C continually, except during leaching (14 hours at room temperature).

Microbes probably could not accelerate mineralization to the extent observed during that 14 hour time period. Since leachates were not collected following the addition of each added increment of 0.01M $CaCl_2$, and these leachates were not analyzed individually after passing through soil columns, there is no record of leachate content through the day. Soils incubated at 0°C mineralized between 21 and 83 kg N ha^{-1}. The credibility of using fall soil N status for predicting spring crop NO_3-N requirements is questionable.

The computer model (Appendix Table 20) used included laboratory N mineralization data to estimate the differences in N mineralized by soils varying in OM content. Results of the incubation data are summarized by temperature in Figures 4, 5, and 6 with the equations for each line depicted in Table 3.

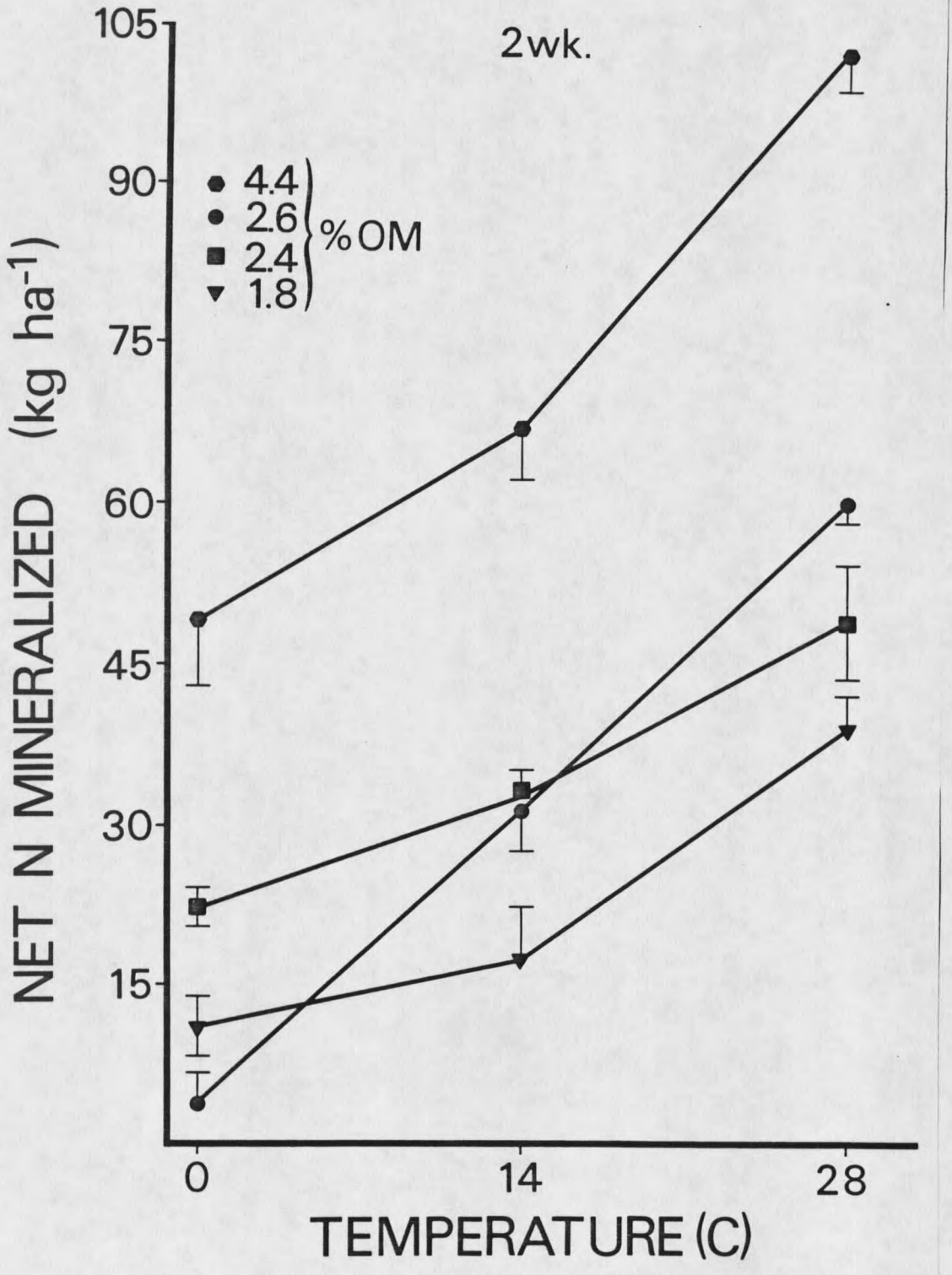

Figure 2. Soil N mineralization by laboratory incubation at two weeks.

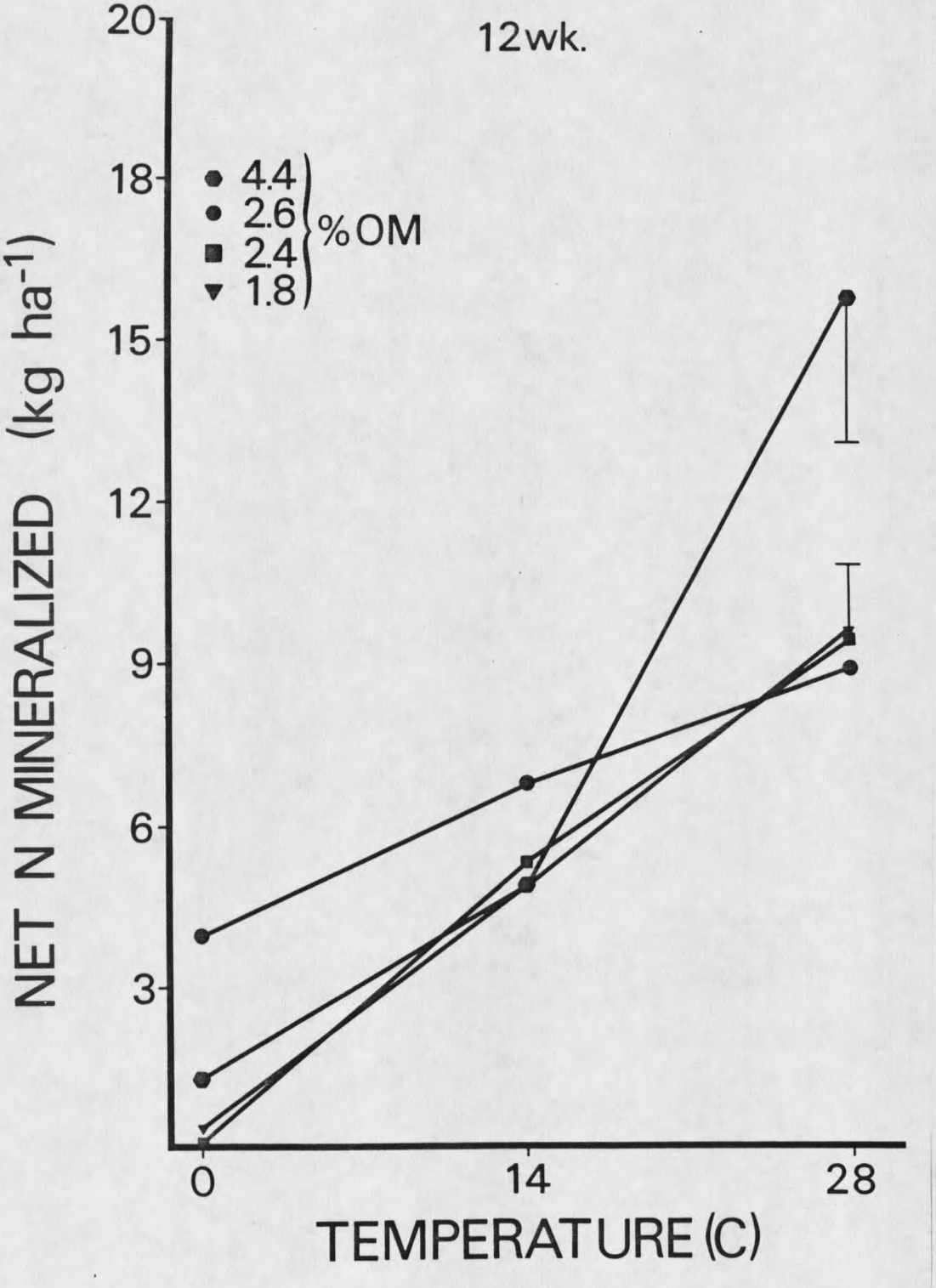

Figure 3. Soil N mineralization by laboratory incubation at twelve weeks.

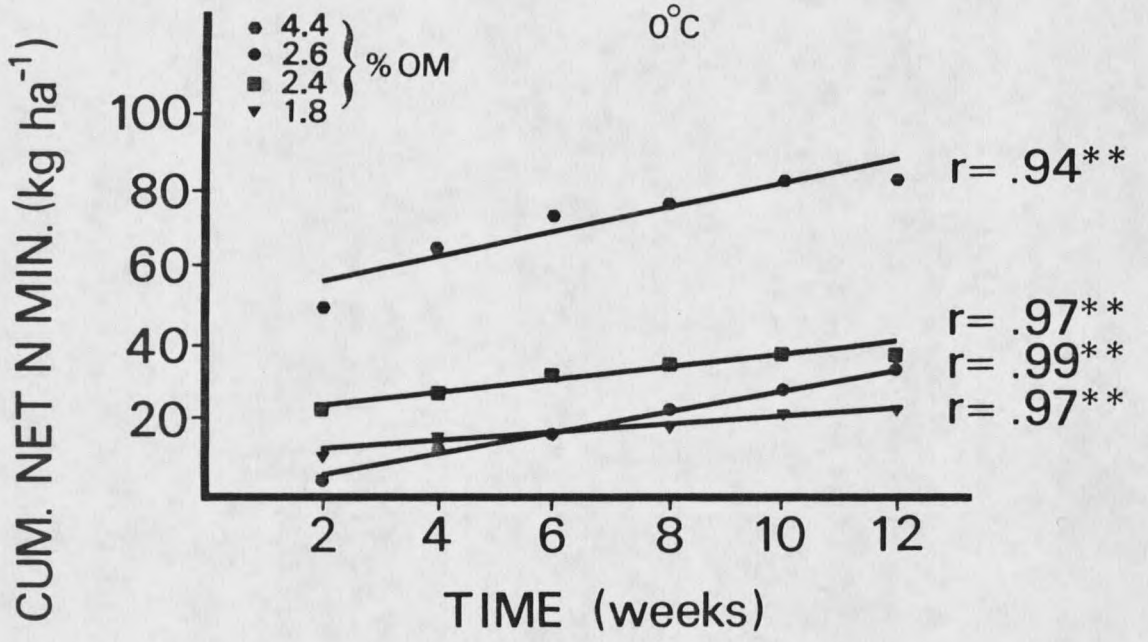

Figure 4. Cumulative net N mineralization of four cultivated soils by laboratory incubation at 0°C.

Table 3. Linear equations for cumulative net N mineralization by organic matter content at three temperatures.

Series	OM	Temperature 0°C	14°C	28°C
	%	kg ha^{-1}		
Bozeman	4.4	Y = 3.21X + 49.13	4.03X + 65.80	9.77X + 91.77
Williams	2.6	Y = 2.68X + 0.79	4.60X + 25.61	6.16X + 49.47
Scobey	2.4	Y = 1.56X + 20.67	3.45X + 27.49	6.91X + 41.80
Sappington Amesha	1.8	Y = 1.02X + 9.88	3.28X + 11.76	7.12X + 30.39

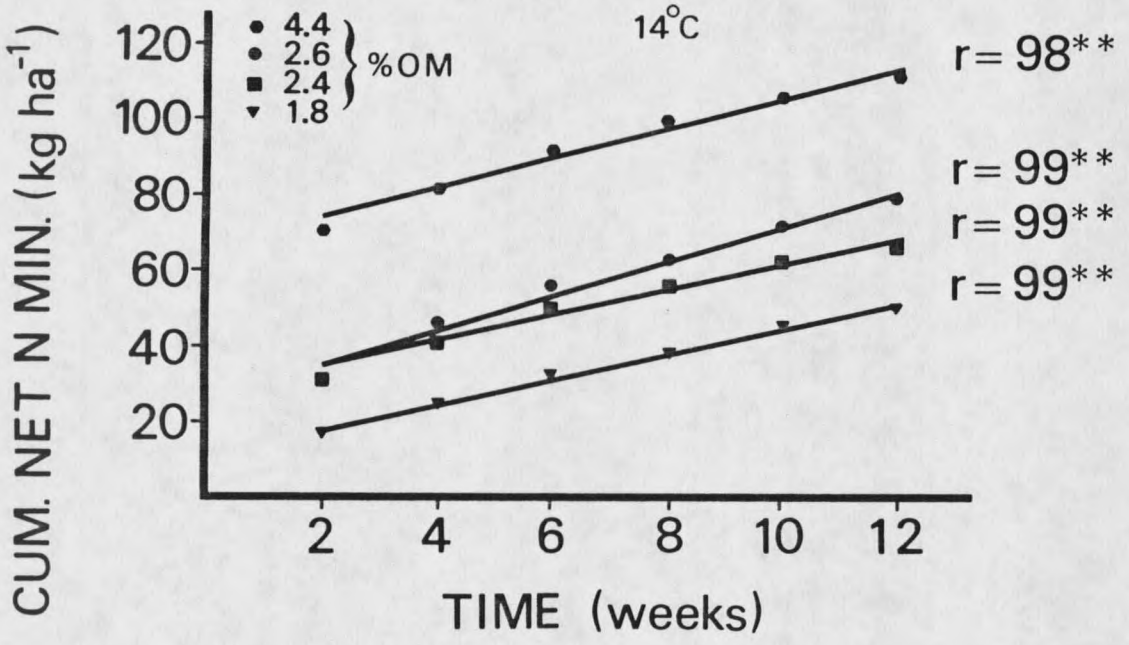

Figure 5. Cumulative net N mineralization of four cultivated soils by laboratory incubation at 14°C.

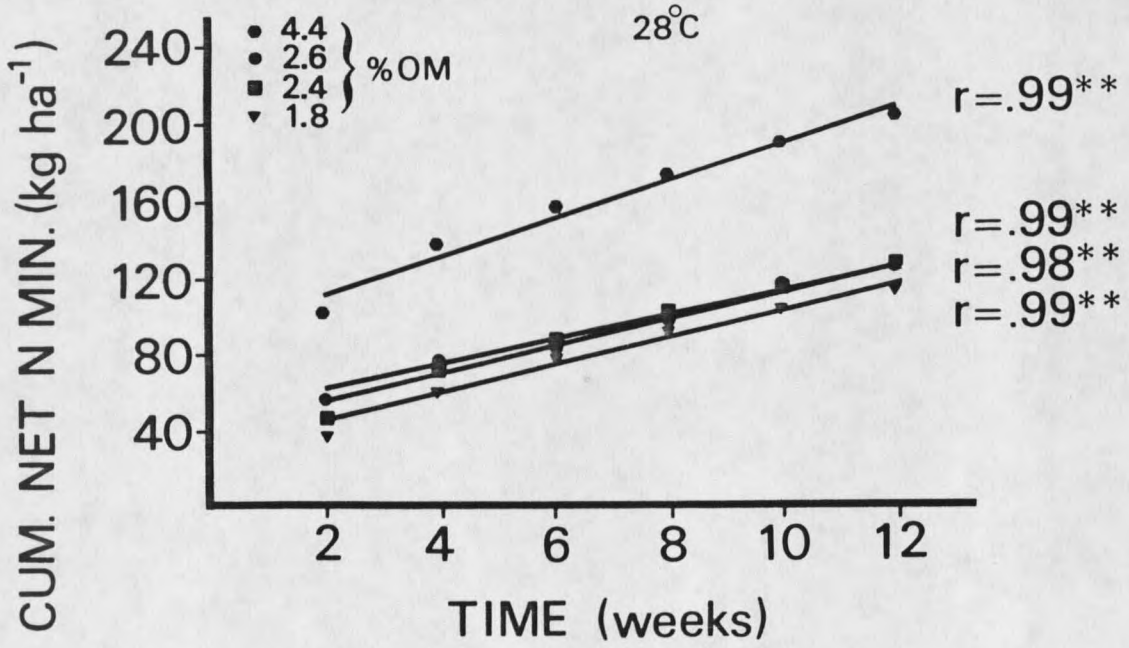

Figure 6. Cumulative net N mineralization of four cultivated soils by laboratory incubation at 28°C.

Field soil temperatures used in the model were obtained from a polynomial equation designed to estimate 10 cm depth soil temperature (1). The temperature equation showed that soil temperatures at Moccasin, Montana ranged from 13.2°C on May 15 (Julian 136) to a maximum of 14.02°C (Julian 153), to a minimum of 7.5°C on July 15. The overall model predicts N mineralized from equation (2)

$$\text{N mineralized (kg ha}^{-1}\text{ day}^{-1}\text{)} = -0.25 + 0.28(\text{OM}) + 0.03(\text{T}^{\circ}\text{C}) \qquad (2)$$

Total N mineralization obtained provides a linear index to the differences in N mineralization (Table 4). Predicted N mineralization values for day 61 were 39, 49, 53, and 84 kg N ha^{-1} for 1.8%, 2.4%, 2.6% and 4.4% OM, respectively. The difference between 1.8% and 2.4% OM was small at 10 kg N ha^{-1} while the difference between 1.8% and 4.4% OM was 45 kg N ha^{-1}. Dividing the total predicted N mineralized from each soil by the amount of OM contained in the soils (%) shows that each 1% OM produces nearly 20 kg ha^{-1} of plant available N for the 61 day period (Table 4).

These data indicate there are differences in soil N mineralization as a function of OM content under optimum conditions and that the differences are substantial across the range of soil OM contents studied. Nitrogen mineralization increases with time even when using field correlated soil temperatures. Irrigated conditions provide a more suitable environment for microbial activity thereby prolonging the period of N mineralization (El-Haris et al., 1983). However, there is little data available relating the magnitude of soil N mineralization under varying field conditions. More research is needed to quantify

actual soil N mineralization over time. This information should enhance our ability to accurately predict crop N requirements.

Table 4. Mineralized N predicted from N mineralization model on a percent organic matter basis at three dates.

		Dates			Dates		
		7/16	7/27	8/8	7/16	7/27	8/8
Series	OM	Total predicted N min.			Pred. N min. by %OM		
	%	kg ha^{-1}					
Bozeman	4.4	84	97	109	19.1	22.0	24.7
	4.2	80	92	104	19.2	22.0	24.7
	4.0	77	88	99	19.3	22.2	24.8
	3.8	74	84	94	19.4	22.2	24.8
	3.6	70	80	90	19.5	22.3	24.9
	3.4	67	76	85	19.6	22.4	24.9
	3.2	63	72	80	19.7	22.5	25.0
	3.0	60	68	75	19.9	22.7	25.1
	2.8	56	64	70	20.1	22.8	25.2
Williams ...	2.6	53	60	66	20.3	23.0	25.3
Scobey	2.4	49	56	61	20.5	23.2	25.4
	2.2	46	52	56	20.8	23.5	25.6
	2.0	42	47	51	21.2	23.8	25.7
S. Am.	1.8	39	43	47	21.6	24.1	25.9
					Mean = 20.0	22.8	25.1

CHAPTER IV

NITROGEN MINERALIZATION MODEL OF SURFACE SOILS FROM FIELD INCUBATIONS

Introduction

Laboratory incubation studies and the resulting models relate different soils' ability to mineralize a maximum amount of N. Temperature, soil water content and the amount of OM present are very important in controlling the breakdown of soil OM. Trends identified under laboratory conditions need to be tested in the harsh field environment. Several workers have described techniques which attempt to quantify the N mineralized in a particular cropping system (Eno, 1960, Smith et al., 1977, Westermann and Crothers, 1980).

This field incubation study was initiated within the confines of another field research project designed to quantify the effects of soil injected raw sewage sludge on heavy metal uptake by crops. The field incubation study will not address the relationship of heavy metal application to soil N mineralization.

The objectives of the field incubation study include the quantification of growing season soil N mineralization and the development of a predictive N mineralization model.

Materials and Methods

Field incubation experiments, conducted on the Diehl Ranch located

5 kilometers east of East Helena, Montana (T10N, R2W), were established at seven sites, three in 1983 and four in 1984. The 1983 sites were designated H, J and M. Sites H and M each had 73,000 liters ha^{-1} of raw sewage sludge applied in the summer of 1982. Site J received only commercial fertilizer. In 1984 sites H, J, and M were reestablished with an additional site, R. Only site R received sludge in 1984.

Results of subsample chemical analyses for the 1983 and 1984 sites are shown in Table 5. Nitrogen species analysis was accomplished on an Auto Analyzer II system with the NO_3-N by cadmium reduction, NH_4-N by the Berthelot reaction and total N digestion by semi-micro Kjeldahl similar to that of Bremner (1965) with the colorimetric portion of the Kjeldahl performed as the Berthelot reaction (see Chapter III). Carbon was determined with a modified Walkley-Black procedure (Sims and Haby, 1970), pH by glass electrode (soil:water ratio 1:2), K from ammonium acetate extraction (Bower, et al.,1952), P by sodium bicarbonate (Olsen, 1954), and EC by Wescan conductivity meter on a 1:2 soil:water mixture (Richards, 1954).

Descriptions of methods for the establishment of incubation sites apply to all sites in both years of the experiment. Soil was removed by a 5.7 cm outside diameter sampling tube to a depth of 30 cm. Each core was split into 3, 10 cm increments and immediately placed into corresponding 85 liter plastic bags. These large plastic bags were sealed after each soil core portion was admitted to reduce of evaporation. Approximately 20 cores were removed per replication with 3 replications assigned to each site. Soil in the large plastic bags was mixed thoroughly, subsampled, then introduced into tubular 5 cm

Table 5. Chemical properties of soils subsampled for field incubation experiments initiated in 1983 and 1984.

Depth	NO_3-N	NH_4-N	C	N	OM	C:N	pH	EC	P	K
- cm ---	- kg ha^{-1} --	- - -	- - % - -	- - -	----------			mmho cm^{-1}	-- ug g^{-1} -	
Site H 5/25/83										
0-10	3.0	4.1	1.04	0.13	1.80	8.00	7.6	0.1	13.7	442
10-20	7.9	3.0	0.93	0.11	1.60	8.45	7.5	0.1	7.8	210
20-30	17.4	3.1	0.81	0.11	1.40	7.36	7.6	0.1	6.0	158
Site J 5/25/83										
0-10	4.8	5.2	1.86	0.18	3.20	10.33	7.4	0.1	122.0	354
10-20	4.1	4.4	1.45	0.15	2.50	9.67	7.3	0.1	52.2	206
20-30	5.9	4.2	1.16	0.13	2.00	8.92	7.4	0.1	14.9	118
Site M 6/1/83										
0-10	2.9	3.6	0.93	0.09	1.60	10.33	7.6	0.3	34.7	670
10-20	1.5	2.7	0.70	0.09	1.21	7.78	7.7	0.2	10.2	530
20-30	0.5	3.2	0.72	0.09	1.25	8.00	8.4	0.4	7.2	322
Site H 5/19/84										
0-10	5.7	4.4	1.22	0.13	2.10	9.38	8.3	0.5	16.0	475
10-20	3.1	4.0	1.04	0.13	1.80	8.00	8.3	0.6	14.4	259
20-30	4.4	4.6	0.75	0.10	1.30	7.50	8.3	0.6	13.3	163
Site J 5/30/84										
0-10	8.1	4.0	1.91	0.18	3.30	10.60	8.0	0.5	38.3	315
10-20	3.5	2.8	1.51	0.16	2.60	9.40	8.1	0.6	17.9	178
20-30	6.6	2.8	1.51	0.15	2.60	10.10	8.2	0.6	24.8	186
Site M 5/11/84										
0-10	16.6	5.0	0.87	0.10	1.50	8.70	7.8	0.6	26.3	450
10-20	28.8	4.0	0.75	0.09	1.30	8.30	7.9	0.7	19.8	378
20-30	33.9	5.9	0.64	0.10	1.10	6.40	8.2	0.8	16.5	227
Site R 5/12/84										
0-10	19.8	2.8	0.81	0.10	1.40	8.10	8.3	0.5	19.9	445
10-20	24.2	3.0	0.64	0.10	1.10	6.40	8.2	0.6	15.5	332
20-30	29.1	3.3	0.58	0.10	1.00	5.80	8.4	0.9	10.9	223

diameter (5.9 um thick) polyethylene bags sealed on one end. Soil from the large plastic bags was placed into the tubular polyethylene bags by corresponding depth increment so that the 20-30 cm increment was introduced first, the 10-20 cm increment next and so on. Bags were carefully dropped on a hard surface (to compress the disturbed soil) and sealed when filled, then inserted into the holes from which they originally were removed (Westermann and Crothers, 1980). Where sludge was injected, core samples were taken between injection paths. Where sites were cropped, cores were taken from between drill rows. The N mineralization (NM) bags were then extracted from the ground at weekly intervals, one per replication per site in 1983 and 1984. Extracted NM bags were immediately frozen on dry ice to inhibit further nitrification during transportation to the laboratory. At the laboratory the NM bags were split into the corresponding 10 cm depth increments, dried at 36°C, then analyzed for NO_3-N and NH_4-N.

Soil temperature probes were assembled from 5 cm plastic tubing. Thermistors (Omega Part No. 44005) were bedded in silicone-filled 1 cm x 1 cm plastic coupling material with insulated wires running through the 5 cm tubing to the upper end, the end at the soil surface. The bedded thermistors were cemented into holes drilled into the 5 cm tubing at 10, 20 and 50 cm depths (distances) from the upper end. Once the cement dried and the bedded thermistors were secure the tubes were sealed with silicone caulking at each end with the thermistor wires protruding from the upper end of the tube. Temperature probes were installed at each site the day NM bags were placed into the ground. Soil temperature readings were made concurrently with NM bag extraction

with a Simpson Model 461 digital multimeter (Appendix Table 24).

Data were analyzed by stepwise multiple linear regression using the maximum R^2 improvement technique (Statistical Analysis System or SAS) on a VAX model 11/780.

Nitrogen species produced by mineralization were quantified from weekly analyses of soil contained in NM bags (Appendix Table 21). Totals of N species by week and soil depth from NM bags are summarized in Appendix Table 22.

Development of a predictive model of field N mineralization from field incubations requires initial definition of variables included in the selected multiple regression analysis (Table 6). Tables 7 and 8 further identify variables SITE and WEEK respectively. The variables, (Table 6) reflect the total depth of the study profile or 30 cm. In the case of the N species, values used in the multiple regression analysis constitute the sum of all 10 cm increments by site (Table 11). Total Kjeldahl N and OM levels used result from the mean of 10 cm increments by site (Table 5). Air temperature was obtained from Helena Airport climatological data summaries published by the National Oceanographic and Atmospheric Administration. The AIRTC parameter was calculated as the mean of the maximum daily air temperature for the 6 day period preceding and the day of NM bag extraction (Appendix Table 23).

Results and Discussion

Results of the maximum R^2 multiple linear regression analysis (Table 9) indicate the independent variables most influential in predicting N mineralization as measured by total mineral N production.

Table 6. Variables included in the multiple linear regression analysis (I=independent, D=dependent).

Variable	Identification	
Site	SITE	I
Week	WEEK	I
Total NO3-N 30 cm^{-1}	NO3T	D
Total NH4-N 30 cm^{-1}	NH4T	D
Total NO3-N + NH4-N 30 cm^{-1}	NO3NH4T	D
Mean weekly maximum air temperature ^{o}C	AIRTC	I
Weekly soil temperature at 10 cm ^{o}C	SOILT10	I
Weekly soil temperature at 20 cm ^{o}C	SOILT20	I
Weekly soil temperature at 50 cm ^{o}C	SOILT50	I
Mean % organic matter content 30 cm^{-1}	OM	I
Mean % total nitrogen content 30 cm^{-1}	N	I

Table 7. Description of independent variable SITE used in the model.

Variable	Identification*		Management History
SITE	1983	H	Sludge injected into fallow 1982, seeded to winter wheat 1982.
	1983	J	Commercial fertilized fallow 1982, seeded to winter wheat 1982.
	1983	M	Winter wheat 1982, fallow 1983
	1984	H	Fallow 1984
	1984	J	Fallow 1984
	1984	M	Sludge injected into fallow 1983, seeded to spring wheat 1984.
	1984	R	Sludge injected into fallow 1983, seeded to winter wheat 1983.

* Year and site.

The statistical treatment introduced SITE as the first independent variable (R^2 = 0.503), followed by WEEK (R^2 = 0.805), then SOILT10 (R^2 = 0.824), OM (R^2 = 0.825), and N (R^2 = 0.842). Table 10 shows the equation which constitutes the "best" 5 independent variable model.

Three of the 5 independent variables were positively related to N mineralized (NO3NH4T), however, SOILT10 and N were negatively related to the dependent variable. This negative relationship was probably due to the statistical manipulations which interrelate independent variables within the model and, therefore, may not describe a particular functional relationship among variables.

Table 8. Description of independent variable WEEK used in the model.

Variable	SITE	Julian Days	WEEKS
WEEK	H	141-257	1-17
	J	141-257	1-17
	M	152-257	1-16
	H	140-249	1-17
	J	151-249	1-15
	M	132-249	1-18
	R	133-249	1-18

Table 9. Results of multiple linear regression analysis; F and coefficient of multiple determination (R^2) for NO3NH4T as the dependent variable.

	DF	R^2	F
Regression	5	0.842	119.61
Error	112		
Total	117		
Independent Variable			
SITE			257.97
WEEK			231.45
SOILT10			17.12
OM			12.41
N			12.15

The inclusion of all sites in the analysis provided a broad selection of production management levels. Site treatments included formerly fallowed, cropped the previous year, commercially fertilized, and injected with sewage sludge (Table 7). The importance of the previous treatment to each site was accounted for in the model by assessing the level of mineral N present at the time of initial sampling. Sites were indexed in ascending order according to early season mineral N levels (Table 11). For example, site M contained 14.4 kg mineral N ha^{-1} at the initial sampling while site R had 82.2 kg ha^{-1} mineral N in the upper 30 cm at the initial sampling. These sites represented the minimum and maximum mineral N levels and were assigned index numbers 1 and 7 respectively. The NM bags provided an ideal environment for measurement of N mineralization within the cropped field because plant roots were unable to extract mineral N from the NM bags. Predicted values of N mineralized must include an indexing variable to account for variation in initial soil mineral N content. It is probably

because of the considerable difference among management levels that SITE was the most important independent variable in the model.

The next variable into the model was WEEK. The addition of this variable was expected because under optimum conditions N mineralization increases with time as shown in the laboratory incubations in Chapter III and those conducted by Stanford and Smith (1972).

Soil temperature at the 10 cm depth (SOILT10) was the next independent variable to enter the model. Temperature influences biological activity and was therefore considered in the model.

Table 10. Multiple linear regression equation for the model considering NO3NH4T as the dependent variable.

N MINERALIZED = 53.27 + 12.36(SITE) + 4.17(WEEK) - 1.25(SOILT10)
+41.80(OM)- 991.74(N)

Table 11. Stratification of SITE by initial mineral nitrogen levels for dependent variables NO3NH4T and NO3T.

		INDEX NUMBER			
NO3NH4T	NO3T	NO3NH4T	SITE/YEAR	NO3T	SITE/YEAR
- - - - - kg ha-1 - - - - -					
14.4	4.9	1	M 83	1	M 83
26.2	13.2	2	H 84	2	H 84
27.8	14.8	3	J 84	3	J 83
28.6	18.2	4	J 83	4	J 84
38.5	28.3	5	H 83	5	H 83
82.2	73.1	6	R 84	6	R 84
94.2	79.3	7	M 84	7	M 84

At this point the model contains 5 independent variables considered very important in predicting total mineral N production over the 15 to 18 week study period. Additional independent variables were included in subsequent models, however, the improvement in R^2 or the model's ability to account for the variability in N mineralization was small. The "best" 6 variable model included AIRTC (R^2 = 0.842). The maximum R^2 technique allows for independent variable replacement and this occured in the best 7 variable model which eventually included SITE, WEEK, SOILT10, SOILT20, SOILT50, OM, and N (R^2 = 0.842). The "best" 8 variable model added AIRTC (R^2 = 0.843). Overall difference between the selected 5 variable model and the 8 variable model in terms of R^2 was 0.001 or 0.1%. The inclusion of the additional variables was not necessary to enhance the model. The 5 variable model accounts for 84% of the variability in total mineral N production and includes independent variables known to influence the rate of N mineralization.

Ammonium (NH4T) as the dependent variable did not result in an acceptable model. This was expected since ammonium is an intermediate product in the formation of nitrate during mineralization and would therefore be the least consistent constituent in the process. The best 8 variable model had an R^2 of 0.310 (Appendix Table 25).

The practicality of measuring nitrate (NO3T) and ammonium (NH4T) along with organic matter (OM) and Kjeldahl nitrogen (N) early in the spring to establish the site class is limited. A second, more functional approach to predicting N mineralization was established by simply arranging the site class by the level of nitrate in the upper 30 cm of the soil (Table 11). Note that the change in site index from

that of NO3NH4T is minimal, that is, site J 84 switched with site J 83.

The model considering NO3T as the dependent variable and the concomitant rearrangement of site index (Table 12) enters SITE as the first independent variable (R^2 = 0.597) and WEEK (R^2 = 0.831) as shown in Table 13. Additional independent variables are entered finally producing a "best" 8 variable model with an R^2 of 0.862. The difference between the 2 and 8 variable models in terms of R^2 is 0.031 or 3.1%. It seems logical to select the 2 variable model when the objective is to provide a functional model.

Table 12. Multiple linear regression equation for the model considering NO3T as the dependent variable.

N MINERALIZED = -18.67 + 11.75(SITE) + 3.15(WEEK)

Table 13. Results of multiple linear regression analysis; F and coefficient of multiple determination (R^2) for NO3T as the dependent variable.

	DF	R^2	F
Regression	2	0.831	283.47
Error	115		
Total	117		
Independent Variable			
SITE			376.12
WEEK			159.69

This functional approach also provided a 2 variable model using the same site index as that of the NO3NH4T model (Table 14) and produced an R^2 of 0.827 (Table 15). The overall significance of the 2 variable models is the simplicity with which the models account for 84% of the variability in predicting either total mineral N or total nitrate N in the surface 30 cm.

The 2 variable model presents a straightforward look at the independent variables deemed most important in predicting N mineralization at this location. The variable SITE is directly related to initial mineral N content in the upper 30 cm. With the addition of time in the variable WEEK the model is essentially complete. For this particular soil this model could be used to predict growing season N mineralization quite accurately. The determination of nitrate in the upper 30 cm is really the only measurement needed to ascertain the mineral N production at a particular time.

Further manipulation of the data to replace SITE with the actual N mineralized in time would allow for field testing of the model in other locations. Similarly, the inclusion of an equation describing the temporal soil water loss would enhance the accuracy of the model.

Table 14. Multiple linear regression equation for the model considering NO3T as the dependent variable.

N MINERALIZED = -18.29 + 11.75(SITE) + 3.08(WEEK)

Table 15. Results of multiple linear regression analysis; F and coefficient of multiple determination (R^2) for NO3NH4T as the dependent variable.

	DF	R^2	F
Regression	2	0.827	275.48
Error	115		
Total	117		
Independent Variable			
SITE			364.61
WEEK			149.57

The objectives of the study were successfully addressed. Nitrogen mineralization was quantified in the field under nonirrigated conditions using the method of Westermann and Crothers (1980). The functional model of field N mineralization included variables identifying an index of initial growing season mineral N status (SITE) and time of incubation (WEEK). Development of the functional model provided a useful tool for the prediction of growing season mineral N. Further development of the model would enhance its use by agronomists for predicting mineral N production thereby increasing precision of fertilizer N recommendations.

CHAPTER V

GENERAL CONCLUSIONS

The objectives of the study were to quantify N mineralization of selected Montana soils by field and laboratory incubation techniques with development of predictive models from field and laboratory data.

Laboratory incubations revealed the linear relationship of N mineralization with time. Considerable mineral N was produced at 0°C which makes fall soil sampling for spring crop N fertilizer requirements questionable. The N mineralization detected at 0°C was probably due to the natural selective processes for microbes that can survive and proliferate under cold Montana soil conditions. Nitrogen mineralization was related to temperature and OM content of the soils incubated in the laboratory. The model developed to predict N mineralization from the laboratory experiment included an equation that predicted field soil temperature at 10 cm. The soil temperature equation predicted 10 cm soil temperatures for Moccasin, Montana which did not exceed 14.1°C. These temperatures were considerably lower than soil temperatures measured in the field study at East Helena, Montana in 1983 and 1984. The laboratory model was found to be linear from 1.8% to 4.4% OM. Approximately 20 kg N ha^{-1} was mineralized for each percent OM as predicted by the computer model when run for the 61 day period. More mineralized N was predicted when the duration of the modeling period was extended. This could be of particular consequence

under irrigated conditions.

Results of the field incubations produced another model which relied on an index of early season mineral N content in the upper 30 cm of the soil profile and time in weeks. Considering seven site years of data the model accounted for 83% of the variability in N mineralization under the experimental conditions. The practicality of the field model is realized when considering the minimal measurements required to use the model. Determination of early season soil nitrate N to 30 cm and an estimate of mineralization time are the only measurements required under the experimental conditions. Inclusion of an equation describing temporal soil water loss and continued experimentation on differing soils at several locations would enhance and validate the field model.

The two models were developed under entirely different conditions which may interject some doubt as to the ability of the models to predict similar results. The temperature equation selected for the laboratory study predicted soil temperatures considerably lower than those measured at the East Helena field location at the same depth in 1983 and 1984.

The two models were contrasted mathematically. The Sappington-Amesha (1.8% OM) bulk soil sample used in the laboratory study was collected from site H following harvest of a 4700 kh ha^{-1} (70 bushel) dryland winter wheat crop in 1983. Yields were above average on the Diehl Ranch in 1983 due to optimum fertility and above normal precipitation. Assuming that little mineral N remained in the soil following the high yielding crop and that some N was mineralized between post-harvest sample collection in 1983 and establishment of the field exper-

iment in the fallowed H site in 1984, the initial or early season nitrate level would be low. As noted in Table 11, 13.2 kg of nitrate N ha^{-1} were measured in the early season sample to 30 cm at site H in 1984 thereby indexing this as site SITE 2. Considering a 12 WEEK period for N mineralization, the same as that of the laboratory incubation, the field model predicted 42.2 kg N ha^{-1} as nitrate N would be mineralized. The laboratory model predicted 46.7 kg ha^{-1} for the 12 week period as total mineral N which included nitrite and ammonium-N (Table 4). Realizing that little ammonium and nitrite-N are present and that these two intermediates would be subtracted from the value predicted by the laboratory model, the two models predicted a surprisingly similar amount of mineralized N. The difference between the predictions, not counting ammonium or nitrite, was only 4.5 kg N ha^{-1}.

With additional experimentation, both in the field and laboratory, the models developed should provide significant improvement in our ability to predict mineral N production of field soils thereby maximizing fertilizer N efficiency.

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APPENDIX

Appendix Table 16. Physical and chemical characteristics of five Montana soils.

Series	Horizon	Depth	OM	C	N	C:N	pH	Texture
		cm			%			
Bridger	A	0-15	10.0	5.80	0.48	12.1	7.0	l
	B	15-45	2.2	1.28	0.13	9.8	6.7	cl
	C	45-96	1.0	0.59	0.08	7.4	7.7	sicl
Bozeman	A	0-15	4.4	2.55	0.22	11.6	7.8	cl
Williams	A	0-15	2.6	1.51	0.15	10.1	6.6	cl
	B	15-43	1.5	0.85	0.10	8.5	8.0	c
	C	43-102	1.0	0.55	0.07	7.9	8.4	c
Scobey	A	0-15	2.4	1.39	0.16	8.7	7.7	c
	B	15-48	2.0	1.18	0.14	8.4	8.3	c
	C	48-122	1.0	0.59	0.09	6.5	8.5	c
Sappington	A	0-15	1.8	1.04	0.11	9.5	8.3	cl
Amesha	B	15-23	1.4	0.81	0.09	9.0	8.5	scl
	C	23-122	0.8	0.49	0.05	9.8	9.0	scl

Appendix Table 17. Summarized laboratory incubation data by soil horizon at 0°C (n=5).

Soil	Horizon		Week 2	4	6	8	10	12	
			ug g^{-1}						
Bozeman	A	NO_2-N	7.3	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	10.5	5.9	2.8	1.7	1.8	0.5	
		NH_4-N	4.1	1.5	0.4	0.2	0.4	0.1	Total
		Total	21.9	7.4	3.2	1.9	2.2	0.6	= 37.2
Bridger	A	NO_2-N	3.8	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	27.0	8.0	3.8	2.8	2.9	2.1	
		NH_4-N	0.2	0.2	0.4	0.3	0.4	0.1	Total
		Total	31.0	8.2	4.2	3.1	3.3	2.2	= 52.0
	B	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.0	0.0	0.0	0.4	0.2	0.0	
		NH_4-N	4.9	3.0	0.4	1.7	1.3	0.6	Total
		Total	4.9	3.0	0.4	2.1	1.5	0.6	= 12.5
	C	NO_2-N	0.3	0.1	0.0	0.0	0.0	0.0	
		NO_3-N	2.9	0.0	0.0	0.0	0.0	0.0	
		NH_4-N	2.6	1.0	0.0	1.1	0.9	0.2	Total
		Total	5.8	1.1	0.0	1.1	0.9	0.2	= 9.1
Sappington Amesha	A	NO_2-N	0.4	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	4.4	1.6	0.6	0.5	0.9	0.3	
		NH_4-N	0.0	0.2	0.3	0.1	0.2	0.0	Total
		Total	4.8	1.8	0.9	0.6	1.1	0.3	= 9.5
	B	NO_2-N	0.1	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NH_4-N	2.8	1.0	1.7	0.9	1.6	0.7	Total
		Total	2.9	1.0	1.7	0.9	1.6	0.7	= 8.8
	C	NO_2-N	0.0	0.1	0.0	0.0	0.0	0.0	
		NO_3-N	0.9	0.0	0.0	0.0	0.0	0.0	
		NH_4-N	1.5	1.0	0.2	0.9	0.8	0.3	Total
		Total	2.4	1.1	0.2	0.9	0.8	0.3	= 5.7

Appendix Table 17. Continued.

Soil	Horizon		Week 2	4	6	8	10	12	
			ug g^{-1}						
Scobey	A	NO_2-N	1.8	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	7.9	2.4	1.2	0.9	1.1	0.3	
		NH_4-N	0.1	0.2	0.4	0.2	0.3	0.1	Total
		Total	9.8	2.6	1.6	1.1	1.4	0.4	= 16.9
	B	NO_2-N	0.1	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.7	0.0	0.0	0.7	0.0	0.1	
		NH_4-N	1.3	1.4	1.2	1.0	1.4	0.6	Total
		Total	2.1	1.4	1.2	1.7	1.4	0.7	= 8.5
	C	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NH_4-N	0.1	1.2	0.4	0.3	1.5	0.1	Total
		Total	0.1	1.2	0.4	0.3	1.5	0.1	= 3.6
Williams	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.0	3.3	1.4	1.5	1.0	1.8	
		NH_4-N	2.2	0.4	0.0	1.3	1.5	0.0	Total
		Total	2.2	3.7	1.4	2.8	2.5	1.8	= 14.4
	B	NO_2-N	0.2	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NH_4-N	0.7	1.4	1.0	1.1	1.3	0.7	Total
		Total	0.9	1.4	1.0	1.1	1.3	0.7	= 6.4
	C	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.3	0.5	0.0	0.0	0.0	0.0	
		NH_4-N	0.2	0.6	0.0	0.0	0.0	0.0	Total
		Total	0.5	1.1	0.0	0.0	0.0	0.0	= 1.6

Appendix Table 18. Summarized laboratory incubation data by soil horizon at 14°C (n=5).

Soil	Horizon		Week 2	4	6	8	10	12	
			ug g^{-1}						
Bozeman	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	31.3	5.7	4.2	2.8	2.7	2.2	
		NH_4-N	0.0	0.1	0.4	0.1	0.2	0.0	Total
		Total	31.3	5.8	4.6	2.9	2.9	2.2	= 49.7
Bridger	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	47.1	9.0	7.4	5.9	5.8	5.9	
		NH_4-N	0.0	0.1	0.3	0.1	0.2	0.0	Total
		Total	47.1	9.1	7.7	6.0	6.0	5.9	= 81.8
	B	NO_2-N	0.5	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	4.6	4.6	2.1	1.9	2.0	1.3	
		NH_4-N	3.4	0.0	0.0	0.3	0.1	0.0	Total
		Total	8.5	4.6	2.1	2.2	2.1	1.3	= 20.8
	C	NO_2-N	0.5	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	3.6	3.6	1.6	1.5	1.7	1.0	
		NH_4-N	0.9	0.0	0.0	0.3	0.0	0.0	Total
		Total	5.0	3.6	1.6	1.8	1.7	1.0	= 14.7
Sappington Amesha	A	NO_2-N	0.2	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	7.5	3.3	3.1	2.5	2.7	2.2	
		NH_4-N	0.0	0.1	0.5	0.0	0.2	0.0	Total
		Total	7.7	3.4	3.6	2.5	2.9	2.2	= 22.3
	B	NO_2-N	0.8	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	6.2	7.5	6.1	6.1	4.5	2.0	
		NH_4-N	0.0	0.0	0.0	0.0	0.0	0.0	Total
		Total	7.0	7.5	6.1	6.1	4.5	2.0	= 33.2
	C	NO_2-N	0.0	0.1	0.0	0.0	0.0	0.0	
		NO_3-N	1.1	0.9	1.0	1.1	1.0	0.4	
		NH_4-N	1.4	0.2	0.0	0.6	0.0	0.0	Total
		Total	2.5	1.2	1.0	1.7	1.0	0.4	= 7.8

Appendix Table 18. Continued.

Soil	Horizon		Week 2	4	6	8	10	12	
			ug g^{-1}						
Scobey	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	14.4	4.1	3.2	2.5	2.4	2.2	
		NH_4-N	0.0	0.2	0.5	0.2	0.2	0.1	Total
		Total	14.4	4.3	3.7	2.7	2.6	2.3	= 30.0
	B	NO_2-N	0.2	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	8.5	8.4	5.9	4.9	4.6	2.8	
		NH_4-N	0.0	0.0	0.0	0.0	0.0	0.0	Total
		Total	8.7	8.4	5.9	4.9	4.6	2.8	= 35.3
	C	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	0.7	1.7	4.9	4.9	3.5	2.0	
		NH_4-N	0.0	0.0	0.0	0.0	0.0	0.0	Total
		Total	0.7	1.7	4.9	4.9	3.5	2.0	= 17.7
Williams	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	14.0	6.6	4.0	3.3	3.4	3.0	
		NH_4-N	0.0	0.0	0.0	0.6	0.2	0.0	Total
		Total	14.0	6.6	4.0	3.9	3.6	3.0	= 35.1
	B	NO_2-N	0.6	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	3.8	5.5	5.7	5.4	4.1	1.6	
		NH_4-N	0.0	0.0	0.0	0.0	0.0	0.0	Total
		Total	4.4	5.5	5.7	5.4	4.1	1.6	= 26.7
	C	NO_2-N	0.5	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	2.6	2.9	4.5	4.3	3.2	1.5	
		NH_4-N	0.0	0.0	0.0	0.0	0.0	0.0	Total
		Total	3.1	2.9	4.5	4.3	3.2	1.5	= 19.5

Appendix Table 19. Summarized laboratory incubation data by soil horizon at 28°C (n=5).

Soil	Horizon		Week 2	4	6	8	10	12	
			ug g^{-1}						
Bozeman	A	NO_2-N	0.8	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	44.8	15.9	7.5	7.7	7.2	7.0	
		NH_4-N	0.0	0.0	0.2	0.1	0.2	0.0	Total
		Total	45.6	15.9	7.7	7.8	7.4	7.0	= 91.4
Bridger	A	NO_2-N	1.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	78.8	28.5	18.3	22.1	25.1	38.6	
		NH_4-N	0.4	0.1	0.3	0.1	0.3	0.2	Total
		Total	80.2	28.6	18.6	22.2	25.4	38.8	= 213.8
	B	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	15.7	7.6	3.0	6.1	5.2	4.2	
		NH_4-N	1.3	0.0	0.0	0.0	0.5	0.0	Total
		Total	17.0	7.6	3.0	6.1	5.7	4.2	= 43.6
Sappington Amasha	A	NO_2-N	0.1	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	17.2	9.6	7.3	6.1	4.5	4.2	
		NH_4-N	0.1	0.0	0.4	0.0	0.1	0.1	Total
		Total	17.4	9.6	7.7	6.1	4.6	4.3	= 49.7
	B	NO_2-N	0.1	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	15.2	3.7	5.1	3.0	2.5	1.9	
		NH_4-N	0.0	0.5	0.0	0.0	1.7	0.0	Total
		Total	15.3	4.2	5.1	3.0	4.2	1.9	= 33.7
Scobey	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	22.0	10.3	6.5	5.9	4.3	4.2	
		NH_4-N	0.0	0.0	0.3	0.0	0.2	0.0	Total
		Total	22.0	10.3	6.8	5.9	4.5	4.2	= 53.2
	B	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	18.5	2.9	6.2	3.0	2.1	1.4	
		NH_4-N	0.0	0.0	0.0	0.0	0.5	0.0	Total
		Total	18.5	2.9	6.2	3.0	2.6	1.4	= 34.6

Appendix Table 19. Continued.

Soil	Horizon		Week 2	4	6	8	10	12	
			ug g^{-1}						
Scobey	C	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	4.2	3.2	4.6	2.5	2.3	1.6	
		NH_4-N	0.1	0.0	0.0	0.0	0.5	0.0	Total
		Total	4.3	3.2	4.6	2.5	2.8	1.6	= 19.0
Williams	A	NO_2-N	0.0	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	26.5	7.5	4.7	5.8	5.1	4.0	
		NH_4-N	0.0	0.0	0.0	0.0	0.6	0.0	Total
		Total	26.5	7.5	4.7	5.8	5.7	4.0	= 54.2
	B	NO_2-N	0.3	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	10.8	4.0	2.0	5.1	4.4	3.6	
		NH_4-N	0.0	0.0	0.0	0.0	0.7	0.0	Total
		Total	11.1	4.0	2.0	5.1	5.1	3.6	= 30.9
	C	NO_2-N	0.1	0.0	0.0	0.0	0.0	0.0	
		NO_3-N	2.1	0.0	0.0	0.0	0.0	0.0	
		NH_4-N	0.0	0.0	0.0	0.0	0.0	0.0	Total
		Total	2.2	0.0	0.0	0.0	0.0	0.0	= 2.2

Appendix Table 20. Listing of nitrogen mineralization computer model.

```
1000 ' Program RGG4
1010 ' Nitrogen Mineralization Model
1020 ' From Laboratory Incubation Data
1030 ' IBM-PC, 04-24-85
1040 :
1050 DIM TN(50),KPP(50)
1060 ' Enter Start and Ending Date
1070 CLS : PRINT
1080 INPUT "Enter Starting Julian Date: ";D1
1090 INPUT "Enter Ending Julian Date  : ";D2
1100 :
2000 ' Start Computation Loop
2010 ' starting, ending and step % OM's times 10
2020 OM1=18 : OM2=44 : OM3=2
2030 FOR I=D1 TO D2
2040     'Generate soil temperature in Celsius
2050     T=30.5-(.401*I)+(.00939*(I^2))-(.0000417*(I^3))+(3.22E-08*(I^4))
2060     T=(T-32)*.55556
2070     FOR J=OM1 TO OM2 STEP OM3
2080             'NMIN is daily kg N, TN(J) is total kg at each %
2090             NMIN=(.28*(J/10))+(.03*T)-.25
2100             TN(J)=TN(J)+NMIN
2110     NEXT J
2120 NEXT I
2130 :
2140 ' Calculate Kg N/% OM
2150 FOR J=OM1 TO OM2 STEP OM3
2160     KPP(J)=TN(J)/(J/10)
2170     KA=KA+KPP(J)
2180 NEXT J
2190 KA=KA/(((OM2-OM1)/OM3)+1)
2200 :
2210 :
4000 ' Screen Output
4010 CLS
4020 PRINT
4030 PRINT TAB(10);"NITROGEN MINERALIZATION"
4040 PRINT TAB(10);"DAY ";D1;" THROUGH ";D2
4050 PRINT : PRINT
4060 PRINT "     %OM     Kg N/ha     Kg N/% OM"
4070 PRINT "     ____     _______     _________"
4080 FOR J=OM1 TO OM2 STEP OM3
4090     PRINT USING "     #.#      ###.#        ##.##";J/10;TN(J);KPP(J)
4100 NEXT J
4110 A$="AVERAGE Kg per % OM = "
4120 PRINT : PRINT USING "     & ##.##";A$;KA
4130 :
4140 ' Printer Output
4150 LPRINT TAB(5);"NITROGEN MINERALIZATION MODEL"
4160 LPRINT TAB(15);"RGG3"
4170 LPRINT
4180 LPRINT TAB(5);"DAY ";D1;" THROUGH ";D2
4190 LPRINT : LPRINT
4200 LPRINT "    %OM     KG N/HA     KG N/% OM"
4210 LPRINT "    ____     _______     _________"
4220 FOR J=OM1 TO OM2 STEP OM3
4230    LPRINT USING "    #.#     ###.#         ##.##";J/10;TN(J);KPP(J)
4240 NEXT J
4250 LPRINT : LPRINT USING "    & ##.## ";A$;KA
```

Appendix Table 21. Nitrogen mineralization data from field incubations by 10 cm depth increments (n=3).

Site	1983 Julian Date	Depth (cm) NH_4-N 0-10	NH_4-N 10-20	NH_4-N 20-30	NO_3-N 0-10	NO_3-N 10-20	NO_3-N 20-30
		kg ha^{-1}					
H	142	4.0	3.0	3.1	3.0	7.9	17.4
H	152	5.1	4.6	3.6	5.5	7.6	14.4
H	159	5.4	4.6	4.5	6.4	9.4	14.6
H	166	3.4	4.5	3.2	8.3	10.0	14.1
H	173	8.0	5.1	5.4	6.3	9.5	16.7
H	180	3.4	3.6	3.6	6.8	10.7	14.6
H	187	4.9	5.4	3.9	11.9	15.0	24.9
H	194	2.7	2.5	2.2	13.1	14.3	20.7
H	201	4.9	4.2	4.6	13.0	16.5	21.3
H	208	4.2	4.5	6.0	15.3	13.4	20.7
H	215	5.7	5.5	5.5	22.8	20.4	21.5
H	222	8.5	8.0	7.9	20.7	18.2	21.0
H	229	4.2	4.3	7.1	21.6	19.2	20.7
H	236	4.8	3.6	6.0	32.8	21.7	21.6
H	243	4.8	6.3	4.9	27.0	24.7	19.8
H	250	6.3	5.8	4.8	22.9	18.5	17.7
H	257	5.1	4.8	4.5	27.9	22.6	22.9
J	141	5.2	4.5	4.2	4.8	4.1	5.8
J	152	7.1	5.8	4.2	8.6	7.9	8.9
J	159	6.8	5.7	5.1	10.1	9.8	10.9
J	166	5.7	4.5	3.6	9.7	9.5	11.3
J	173	8.2	6.7	5.7	8.9	8.8	9.1
J	180	6.6	5.5	5.2	10.4	10.7	11.0
J	187	8.6	6.7	6.0	18.5	15.2	14.0
J	194	3.7	2.7	2.2	21.2	15.9	13.9
J	201	6.0	5.7	3.7	18.3	11.9	15.0
J	208	5.8	5.1	4.5	22.9	17.1	14.9
J	215	9.8	7.4	7.3	32.2	22.3	17.1
J	222	9.5	9.2	7.3	28.2	21.6	15.9
J	229	5.1	4.8	4.6	29.2	22.3	17.6
J	236	5.2	6.6	5.2	34.6	21.7	12.8
J	243	7.6	6.2	6.0	23.5	18.5	15.2
J	250	5.4	5.7	4.2	40.4	26.5	17.7
J	257	7.6	6.4	5.1	33.8	27.3	21.6

Appendix Table 21. Continued.

Site	1983 Julian Date	Depth (cm)					
		NH_4-N			NO_3-N		
		0-10	10-20	20-30	0-10	10-20	20-30
		kg ha^{-1}					
M	152	3.6	2.7	3.3	3.0	1.5	0.4
M	159	5.5	4.8	4.8	7.7	7.3	7.3
M	166	4.5	3.9	3.6	6.7	6.6	5.8
M	173	5.8	5.8	5.1	3.4	3.3	3.0
M	180	4.0	4.2	4.0	3.3	3.1	3.3
M	187	5.5	5.5	4.3	4.2	4.5	4.2
M	194	2.7	2.2	2.2	4.6	4.3	4.3
M	201	4.9	5.2	5.1	4.8	4.2	3.1
M	208	4.5	1.9	1.9	4.0	4.3	2.8
M	215	6.3	7.7	7.4	11.6	8.9	8.2
M	222	7.4	7.1	7.0	7.3	7.1	4.8
M	229	6.4	6.0	6.4	13.7	10.3	9.1
M	236	5.8	5.7	4.8	8.2	8.2	6.1
M	243	7.9	7.0	8.9	23.2	13.1	9.8
M	250	6.6	7.6	7.4	19.7	14.3	8.5
M	257	7.6	5.5	6.6	7.3	12.7	17.0

Appendix Table 21. Continued.

Site	1984 Julian Date	Depth (cm) NH_4-N 0-10	NH_4-N 10-20	NH_4-N 20-30	NO_3-N 0-10	NO_3-N 10-20	NO_3-N 20-30
		kg ha^{-1}					
H	144	1.6	0.9	0.7	4.2	5.2	5.7
H	151	2.4	1.6	1.0	1.2	2.2	1.5
H	158	4.2	3.3	3.1	4.9	5.2	6.7
H	165	2.4	1.8	2.2	5.8	6.3	8.0
H	172	3.1	3.1	2.7	5.5	5.2	6.8
H	179	6.2	4.8	5.1	7.4	6.8	6.1
H	186	6.7	6.2	6.4	4.3	4.8	3.9
H	193	4.2	3.6	3.4	10.0	7.6	8.8
H	200	3.6	3.0	3.1	9.7	10.9	9.4
H	207	6.4	5.5	5.4	20.3	19.8	9.4
H	214	3.6	3.3	3.3	13.6	16.4	15.0
H	221	4.9	4.6	4.3	20.4	15.8	13.7
H	228	4.5	5.2	4.9	16.7	16.8	13.8
H	235	3.7	4.2	3.3	17.9	18.0	18.5
H	242	7.3	6.1	7.0	40.7	24.7	21.7
H	249	23.7	14.9	18.9	29.2	25.0	22.3
J	151	4.0	2.8	2.7	8.1	3.6	6.7
J	158	5.5	4.2	3.4	13.1	11.0	15.0
J	165	4.3	2.7	2.6	14.9	10.9	13.0
J	172	3.1	3.1	3.1	10.1	10.4	11.3
J	179	6.0	6.7	5.7	12.2	8.9	10.4
J	186	7.7	7.3	6.2	15.2	12.4	11.5
J	193	5.2	3.9	4.0	14.1	11.3	15.5
J	200	6.7	4.5	4.6	14.6	11.9	14.0
J	207	6.4	6.4	4.6	23.8	20.4	21.2
J	214	5.8	3.9	4.0	21.5	13.4	14.0
J	221	5.2	3.9	4.2	17.9	19.5	20.3
J	228	6.8	6.0	4.8	21.3	17.3	21.2
J	235	6.0	3.2	2.8	22.2	22.6	25.9
J	242	9.1	6.8	7.7	20.9	23.2	26.7
J	249	13.6	9.2	9.4	22.3	22.5	33.2

Appendix Table 21. Continued.

Site	1984 Julian Date	Depth (cm) Nh_4-N 0-10	Nh_4-N 10-20	Nh_4-N 20-30	NO_3-N 0-10	NO_3-N 10-20	NO_3-N 20-30
		kg ha^{-1}					
M	137	2.8	3.0	2.2	17.4	27.4	25.9
M	144	2.4	1.3	1.2	20.9	29.8	32.8
M	151	2.4	1.8	1.2	12.5	22.3	25.9
M	158	5.8	4.2	3.0	29.3	37.1	40.4
M	165	3.0	2.1	2.2	26.8	28.2	33.5
M	172	4.9	5.4	4.9	26.1	27.0	30.8
M	179	5.2	5.1	3.9	23.8	28.3	30.8
M	186	5.2	4.3	10.6	26.7	26.4	26.7
M	193	4.8	3.7	4.9	34.6	26.7	31.9
M	200	5.8	7.8	5.1	21.7	25.5	33.5
M	207	7.1	6.7	6.1	41.4	27.7	32.3
M	214	4.0	3.7	3.7	37.4	32.3	32.6
M	221	7.9	5.7	6.0	42.2	30.7	33.2
M	228	4.6	4.0	4.0	43.8	31.9	35.9
M	235	3.0	2.7	2.7	69.7	34.0	33.2
M	242	8.6	9.7	5.7	53.9	34.9	34.9
M	249	14.4	15.6	14.4	54.4	44.2	49.3
R	133	2.8	3.0	3.3	19.8	24.1	29.2
R	137	1.6	2.1	3.0	15.5	25.0	28.8
R	144	1.5	1.8	1.6	24.7	26.8	33.4
R	151	2.4	2.2	2.2	29.9	39.3	33.7
R	158	3.6	4.3	3.7	23.2	36.1	43.7
R	165	3.7	3.6	3.6	20.9	30.2	36.1
R	172	5.7	4.9	5.1	25.0	28.6	33.5
R	179	4.3	4.5	4.3	24.1	26.8	30.8
R	186	4.9	4.6	4.2	25.8	29.8	32.9
R	193	3.1	3.1	3.7	28.6	32.0	31.1
R	200	3.6	3.4	3.9	30.7	33.8	29.9
R	207	6.6	5.5	4.0	30.7	21.2	32.5
R	214	3.9	3.9	4.6	27.6	31.6	33.2
R	221	4.8	4.6	4.6	37.7	35.6	31.0
R	228	3.6	3.9	3.6	40.5	35.2	30.1
R	235	3.1	2.1	2.9	37.1	31.0	28.0
R	242	6.2	7.9	9.1	34.4	37.5	30.2
R	249	10.7	11.8	14.4	34.4	34.3	35.5

Appendix Table 22. Nitrogen mineralization data from field incubations by 10 cm depth increments (n=3), total of NH_4-N and NO_3-N.

1983 Julian Date	Total Mineral N					
	Site H			Site J		
	Depth (cm)			Depth (cm)		
	0-10	10-20	20-30	0-10	10-20	20-30
	kg ha^{-1}					
141	7.0	10.9	20.5	10.0	8.6	10.0
152	10.6	12.2	18.0	15.7	13.7	13.1
159	11.8	14.0	19.1	16.9	15.5	16.0
166	11.7	14.5	17.3	15.4	14.0	14.9
173	14.3	14.6	22.1	17.1	15.5	14.8
180	10.2	14.3	18.2	17.0	16.2	16.2
187	16.8	20.4	28.8	27.1	21.9	20.0
194	15.8	16.8	22.9	24.9	16.6	16.1
201	17.9	20.7	25.9	24.3	17.6	18.7
208	19.5	17.9	26.7	28.7	22.2	19.4
215	28.5	25.9	27.0	42.0	29.7	24.4
222	29.2	26.2	28.9	37.7	30.8	23.2
229	25.8	23.5	27.8	34.3	27.1	22.2
236	37.6	25.3	27.6	39.8	28.3	18.0
243	31.8	31.0	24.7	31.1	24.7	21.2
250	29.2	24.3	22.5	45.8	32.2	21.9
257	23.0	27.4	27.4	41.4	33.7	26.7
	Site M					
152	6.6	4.2	3.7			
159	13.2	12.1	12.1			
166	11.2	10.5	9.4			
173	9.2	9.1	8.1			
180	7.3	7.3	7.3			
187	9.7	10.0	8.5			
194	7.3	6.5	6.5			
201	9.7	9.4	8.2			
208	8.5	6.2	4.7			
215	17.9	16.6	15.6			
222	14.7	14.2	11.8			
229	20.1	16.3	15.5			
236	14.0	13.9	10.9			
243	31.1	20.1	18.7			
250	21.3	21.9	15.9			
257	14.9	18.2	23.6			

Appendix Table 22. Continued.

1984 Julian Date	Total Mineral N					
	Site H			Site J		
	Depth (cm)			Depth (cm)		
	0-10	10-20	20-30	0-10	10-20	20-30
	kg ha^{-1}					
140	10.0	7.1	8.9			
144	5.8	6.1	6.4			
151	3.6	3.8	2.5	12.1	6.4	9.4
158	9.1	8.5	9.8	18.6	15.2	18.4
165	8.2	8.1	10.2	19.2	11.6	15.6
172	8.6	8.3	9.5	13.2	13.5	14.4
179	13.6	11.6	11.2	18.2	15.6	16.1
186	11.0	11.0	10.3	22.9	19.7	17.7
193	14.2	11.2	12.2	19.3	15.2	19.5
200	13.3	13.9	12.5	21.3	16.4	18.6
207	26.7	25.3	14.8	30.2	26.8	25.8
214	17.2	19.7	18.3	27.3	17.3	18.0
221	25.3	20.4	18.0	23.1	23.4	24.5
228	21.2	22.0	18.7	28.1	23.3	26.0
235	21.6	22.2	21.8	28.2	25.8	28.7
242	48.0	30.8	28.7	30.0	30.0	34.4
249	52.9	39.9	41.2	35.9	31.7	42.6
	Site M			Site R		
132	21.4	33.8	39.6			
133				22.6	27.1	32.5
137	20.2	30.4	28.1	17.1	27.1	31.8
144	23.3	31.1	34.0	26.2	28.6	35.0
151	14.9	24.1	27.1	32.3	41.5	35.9
158	35.1	41.3	43.7	26.8	40.4	47.4
165	29.8	30.3	35.7	24.6	33.8	39.7
172	31.0	32.4	35.7	30.7	33.5	38.6
179	29.0	33.4	34.7	28.4	31.3	35.1
186	31.9	30.7	37.3	30.7	34.4	37.1
193	39.4	30.4	36.8	31.7	35.1	34.8
200	27.5	33.3	38.6	34.3	37.2	34.8
207	48.5	34.4	38.4	37.3	26.7	36.5
214	41.4	36.0	36.3	31.5	35.5	37.8
221	50.1	36.4	39.2	42.5	40.2	35.6
228	48.4	35.9	39.9	44.1	39.1	33.7
235	72.7	36.7	35.9	40.2	33.1	30.9
242	62.5	44.6	40.6	40.6	35.4	39.3
249	68.8	59.8	63.7	45.1	46.1	49.9

Appendix Table 23. Summary of mean weekly air temperatures (AIRTC) derived from Helena Airport climatological data for 1983 and 1984 by Julian Date.

1983 Julian Date	SITE	AIRTC °C	1983 Julian Date	SITE	AIRTC °C
141	H	17.8	141	J	17.8
152	H	26.1	152	J	26.1
159	H	22.7	159	J	22.7
166	H	21.7	166	J	21.7
173	H	20.9	173	J	20.9
180	H	24.6	180	J	24.6
187	H	24.3	187	J	24.3
194	H	27.4	194	J	27.4
201	H	24.9	201	J	24.9
208	H	28.1	208	J	28.1
215	H	31.1	215	J	31.1
222	H	32.9	222	J	32.9
229	H	29.0	229	J	29.0
236	H	26.0	236	J	26.0
243	H	29.7	243	J	29.7
250	H	24.4	250	J	24.4
257	H	20.6	257	J	20.6
152	M	25.3			
159	M	22.7			
166	M	21.7			
173	M	20.9			
180	M	24.6			
187	M	24.3			
194	M	27.4			
201	M	24.9			
208	M	28.1			
215	M	31.1			
222	M	32.9			
229	M	29.0			
236	M	26.0			
243	M	29.7			
250	M	24.4			
257	M	20.6			

Appendix Table 23. Continued.

1984 Julian Date	SITE	AIRTC °C	1984 Julian Date	SITE	AIRTC °C
140	H	21.5			
144	H	16.9			
151	H	21.2	151	J	21.2
158	H	18.4	158	J	18.4
165	H	17.5	165	J	17.5
172	H	24.2	172	J	24.2
179	H	25.0	179	J	25.0
186	H	29.0	186	J	29.0
193	H	29.5	193	J	29.5
200	H	30.9	200	J	30.9
207	H	28.6	207	J	28.6
214	H	30.1	214		30.1
221	H	30.6	221	J	30.6
228	H	32.1	228	J	32.1
235	H	29.9	235	J	29.9
242	H	28.3	242	J	28.3
249	H	24.1	249	J	24.1
132	M	18.0	133	R	17.5
137	M	21.5	137	R	21.7
144	M	19.0	144	R	19.0
151	M	21.2	151	R	21.2
158	M	18.4	158	R	18.4
165	M	17.5	165	R	17.5
172	M	24.2	172	R	24.2
179	M	25.0	179	R	25.0
186	M	29.0	186	R	29.0
193	M	29.5	193	R	29.5
200	M	30.9	200	R	30.9
207	M	28.6	207	R	28.6
214	M	30.1	214	R	30.1
221	M	30.6	221	R	30.6
228	M	32.1	228	R	32.1
235	M	29.9	235	R	29.9
242	M	28.3	242	R	28.3
249	M	24.1	249	R	24.1

Appendix Table 24. Summary of weekly soil temperatures (SOILT10, SOILT20, SOILT50) measured at each site in 1983 and 1984 by Julian Date.

Site	1983 Julian Date	SOILT10	SOILT20	SOILT50
			°C	
H	141	19.0	13.0	9.0
H	152	23.0	20.0	16.0
H	159	24.5	18.5	16.0
H	166	15.0	14.0	14.0
H	173	22.0	15.5	13.0
H	180	16.0	15.5	15.0
H	187	25.0	20.5	15.0
H	194	24.0	18.5	16.0
H	201	20.0	18.5	16.0
H	208	19.5	19.0	18.0
H	215	28.0	21.0	19.0
H	222	21.0	21.0	20.5
H	229	25.0	20.5	19.0
H	236	22.0	18.0	18.0
H	243	22.0	19.0	17.0
H	250	20.5	16.0	15.5
H	257	14.0	13.0	14.5
J	141	19.0	13.0	8.5
J	152	21.0	18.0	14.0
J	159	24.0	18.0	14.0
J	166	15.0	13.5	13.0
J	173	23.0	15.5	12.5
J	180	17.0	15.0	14.5
J	187	24.5	21.0	15.0
J	194	25.0	19.0	15.5
J	201	22.0	18.0	16.0
J	208	20.0	19.0	18.0
J	215	29.0	22.0	19.0
J	222	23.0	21.0	19.5
J	229	28.0	21.0	19.0
J	236	25.0	18.0	16.5
J	243	26.0	20.0	16.5
J	250	23.0	17.0	15.0
J	257	16.0	14.0	13.0

Appendix Table 24. Continued.

Site	1983 Julian Date	SOILT10	SOILT20	SOILT50
			°C	
M	152	20.5	18.5	15.0
M	159	24.0	19.0	16.0
M	166	16.0	14.5	14.0
M	173	21.0	16.0	13.0
M	180	16.5	16.0	15.5
M	187	24.0	21.0	16.0
M	194	26.0	20.0	16.0
M	201	22.0	20.0	17.0
M	208	19.0	18.5	19.0
M	215	24.0	20.5	19.5
M	222	20.5	21.0	20.5
M	229	24.5	20.5	19.5
M	236	22.5	19.0	18.0
M	243	25.0	20.5	18.0
M	250	20.5	16.5	16.0
M	257	13.5	14.0	15.0

Site	1984 Julian Date	SOILT10	SOILT20	SOILT50
			°C	
H	140	14.0	12.0	10.0
H	144	10.0	11.0	10.0
H	151	18.0	15.0	11.5
H	158	11.0	12.0	12.5
H	165	12.0	11.5	11.5
H	172	16.0	15.0	14.0
H	179	16.0	16.0	15.5
H	186	19.5	19.0	17.0
H	193	23.0	20.0	19.0
H	200	22.0	22.0	20.0
H	207	22.5	20.0	19.0
H	214	20.5	20.0	19.5
H	221	22.0	20.0	19.5
H	228	19.5	19.5	19.0
H	235	17.0	18.0	19.5
H	242	15.5	16.0	17.5
H	249	14.5	14.0	16.0

Appendix Table 24. Continued.

Site	1984 Julian Date	SOILT10	SOILT20	SOILT50
			°C	
J	151	18.0	14.0	9.0
J	158	12.5	12.5	10.5
J	165	14.0	12.0	10.0
J	172	17.5	16.0	13.0
J	179	14.0	17.0	13.5
J	186	21.0	19.0	15.5
J	193	24.0	20.0	16.0
J	200	22.5	21.0	17.0
J	207	24.0	20.0	16.0
J	214	22.5	20.0	17.0
J	221	24.0	19.5	17.0
J	228	21.0	19.0	17.0
J	235	17.0	18.0	19.5
J	242	15.5	16.0	17.5
J	249	14.5	14.0	16.0
M	132	16.0	15.0	13.5
M	137	10.0	11.0	10.5
M	144	11.0	13.0	11.0
M	151	20.0	18.0	12.5
M	158	10.0	13.0	13.0
M	165	12.0	13.0	12.0
M	172	15.0	16.0	14.5
M	179	17.0	17.0	15.0
M	186	19.0	19.0	16.0
M	193	22.5	19.5	16.5
M	200	21.0	22.0	19.0
M	207	21.0	21.0	17.5
M	214	22.5	21.0	18.0
M	221	22.0	21.0	19.0
M	228	25.0	21.0	20.0
M	235	17.0	18.0	19.5
M	242	15.5	16.0	17.5
M	249	14.5	14.0	16.0

Appendix Table 24. Continued.

Site	1984 Julian Date	SOILT10	SOILT20	SOILT50
			°C	
R	133	16.0	12.5	9.0
R	137	10.0	10.0	11.0
R	144	11.0	12.0	11.0
R	151	19.0	16.0	12.0
R	158	10.0	11.5	12.0
R	165	11.5	11.5	11.0
R	172	14.5	14.0	13.5
R	179	16.0	16.0	14.0
R	186	18.0	17.0	15.5
R	193	23.0	19.0	16.0
R	200	19.5	21.0	18.5
R	207	21.0	20.0	17.5
R	214	22.0	19.0	18.0
R	221	23.0	19.0	18.0
R	228	27.0	23.0	21.5
R	235	18.0	16.5	16.0
R	242	16.0	14.0	15.0
R	249	14.0	12.0	13.0

Appendix Table 25. Multiple linear regression model with NH4T as the dependent variable, "best" 8 variables.

	DF	R2	F
Regression	8	0.310	6.13
Error	109		
Total	117		

Variable	b Value	Standard Error	
Intercept	19.57		
SITE	0.04	0.373	0.01
WEEK	0.84	0.204	16.81
AIRTC	-0.15	0.336	0.20
SOILT10	0.11	0.301	0.14
SOILT20	-0.48	0.729	0.43
SOILT50	0.25	0.655	0.14
OM	9.86	5.485	3.23
N	-195.87	131.582	2.22