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Estimating Potential Ground and Surface Water Pollution from Land Application of Poultry Litter

J. T. Gilmour
University of Arkansas, Fayetteville

D. C. Wolf
University of Arkansas, Fayetteville

P. M. Gale
University of Arkansas, Fayetteville

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ESTIMATING POTENTIAL GROUND AND SURFACE WATER POLLUTION FROM LAND APPLICATION OF POULTRY LITTER

J.T. Gilmour, D.C. Wolf and P.M. Gale
Department of Agronomy

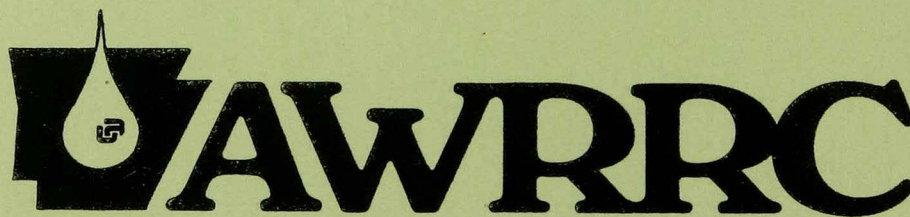
University of Arkansas
Fayetteville, AR 72701

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J.T. Gilmour, D.C. Wolf, and P.M. Gale
Department of Agronomy
University of Arkansas
Fayetteville, AR 72701

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Arkansas Water Resources Research Center
University of Arkansas
223 Ozark Hall
Fayetteville, Arkansas 72701

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A B S T R A C T

ESTIMATING POTENTIAL GROUND AND SURFACE WATER POLLUTION FROM LAND APPLICATION OF POULTRY LITTER

In 1985, more than 750 million broiler chickens were produced in Arkansas. During the same year over 15 million laying chickens produced 3.6 million eggs. The waste products of these agricultural production systems, poultry litter and manure, were about 1 million metric tons. As a result of land application of these wastes, about 5,000 metric tons of ammonium N and 12,000 metric tons of mineralized nitrogen were applied to Arkansas pastures in 1985. Manures contributed about 2-3 percent of the total. The objective of this research was to quantify major components of the nitrogen cycle which influence the ground and surface water pollution potential and the proper use of poultry or hen manure in a land application program. Both decomposition and N mineralization of representative samples of surface applied hen manure were evaluated. During the decomposition, N mineralization followed two patterns. Initially, N mineralization was rapid and the mineralized N plus initial inorganic N was converted to volatile ammonia and lost to the atmosphere. Later, one of two scenarios appeared to be operative. If nitrification and denitrification were small, then N immobilization likely occurred at a rate near that of N mineralization resulting in only small increases in inorganic N. Undigested feed was suggested as the immobilizing agent. If nitrification and denitrification were large, then N mineralization could have proceeded at expected rates and would not be measured by the methods employed herein. In a practical vein, the initial inorganic N and mineralized N in surface applied hen manure has a low N fertilizer value and water pollution potential due to volatilization of N. If the manure is incorporated or a rainfall event occurs soon after surface addition, more than 50 percent of the manure N could be available for plant uptake and contamination of ground and surface waters.

J.T. Gilmour, D.C. Wolf, and P.M. Gale

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INTRODUCTION

In 1985, more than 750 million broiler chickens were produced in Arkansas. During the same year over 15 million laying chickens produced 3.6 million eggs. The waste products of these agricultural production systems, poultry litter and manure, were about 1 million metric tons. Most of the litter was applied to pasture land directly as fertilizer or indirectly through cattle feeding programs. Since a typical litter contains 0.5% ammonium N and 4% organic N and about 30% of the organic N is mineralized during the first month after application, about 5,000 metric tons of ammonium N and 12,000 metric tons of mineralized nitrogen were applied to Arkansas pastures in 1985. Manures contributed about 2-3 percent of the total mineralized N as they contain similar amounts of organic N and approximately 4 times the amount of ammonium N.

The nitrogen applied to pastures can be nitrified and enter both ground and surface water supplies as the mobile and potentially harmful form of nitrogen, nitrate N. In situations where the amount of litter or manure applied is higher than pasture requirements and weather patterns facilitate runoff and leaching, nitrate contamination of ground and surface waters is possible. In addition, high rates of poultry litter or manure can be toxic to pasture grasses. An understanding of the components of the nitrogen cycle which are operative in a land application program

is a prerequisite to proper management of these valuable resources.

A. Purpose and Objectives

The objective of this research was to quantify major components of the nitrogen cycle which influence the ground and surface water pollution potential and the proper use of poultry or hen manure in a land application program. Three subobjectives were to determine: a) the amount of inorganic N released from manure by decomposition, b) the proportion of the inorganic N volatilized or lost to the atmosphere, and c) the proportion of the inorganic N nitrified or converted to nitrate N.

B. Related Research and Activities

Poultry litter has long been recognized as a valuable fertilizer source. Hileman (1973) conducted extensive work in Arkansas comparing broiler litter to commercial fertilizers. Perkins et al. (1964), working in Georgia, evaluated the composition and fertilizer value of poultry litter. Both studies concluded that poultry litter was an important source of plant nutrients which included N, P, and K. Siegal et al. (1975) also pointed out the fertilizer value of poultry litter, but cautioned that the application rate should be such that uric acid toxicity to pasture plants does not occur. Hileman (1965) verified this toxicity as fescue yields were reduced at high rates of poultry litter application.

Other studies have characterized the mineralization of N from poultry manure or litter. Castellanos and Pratt (1981) found a relationship between the N released during 10 weeks incubation and the CO_2 evolved during 4 weeks for poultry manure. Gale and Gilmour (1986) extended this relationship between N mineralization and C mineralization for poultry litter over the entire decomposition period. Hadas et al. (1983) reported N mineralization from poultry litter as a two phase, first order kinetic process. Both Castellanos and Pratt (1981) and Hadas et al. (1983) found a majority of N mineralization occurred during the first day of decomposition. Gale and Gilmour (1986) substantiated this rapid conversion of organic N to ammonium N. Schefferle (1965) found that decomposition of uric acid in poultry manure was rapid and likely contributed to volatile losses of ammonia.

Data from Castellanos and Pratt (1981) showed 33% in the first or rapid phase of N mineralization. Hadas et al. (1983) reported from 30 to 47 percent of mineralizable N in the rapid phase. Gale and Gilmour (1986) found that about 40 percent of the litter organic N was mineralized over a 34 d period.

Castellanos and Pratt (1981) presented data from which first order rate constants were calculated for chicken manure decomposition. In their study at 30 C k values were 0.06, 0.01, and 0.005 d^{-1} for 0-7, 7-14, and 14-28 d periods, respectively. Gale and Gilmour (1986) reported first order rate constants of 0.046

and 0.019 d^{-1} for rapid and intermediate fractions of poultry litter, respectively. Hadas et al. (1983) reported rate constants for a two phase N mineralization process for ground poultry litter at 25 C. The first phase rate constant was computed prior to the first data point and appeared to be an unreasonably large value. The second, slower phase rate constant ranged from 0.013 to 0.78 d^{-1} .

Nitrification has been shown to depend upon the availability of substrate, O_2 , CO_2 , soil water and adequate temperature (Schmidt, 1982), while conditions for loss of nitrate are usually dependent upon periods of high soil moisture where nitrate leaching and/or denitrification occur (Tanji, 1982). Gilmour (1984) presented a model of the nitrification process which used zero order kinetics and corrected rate for temperature, moisture and initial ammonium concentration.

Nitrification has been shown to occur in poultry manure. Giddens and Rao (1975) found nitrate in both surface applied and incorporated manure. The nitrate concentrations were higher in the incorporated case. Hadas et al. (1983) also found nitrification when pelleted poultry manure was incorporated into soil. Nitrification occurred over the 90 d period of their study and followed zero order kinetics during the first month after an initial lag period of a few days. After the first month, a second slower zero rate of nitrification was reported. Gale and Gilmour

(1986) found nitrification to be small for poultry litter applied to the surface of the soil.

When soil is amended with poultry litter or manure and subjected to excessive rainfall, losses of nitrogen likely occur via denitrification. Meek et al. (1974) reported that annual additions of feedlot manure appeared to result in substantial denitrification which was caused by higher levels of soluble organic carbon being added to the soil. Their data indicated that as the nitrate and soluble organic carbon moved to a depth of 80 cm in the soil, conditions were favorable for reduction of the nitrate to nitrogen gas. Gilbertson and Norstadt (1979) indicated that denitrification losses from poultry manure were 35, 20, 10, and 0 percent for clay, clay loam, silt loam, and sandy soil textures, respectively, and suggested that manure application rates should be increased to compensate for denitrification losses.

In addition to loss of nitrogen in the form of nitrate, the nitrogen contained in poultry litter may be lost in the form of ammonia which can be volatilized and lost to the atmosphere. Giddens and Rao (1975) reported that poultry manure lost 47.6% of the total nitrogen upon air-drying for 10 days. They suggested that hydrolysis of uric acid in the manure played a major role in determining the rate of ammonia volatilization and that rapid drying of the poultry manure would reduce the amount of ammonia lost by volatilization but would increase the amount of nitrate

formed in the soil. Adriano et al. (1974) suggested that ammonia volatilization from surface-applied manure represented a significant avenue of nitrogen loss. Their results indicated that ammonia loss was greater in a saturated soil at 25 C than in the same soil at 10 C and a lower moisture content. In a series of five field experiments, Lauer et al. (1976) measured the amount of ammonia volatilization from surface-applied dairy manure and reported that 61 to 99 percent of the total ammoniacal nitrogen in the manure was lost as ammonia volatilized. They also noted that ammonia volatilization was greatest when the environmental conditions led to sustained drying of the manure.

Various soil conditions would also be expected to be important in determining the amount and rate of ammonia volatilization from poultry manure or litter. Increased pH has been shown to increase ammonia volatilization from sewage sludge (Donovan and Logan, 1983). Fenn and Kissel (1976) showed decreased ammonia volatilization with increased soil cation exchange capacity. Ryan and Keeney (1975) reported ammonia volatilized from wastewater sludge ranged from 20 to 56 percent of the applied ammoniacal nitrogen on a clay loam with a cation exchange capacity of 41.1 $\text{cmol H}^+ \text{kg}^{-1}$ and a sand with a cation exchange capacity of 4.2 $\text{cmol H}^+ \text{kg}^{-1}$, respectively. Recently, Ferguson et al. (1984) concluded that ammonia volatilization from urea was related more directly to the hydrogen ion buffering capacity of a soil rather

than to the initial soil pH.

No studies on the decomposition and N mineralization characteristics for hen manure from a laying operation were found in the literature.

METHODS AND PROCEDURES

Twenty samples of fresh hen manure were collected at Hope, Arkansas and frozen. Subsamples of each were dried and analyzed for total N using a modified Kjeldahl technique. From these data six of the manures were selected to give a range in TKN values. These six manure samples were then used for all subsequent analyses. Soil was collected from the Ap horizon of a Bowie fine sandy loam (fine-loamy, siliceous, thermic Fragic Paleudult). The soil was wet sieved through a 2-mm sieve to remove small stones and plant material. The sieved soil was kept in a closed container at field moisture content (0.11 g kg^{-1}) prior to the incubations.

Selected physical and chemical properties of the soil and manures were determined and these data are presented in Table 1. The methods used for these analyses included total C by dry combustion (Nelson and Sommers, 1982) and total Kjeldahl N using the salicylic acid modification of Bremner and Mulvaney (1982). Inorganic-N was determined following the procedures of Keeney and Nelson (1982) by steam distillation of a 2 M KCl extract of the soil or manure. Total

Table 1. Selected physical and chemical properties of soil and hen manure.

Property	Soil	Manure
Total C	7.8 (0.071)*	328 (5.43)
Organic N	0.8 (0.003)	38 (2.22)
NH ₄ -N	0.005 (0.003)	19 (1.27)
NO ₃ -N	0.045 (0.005)	0 (0.06)
Water content	83.0 (2.47)	670 (10.9)
C/N**	9.8	8.4
pH (1:1)	5.9	8.1

* Standard error

** Organic fraction

organic N was obtained by subtracting the initial inorganic N from the total Kjeldahl N. The pH of the soil and manure was measured in a 1:2 mixture with water. Mechanical analysis of the soil was accomplished by the hydrometer method (Day, 1965), and the particle size distribution was 63% sand, 26% silt, and 11% clay.

The experimental design was based on that of Clark and Gilmour (1983). The equivalent of 100 g air dry soil was added to 500 mL soil respiration vessels. The bottles were placed on their sides. The soil surface area was 80 cm² and the depth of the soil was < 1 cm. The wet manure, 13.7 g, was spread over the soil surface as evenly as possible. This rate of addition was approximately equal to 5.5 Mg dry manure ha⁻¹. The soil moisture potential was adjusted to -34 kPa, which corresponded to 50% of the water holding capacity (Pramer and Schmidt, 1964). Controls consisted of vessels containing soil only. All incubations were conducted at 25 C for 60 d and replicated 3 times.

A flow-through system was used to collect CO₂ and NH₃ evolved during decomposition. A flow meter regulated the air flow through the system at 0.8 mL s⁻¹. Inlet air passed through a scrubber containing 4 L of 4 M NaOH, into a distilled water scrubber, and into manifolds which distributed the air over the samples. Traps at the outlet of the

vessels contained 10 mL of 2 M NaOH or 10 mL of 1 M H₂SO₄ to absorb CO₂ or NH₃, respectively. Carbon dioxide absorbed by the traps was determined by precipitation of carbonates with BaCl₂ and then titration of remaining base with standard HCl (Stotzky, 1965). Ammonia traps were analyzed by steam distillation with 10 M NaOH (Bremner and Mulvaney, 1982).

In an attempt to determine the amount of N mineralized from the manures a static incubation experiment was conducted. Twenty g soil plus or minus 2.7 g wet manure were added to small 50 mL glass jars. The soil moisture was adjusted as above and the sample containers were then covered with saran wrap. Periodically replicate samples were removed and extracted with 50 mL 2 M KCl. The extracts were then analyzed for inorganic N as described above.

The computer model, DECOMPOSITION, was used to simulate the decomposition and N mineralization characteristics of the litter. The model used as inputs the data presented below for first order rate constants and C:N ratio of the manure. Microbial efficiency was set at 0.4. The loading rate was similar to that employed in the analytical portion of the study.

PRINCIPAL FINDINGS AND SIGNIFICANCE

A. Sample Variability

Six hen manures, each replicated three times were used in this study. Table 1 presents the mean analytical data with standard errors, while Table 2 presents the statistics associated with analytical variability. Total C and total N (wet sample) values were not significantly different among manures. Inorganic N (wet sample), inorganic N (dry sample), total N (dry sample), and % solids were significantly different attesting to the variable nature of hen manure. This variability was not present within manures as replication differences were not significant.

In order to simplify data presentation, only the mean results with appropriate statistics will be given. Where variability appears to be large it is due in large part to the inherent variability of the hen manure.

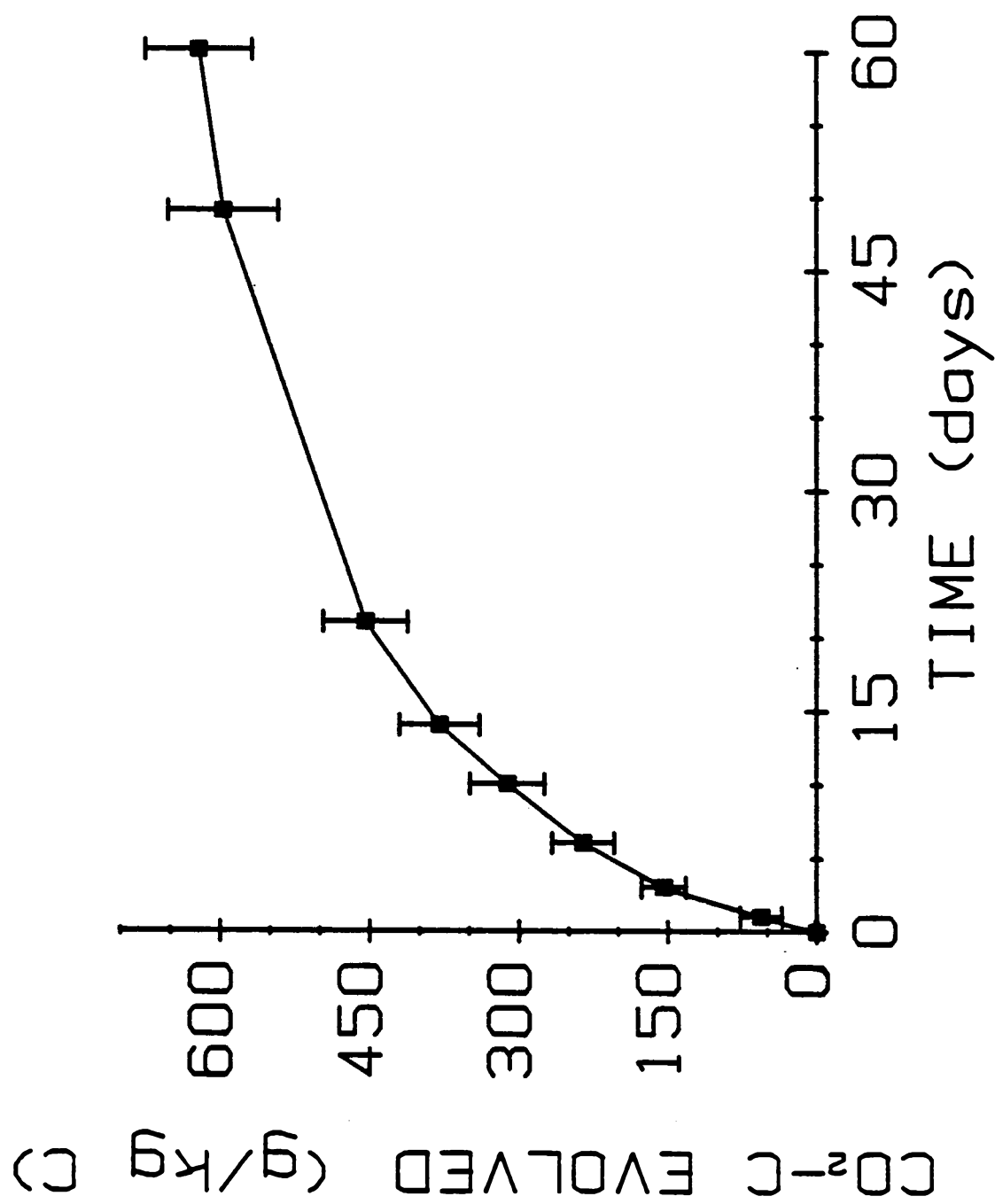
B. Decomposition

The evolution of carbon dioxide from the hen manure during decomposition is presented in Figure 1. The final value of 640 g C (kg manure C)⁻¹ represented 64 percent conversion of the manure to carbon dioxide during the 60 d period. Castellanos and Pratt (1981) found about 45 % conversion of poultry manure to CO₂ over a 4 week period as compared to approximately 53 percent in Figure 1. Gale and Gilmour (1986) reported 40 percent conversion of poultry litter to CO₂ in 34 d.

Table 2. Variability components of the chemical properties of the manures.

Parameter	df	MSE	F	significance
MANURES				
total C	5	7.722	1.57	NS
total N (wet)	11	1.095	2.13	NS
inorganic N (wet)	11	1.019	446	S
% solids	11	8.548	22.2	S
total N (dry)	11	0.992	24.7	S
inorganic N (dry)	11	0.002	31.5	S
REPS				
total C	1	0.030	0.06	NS
total N (wet)	1	0.317	0.62	NS
inorganic N (wet)	1	0.003	1.43	NS
% solids	1	0.510	1.33	NS
total N (dry)	1	0.099	2.46	NS
inorganic N (dry)	1	0.000	0.05	NS

Figure 1 - Cumulative CO_2 -C evolved from hen manure incubated at 25 C



First order rate constants for the apparent decomposition data in Figure 1 were calculated by regressing the natural logarithm of the hen manure C remaining in the soil (original hen manure C minus $\text{CO}_2\text{-C}$ corrected for appropriate controls) against time as shown in Figure 2. The slopes of the linear segments in Figure 2 corresponded to rate constants for the rapid, intermediate, and slow fractions of the manure in terms of decomposability. The extent of each linear segment determined the amount of manure C in each fraction.

Table 3 presents the first order rate constants (k) and the percentage of the manure C in each group. Rate constants were 0.041, 0.018, and 0.09 d^{-1} for the rapid, intermediate, and slow fractions, respectively. Corresponding percentages for these fractions were 33, 20, and 47 %, respectively. Gale and Gilmour (1986) found first order rate constants for poultry litter of 0.046 and 0.019 d^{-1} and percentages of 25 and 10 percent for the rapid and intermediate fractions.

C. N Mineralization and Volatilization

Mean inorganic N in the static system increased rapidly during the first 10 d reaching a peak value of $575 \text{ g N (kg manure N)}^{-1}$ at 14 d as given in Figure 3. The apparent decline after 14 d was attributed to losses as ammonia through the saran wrap cover which was verified in a separate experiment (data not reported), denitrification, and/or immobilization; thus, the data

Figure 2 - Natural log of % C remaining as a function of time for hen manure at 25 C

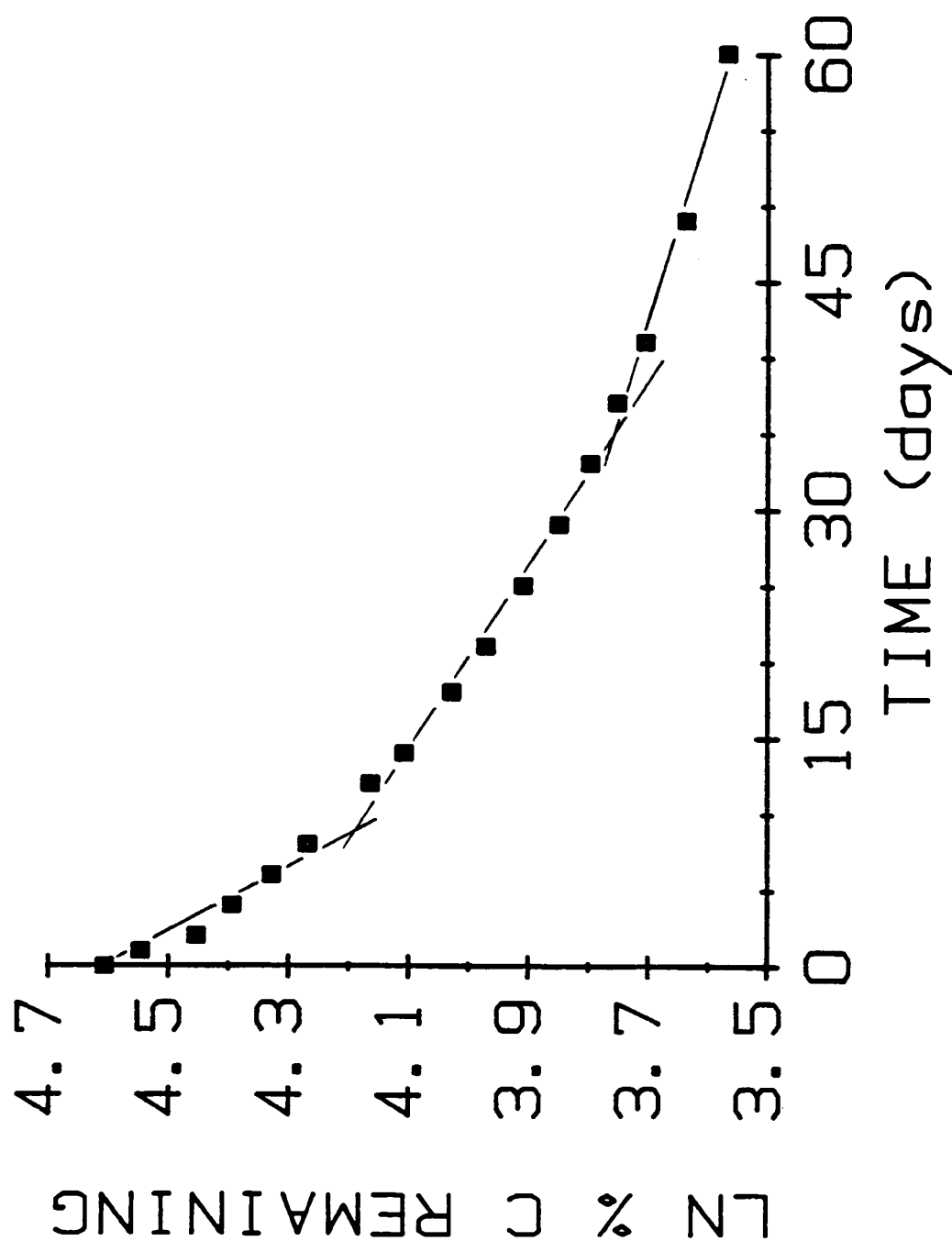
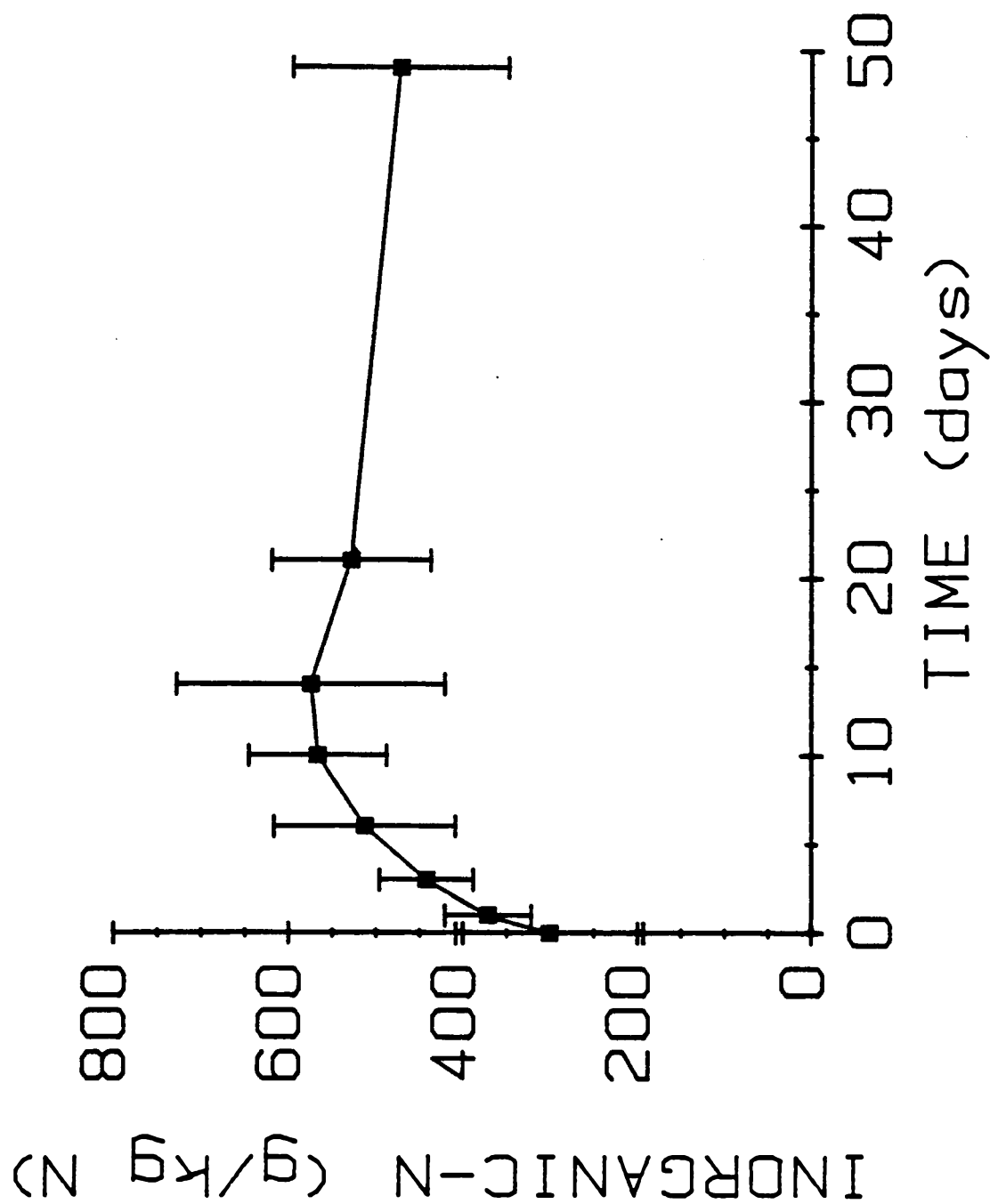


Table 3. First order rate constants for the decomposition of hen manure at 25 C.

Fraction	k	Percent of Manure C or N
	d ⁻¹	%
CARBON MINERALIZATION		
Rapid	0.041 (0.0014)*	33
Intermediate	0.018 (0.0010)	20
Slow	0.009 (0.0088)	47
AMMONIA VOLATILIZATION		
Rapid	0.081 (0.0056)	43
Intermediate	0.013 (0.0028)	11
Slow	0.0009 (0.0002)	46

* Standard error

Figure 3 - Changes in inorganic-N with time for hen manure incubated in a static system at 25 C

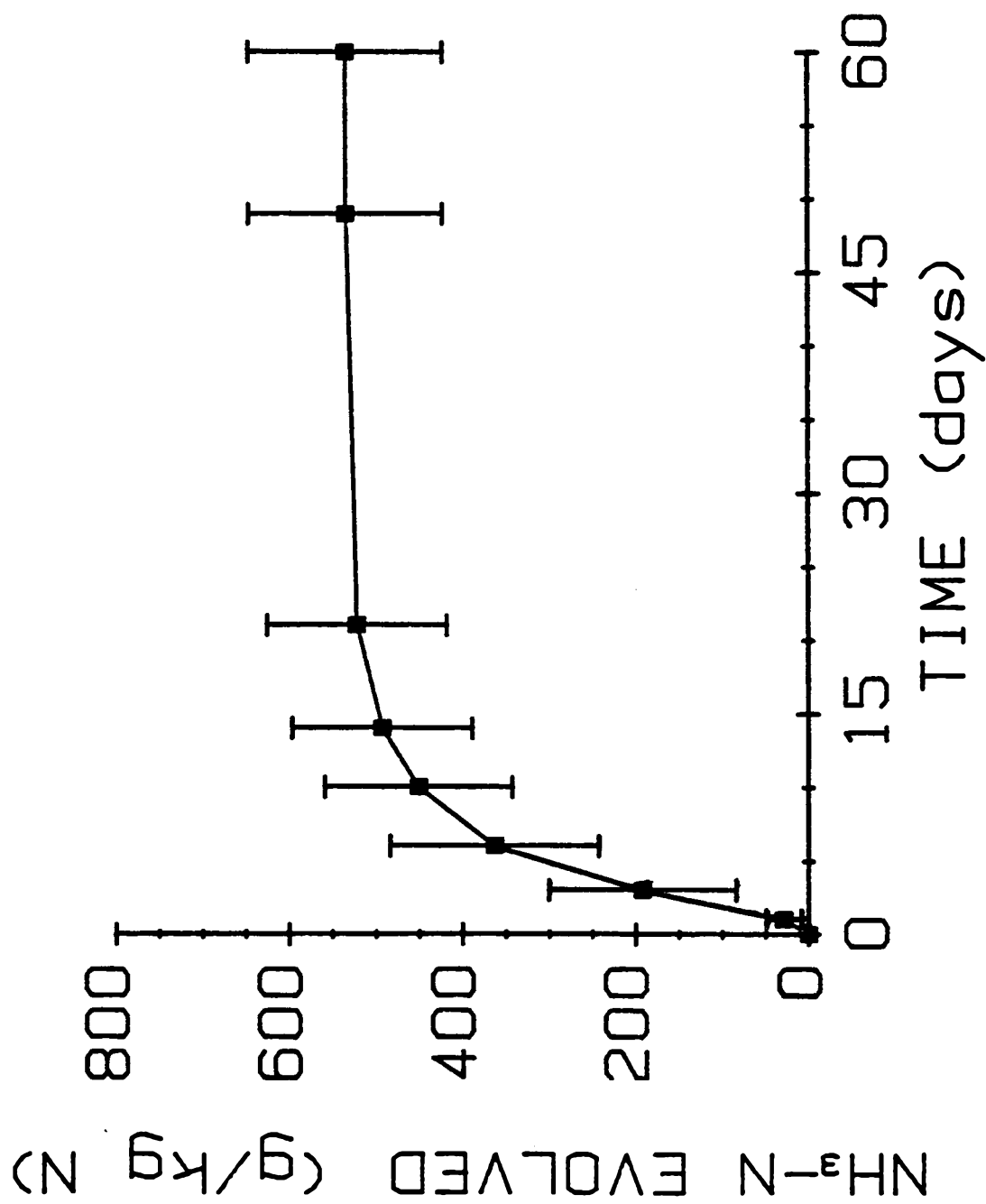


from the static system likely were underestimates of actual N mineralization. The large standard errors were a result of sample to sample variability and not within sample variability.

The inorganic N in the flow through system (Figure 4) was obtained by making the assumption that the initial ammonium N and mineralized N were converted to volatile ammonia N and lost from the system before denitrification could occur. This assumption appeared to be valid during early stages of decomposition as the pattern of ammonia N volatilization followed the expected N mineralization pattern. Essentially no inorganic N was found in the soil-manure combination at the termination of the experiment which in combination with the data in Figure 4 suggested that as decomposition proceeded, denitrification and/or immobilization may have occurred. Other researchers (Giddens and Rao, 1975) have also found large amounts of volatilization for poultry manures and have observed denitrification (Gilbertson and Norstadt, 1979).

The pattern of ammonia volatilization shown in Figure 3 was different than the pattern of carbon dioxide evolution shown in Figure 1. Ammonia losses were large as the rapid fraction was undergoing decomposition, slowed during decomposition of the intermediate fraction, and were small during slow fraction decomposition. Again, the standard errors reflect sample to sample variability and not replication variability.

Figure 4 - Cumulative $\text{NH}_3\text{-N}$ evolved from hen manure incubated in a flow through system at 25 C



First order rate constants for volatilization were obtained by regressing the natural logarithm of the percent total N remaining in the soil-manure combination (organic N plus inorganic N corrected for appropriate controls) versus time as shown in Figure 5. As was the case with decomposition, three linear segments were obtained. The rate constants or slopes of these linear segments for ammonia N volatilization are presented in Table 3. The values for the rapid, intermediate, and slow fractions were 0.081, 0.013, and 0.009 d⁻¹, respectively. Corresponding percentages were 43, 11, and 46, respectively.

The rate constant and percentage for the ammonia volatilization was larger than the corresponding C mineralization rate constant and percentage for the rapid fraction because of the contribution of the initial level of inorganic N to volatilization. During the intermediate phase rate constants for the two processes were similar which suggested that the portion of the hen manure undergoing decomposition was the source of both volatile materials. During the slow phase the ammonia volatilization rate constant was much smaller than the carbon mineralization rate constant.

D. Relationships Between N and C mineralization

The relationship between ammonia volatilized (Figure 4) and C mineralized (Figure 1) expressed on a percentage basis is presented in Figure 6. During the initial stages of decomposition

Figure 5 - Natural log of % N remaining as a function of time for $\text{NH}_3\text{-N}$ volatilization from hen manure incubated in a flow through system at 25 C

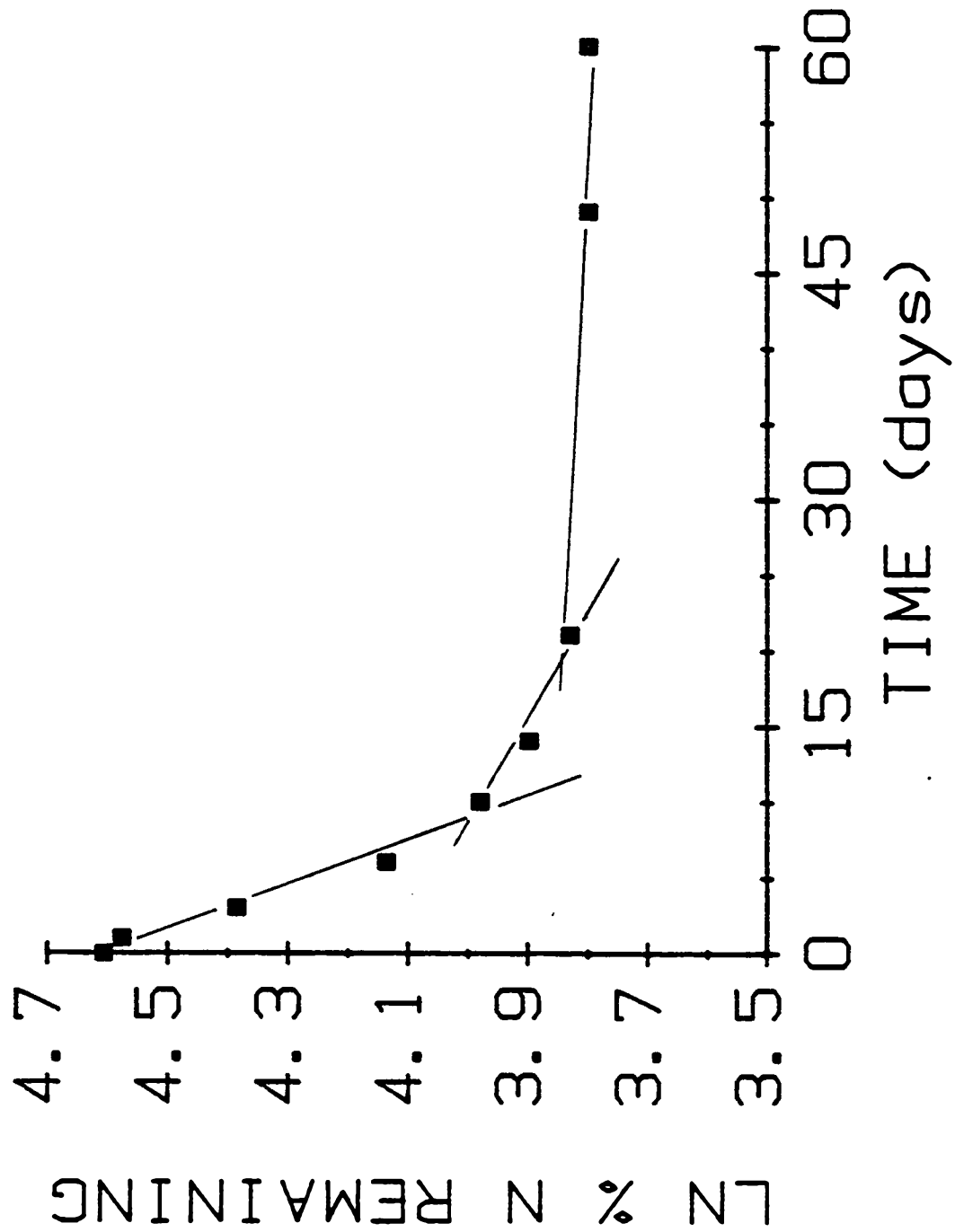
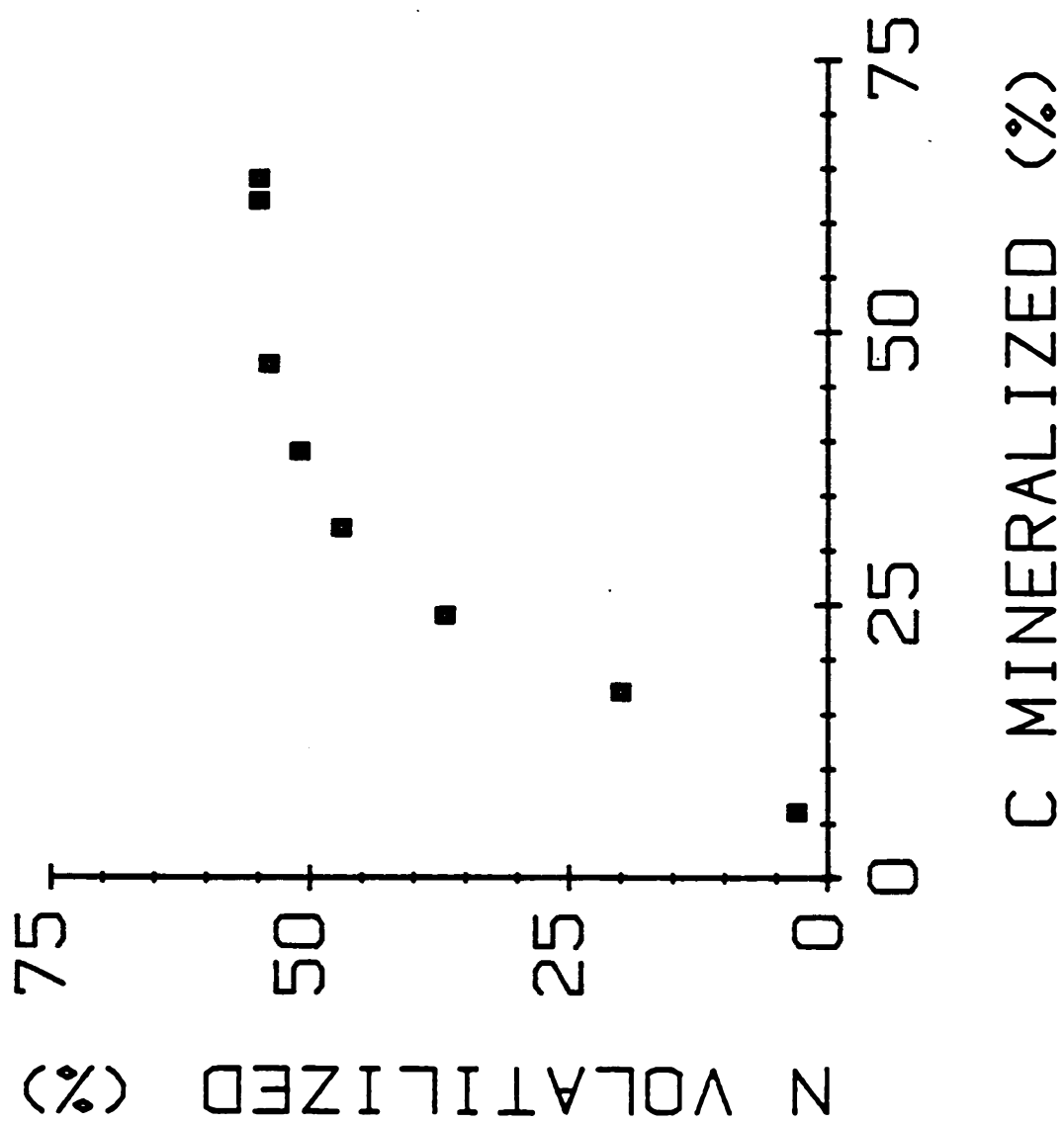


Figure 6 - N volatilized versus C mineralized in the flow through system at 25 C



(<35 % C mineralized) about half of the total N in the manure was converted to volatile ammonia and lost from the system. After that time, C mineralization continued with only small amounts of ammonia volatilization. It is likely that the initial, large losses of ammonia can be attributed to the high pH of the manure, high initial ammonium N, and some conversion of uric acid to ammonia to increase the inorganic N pool. The total losses of about 50 percent of the manure N corresponded well to findings of Wolf (unpublished data, 1987) which showed that about half of the total N in hen manure is uric acid for fresh samples. The manure studied here had been removed from the laying operation a few hours prior to freezing and so uric acid contents were low (Wolf, unpublished data, 1987) and ammonium N levels were high indicating that substantial uric acid hydrolysis had already occurred.

The relatively small amounts of N volatilization at C mineralization values >35 percent in Figure 6 were not expected as the C:N ratio of the hen manure was low. The possibility that denitrification was occurring remains and will be evaluated during the next year of the project. The possibility that simultaneous N mineralization and immobilization were occurring at approximately equal rates was also a probable explanation of at least part of the effect as the manure did contain undigested feed. Immobilization was found to be responsible for

cessation of net N mineralization in poultry litter where straw and sawdust were the immobilizing agents (Gale and Gilmour, 1986).

While Figure 6 compares total N and C dynamics for the hen manure, Figures 7 and 8 present the N dynamics for the organic N fraction as a function of C mineralization. In Figure 7, N mineralization was estimated from volatile ammonia losses, while in Figure 8, N mineralization was estimated from extracted soil inorganic N. In both cases corrections for initial inorganic N and inorganic N in controls were made.

Using either estimate of N mineralization for the first, linear portion of the relationship, the slope was near unity which would be expected for hen manure with a C:N ratio of 8.4 (Gilmour et al., 1985). The lag in Figure 7 for N mineralization was due to losses of initial inorganic N prior to losses of mineralized N. The smaller slope in Figure 7 as compared to Figure 8 and the decreases in N mineralization later in the decomposition process in Figure 7 were attributed to volatile losses of ammonia through the saran cover on the incubation bottles and the potential for denitrification and/or immobilization as discussed above. The cessation of N mineralization in Figure 8 was also attributed to denitrification and/or immobilization reactions.

Figure 7 - N mineralized versus C mineralized in the flow through system for hen manure at 25 C

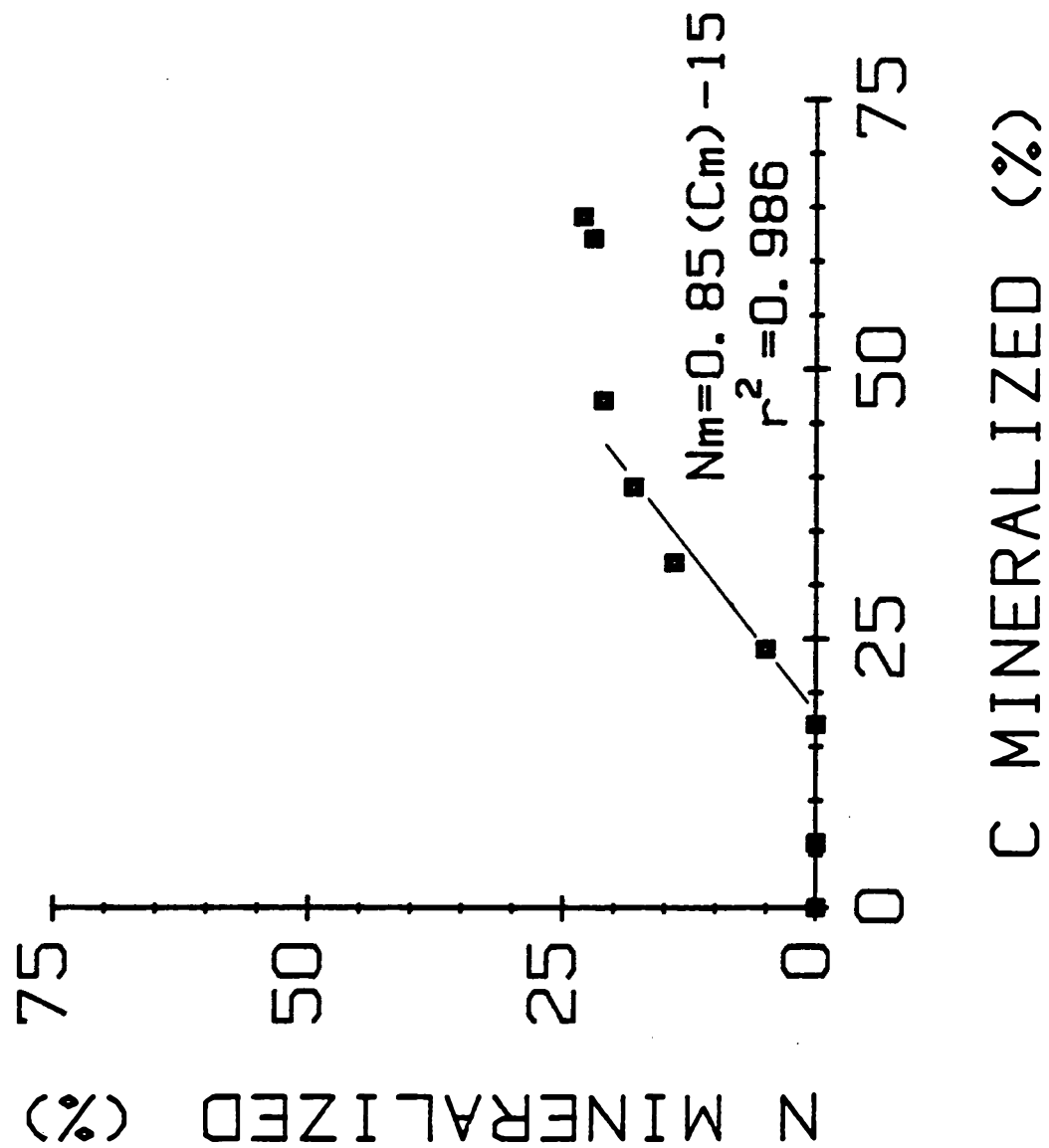
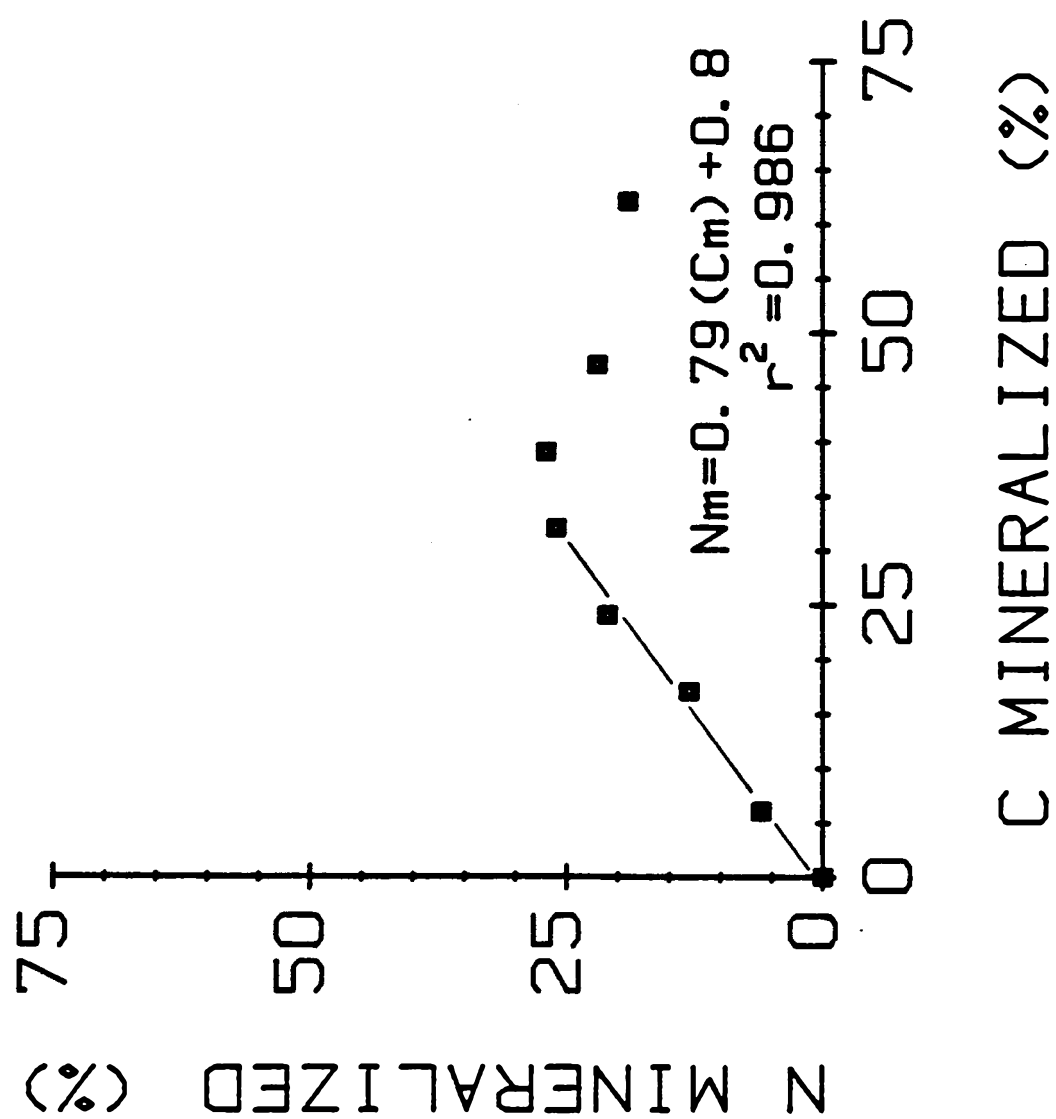


Figure 8 - N mineralized in the static system versus C mineralized in the flow through system for hen manure at 25 C



E. Predictions of C and N Mineralization

The computer model, DECOMPOSITION, described by Gilmour et al. (1985) was used to describe the decomposition and N mineralization processes. Figure 9 presents the relationship between predicted and observed C mineralization or decomposition. The agreement was excellent as expected because the input to the model was the observed decomposition rate constants given in Table 3.

The prediction of N mineralization versus N mineralization estimated from volatilization of ammonia is given in Figure 10. With hen manure a slope near unity is expected. The slope of 1.89 was much larger which was attributed to the small amounts of observed N mineralization as compared to predictions during the period when denitrification and/or immobilization reactions were probable.

The prediction of N mineralization during the initial phases of decomposition where loss mechanisms did not appear to be operative was good as shown by the initial linear relationship in Figure 11. The slope was near the expected value of unity. After that time, however, predictions were poor as increases in soil inorganic N slowed and eventually decreased as discussed above.

Figure 9 - Predicted (from model) C mineralized versus observed C mineralized from flow through system for hen manure at 25 C

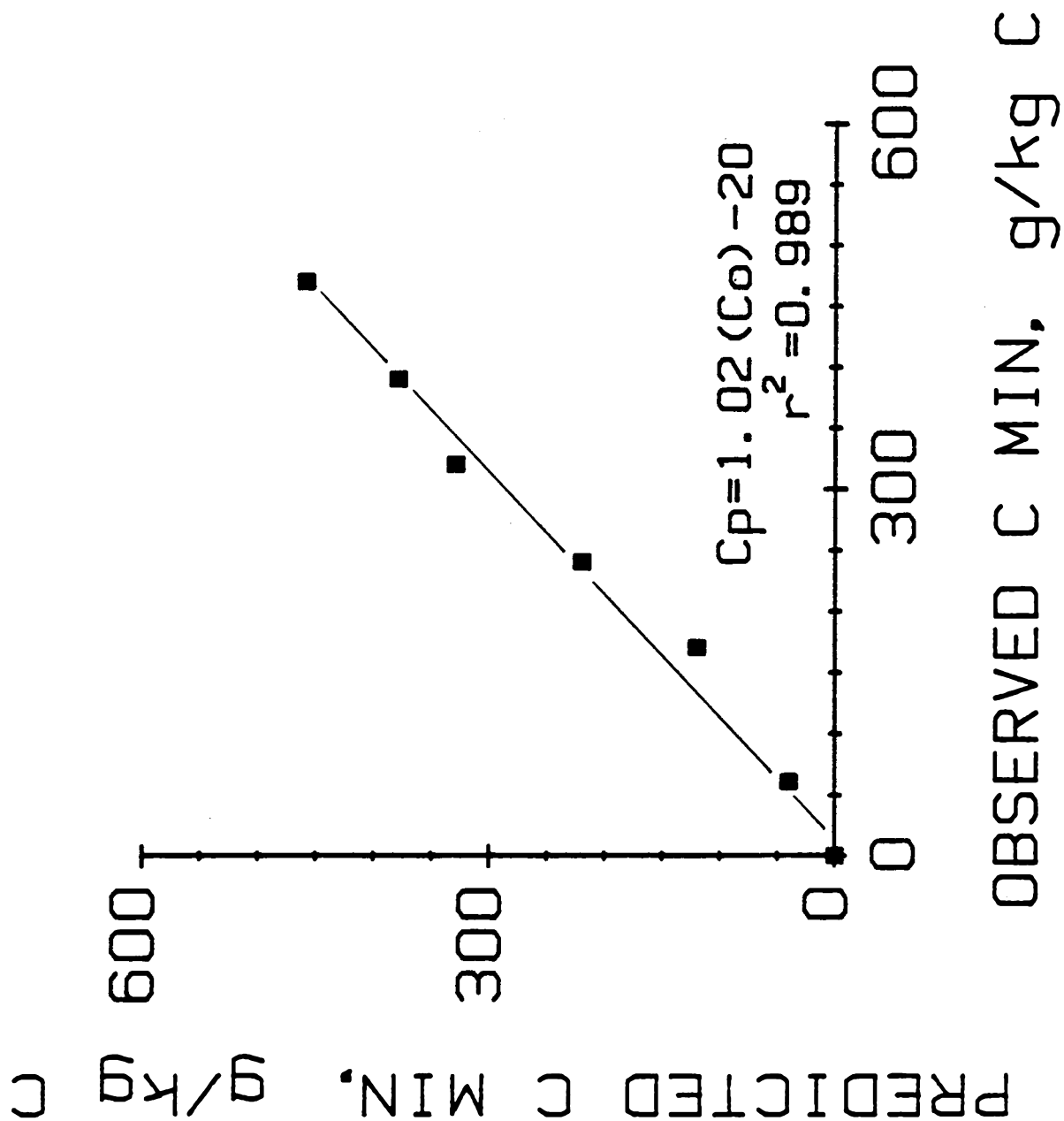


Figure 10 -Predicted (from model) N mineralized versus
observed N mineralized from flow through system
for hen manure at 25 C

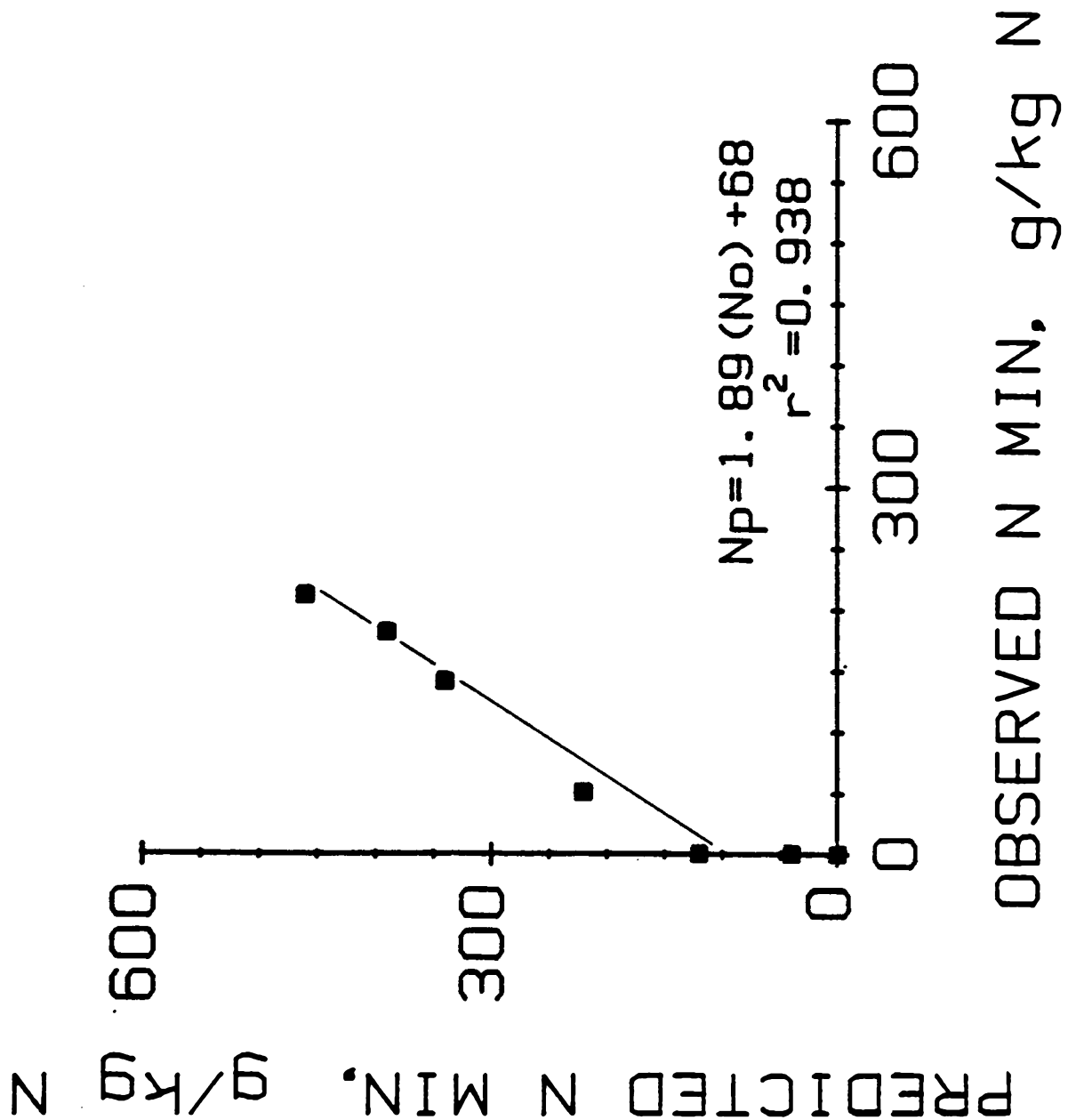
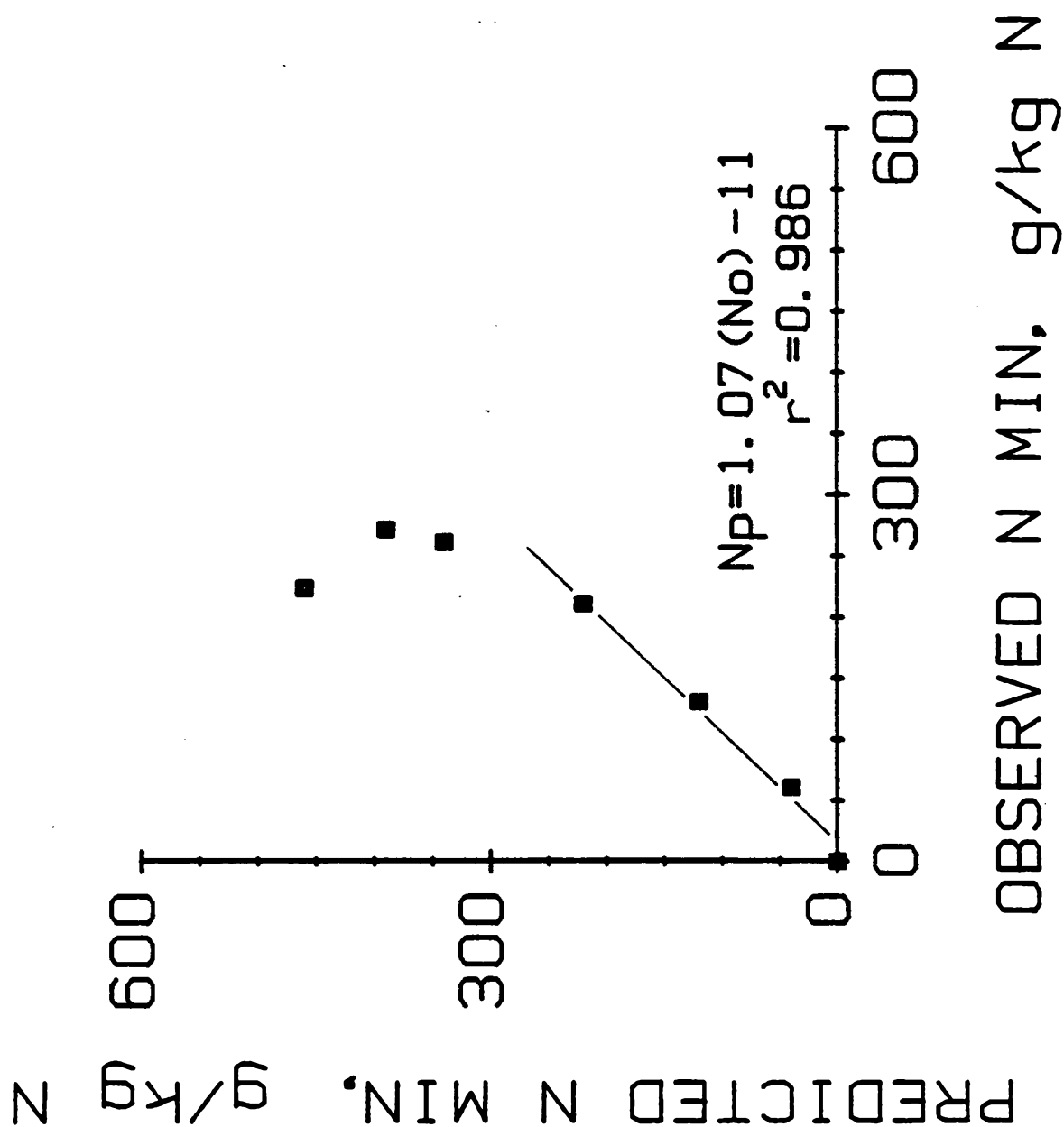


Figure 11 - Predicted (from model) N mineralized versus observed N mineralized from static system for hen manure at 25 C



F. Nitrification

The distribution of ammonium and nitrate N in the static system is presented in Table 4. Little nitrate N was found during the experiment which suggests that either nitrification was small or that nitrate N was rapidly converted to gaseous forms via denitrification. Similar, small amounts of nitrate N were found by Giddens and Rao (1975) for poultry manure, while Hadas et al. (1983) reported large amounts of nitrate N for pelleted manure.

CONCLUSIONS

During the decomposition of surface applied hen manure, N mineralization followed two patterns. Initially, N mineralization was rapid and the mineralized N plus initial inorganic N were converted to volatile ammonia and lost to the atmosphere. Later, one of two scenarios appeared to be operative. If nitrification and denitrification were small, then N immobilization likely occurred at a rate near that of N mineralization resulting in only small increases in inorganic N. Undecomposed feed was suggested as the immobilizing agent. If nitrification and denitrification were large, then N mineralization could have proceeded at expected rates and would not be measured by the methods employed herein. Future studies will assess the role of denitrification.

In a practical vein, the initial inorganic N and mineralized N in surface applied hen manure has a low N fertilizer value and

Table 4. Changes in inorganic-N with time in the static system.

Day	NH ₄ -N	NO ₃ -N
-----g N/kg manure -----		
0	19.0 (6.8)*	0.02 (0.024)
1	21.5 (2.9)	0.17 (0.19)
3	25.6 (3.1)	0.31 (0.36)
6	29.8 (6.0)	0.31 (0.36)
10	32.9 (4.6)	0.22 (0.29)
14	33.4 (8.9)	0.05 (0.18)
21	30.7 (5.3)	0.10 (0.39)
49	27.6 (7.3)	1.45 (2.26)

* Standard deviation

water pollution potential due to volatilization of N. If the manure is incorporated or a rainfall event occurs soon after surface addition, more than 50 percent of the manure N could be available for plant uptake and contamination of ground and surface waters.

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