RESEARCH SUB-PROGRAM

Influence of Soil Texture and Tillage-Induced Changes on the Susceptibility of Legume-N to Leaching

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FORWARD

This report is one of a series of **COESA** (Canada-Ontario Environmental Sustainability Accord) reports from the Research Sub-Program of the Canada-Ontario Green Plan. The **GREEN PLAN** agreement, signed Sept. 21, 1992, is an equally-shared Canada-Ontario program totalling $64.2 M, to be delivered over a five-year period starting April 1, 1992 and ending March 31, 1997. It is designed to encourage and assist farmers with the implementation of appropriate farm management practices within the framework of environmentally sustainable agriculture. The Federal component will be delivered by Agriculture and Agrifood Canada and the Ontario component will be delivered by the Ontario Ministry of Agriculture and Food and Rural Assistance.

From the 30 recommendations crafted at the Kempenfelt Stakeholders conference (Barrie, October 1991), the Agreement Management Committee (AMC) identified nine program areas for Green Plan activities of which the three comprising research activities are (with Team Leaders):

1. **Manure/Nutrient Management and Utilization of Biodegradable Organic Wastes** through land application, with emphasis on water quality implications
   A. Animal Manure Management (nutrients and bacteria)
   B. Biodegradable organic urban waste application on agricultural lands (closed loop recycling) (Dr. Bruce T. Bowman, Pest Management Research Centre, London, ONT)

2. **On-Farm Research**: Tillage and crop management in a sustainable agriculture system. (Dr. Al Hamill, Harrow Research Station, Harrow, ONT)

3. **Development of an integrated monitoring capability** to track and diagnose aspects of resource quality and sustainability. (Dr. Bruce MacDonald, Centre for Land and Biological Resource Research, Guelph, ONT)

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EXECUTIVE SUMMARY

A legume underseeded in cereal represents an important source of nitrogen N, for the subsequent crop in the rotation and can provide a complementary improvement in soil structure. The extent to which the N benefit is realized depends on the rate of mineralization of the legume N in relation to the N requirements of the succeeding crop. The rate of N mineralization may vary with inherent soil conditions as well as properties such as bulk density that change as tillage practices are changed.

The objectives of this study were:

(a) to determine the influence of variations in soil texture, bulk density, and the volume fraction of pores, VFP, belonging to different size classes, on N-mineralization subsequent to red clover incorporation and;

(b) to develop equations to predict the rates of N-mineralization on different soils.

Soil samples for the study were collected from Mr. Don Lobb's farm, near Clinton, in Huron County. This site was one of the T-2000 sites investigated during the Ontario Land Stewardship program and is one of the longest running field scale side-by-side comparison of zero and conventional tillage in Ontario. The comparison is maintained as transects about 500 m in length which traverse soils with clay contents ranging from 7 to 40%. The site was under corn production in 1991, 1992, and 1993.

Soil samples were collected from the conventionally tilled transect at 7 locations. Samples were collected from the top 15 cm depth, air-dried, sieved and the material < 4.00 mm characterized. Bulk soil properties (clay, silt, sand, organic matter, total-N and $CaCO_3$ contents, pH and cation exchange capacity) were determined. Water retention characteristics were measured at two bulk densities that reflected conditions encountered under conventional and zero till conditions at this site. The bulk density for the low density condition ranged from 1.264 to 1.327 g cm-^{3} (depending on the texture) and that of the high density from 1.362 to 1.451 g cm-$^{3.}$

Red clover (only the shoot biomass) was added at a rate equivalent to 6000 kg ha^{-1} (on dry weight basis) and was assumed to be incorporated in the top 15 cm depth. The total-N in the shoot biomass was 2.36% and the amount of legume-N added was about 140 kg ha^{-1} (75 mg legume-N kg^{-1} soil). The legume residue was incubated with soil at 23 +/- 1°C and a soil water potential of -15 kPa.

The water retention and bulk density data indicated that the air-filled porosity, AFP, at -kPa for the low density condition tanged from 0.161 to 0.316% and that of the high density from 0.041 to 0.217%.

The nitrate-N data from the red clover added treatment was fitted to a two pool first order model, whereas the control could only be fitted to a one pool model. Each best fit was significant at P# 0.05 and the R^2 for the best fits ranged from 0.71 to 0.98. The size of the potentially mineralizable resistant N-pool in the red clover added treatment ranged from 28.16 to 68.12 mg kg^{-1} whereas that of the labile pool, N_1, ranged from 10.32 to 27.11 mg $kg^{-1.}$ The corresponding range in the rate constant for the resistant pool, kr, was from 0.0038 to 0.0065 d^{-1} and that of the labile pool, k_1 was from 0.0081 0.0596 $d^{-1.}$ The size of the N-pool in the control, $N_{o,}$ ranged from 11.81 to 25.41 mg kg^{-1} and the corresponding range for the rate constant, k_o, was from 0.0179 to 0.1313 $d^{-1.}$

Simple correlation analyses indicated the values of k_1 were significantly influenced by the largest number of bulk soil properties, followed by N_1 and N_r. The pedotransfer function, PTF, developed to predict k_1 indicated that 93% of the variability in k_1 was accounted for by bulk density, C:N ratio, silt and $CaCO_3$ contents. The PTF to predict N_1 indicated that only 88% of the variability in k_1 was accounted for by bulk density and clay and $CaCO_3$ contents. Bulk density, CEC, and total-N accounted for 85% of the variability in $N_{r.}$ Fifty eight percent of the variability in k_r was accounted for by bulk density, CEC, and organic matter contents. The PTF's developed can be used to predict values for $N_{1,}$, k_1 and k^r, thereby enabling modelling of the temporal variation in legume-N mineralization.

Many of the bulk soil properties had a significant influence on the VFP belonging to different size classes. An assessment of the influence of VFP on N-mineralization parameters indicated that VFP had a significant influence on $N_{1,}$ k_1, and N_r, but not on $k_{r.}$ The stepwise variable selection analysis indicated that 78% of the variability in N_1 was accounted for by VFP with effective diameters in the size range 5 to 10 µm and those # 1.5 µm. Values of k_1 were also influenced by size classes # 1.5 and 1.5 to 3 µm. Values of N_r were less strongly influenced by pore characteristics.

An assessment of the combined influence of bulk soil properties and pore characteristics on N_1 and k_1 indicated that these two parameters are influenced only by pore characteristics whereas N_r was influenced both by pore characteristics and a bulk soil property, ie pH. On the other hand, values of k_r and k_o were influenced only by bulk soil properties.

A comparison of the R^2 values of the PTF's obtained for N_1, N_r, k_1, and k_r as functions of VFP and bulk soil properties with corresponding R^2 values of the PTF's obtained using the information only on bulk soil properties indicated the R^2 values for latter PTF's were greater than the former. Thus, for consistency, it is recommended that PTF's obtained using the information only on bulk soil properties be used to predict values for N-mineralization parameters. Further, the information on bulk soil properties is readily available in soil survey data. Analyses of pore characteristics are more useful in understanding the mechanisms whereby bulk soil properties influence mineralization dynamics.

The amount of N mineralized at any time in the red clover added treatment could be predicted from the bulk soil properties using the two pool model but could not be predicted using simple or multiple correlations between the amount of N mineralized and soil properties. The two pool model and associated pedotransfer functions are, therefore, necessary to provide predictions on mineralization dynamics. These models will be particularly useful in assessing the risk of legume-N leaching to water bodies across a range of soil textures.

1.0 INTRODUCTION

Understanding the influence of legumes, used as winter cover crops or underseeded in row-crops, on soil N dynamics is critical in developing sustainable crop production systems. We are, however, unable to predict the rate of mineralization of legume-N across a range of soil conditions. Such information is crucial if we want to assess the potential for legume-N to be leached to water bodies and if we are to effectively utilize fertilizer-N added to subsequent crops.

The ability of legumes, as a cover or as an underseeded crop, to serve as an effective source of N for row crops depends on the amount of N fixed by the legume and the rate of mineralization of legume-N. The amount of N fixed depends primarily on the legume species (Hargrove, 1986; Christie et al., 1992; Kay et al., 1993a; Reeves et al., 1993) and climate (Cassman and Munns, 1980; Myers et al., 1982; Doran and Smith, 1991). The rate of mineralization depends on the legume species, climate, tillage practices (Wagger, 1989; Varco et al., 1989), indigenous organic N and C (Cabrera and Kissel, 1988), soil texture (Herlihy, 1979), soil pH (Schmidt, 1982), C:N ratio (Harmsen and van Schreven, 1955), and NH_4 retention capacity (Kowalenko and Cameron, 1976). Simard and N'Dayegamiye (1993) have indicated that N mineralization from some meadow soils was more strongly correlated with C or N than with clay content or soil pH. Even though N-mineralization seems to be influenced by bulk soil properties and tillage practices, their influence has not been explored in detail for predictive purposes.

Because, organic matter decomposition is primarily a biological process, the volume fraction of pores, VFP, associated with the decomposers, bacteria, and that of the predators of bacteria are important in determining the rate of decomposition (Killkam, et al., 1993; Amato and Ladd, 1992; Hattori, 1988; Vargas and Hattori, 1990). According to Hattori (1988) soil protozoa (bacterial grazers) are predominantly located in pores > 6 µm in diameter and bacteria in pores < 6µm. Vargas and Hattori (1990) have shown that the distribution of protozoa is very much determined by pore characteristics of aggregates. Amato and Ladd (1992) have shown that turn over of labelled C was greater in larger pores, 6 - 30 µm, than in smaller pores, < 6 µm. Kay et al. (1993b) have shown that pore characteristics can be related to texture and those soil properties which change when tillage is reduced. Practically no information exists on the influence of VFP belonging to different size classes on legume-N mineralization. This information is crucial, because the reduced till system that is being advocated as a sustainable production system can have significant impact on the distribution of VFP, particularly on the larger size pores.

Miller et al. (1992) have shown the amount of N available for leaching depends on the cover crop species. For instance, Miller et al. (1992) found that red clover was more effective in retaining N through winter and spring and releasing the N to the succeeding row crop than rye grass, thereby reducing the potential risk for leaching. They, however, suggested that considerable leaching may occur in sandy soils. Reeves et al. (1993) have indicated the temporal variation in legume-N mineralization is more important than the total-N produced from the perspective of the potential for leaching.

The temporal variation in legume N mineralization in a given soil can be modelled using the first order rate equation proposed by Stanford and Smith (1972)

$$\mathbf{N_m = N_0\,[1- exp\,(- k_0\,t)]} \qquad [1]$$

where $\mathbf{N_m}$ is the amount of N mineralized at time t, N_0 is the amount of potentially mineralizable N and k_0 is the first order rate constant. The estimates for N_0 and k_0 have usually been obtained from aerobic incubation experiments (Stanford and Smith, 1972; Stanford et al. , 1973; 1977, Smith et al., 1977; Marion et al., 1981, Campbell et al., 1984; Bonde and Rosswall, 1987). Stanford and Smith (1972) consider the potentially mineralizable N as a definable quantity that depends on total-N, and the rate constant as a true constant for the 39 soils included in their study. Because, different fractions of organic N. in soil may be differentially susceptible to mineralization (Paul and Juma, 1981; van Veen and Frissel, 1981; Cabrera and Kissel, 1988; Cabrera, 1993) the first order one pool model (Eq.[1]) has often been found to be inadequate in describing N-mineralization in soil, particularly when fresh organic material is incorporated, and has been modified to a two pool model, i.e.,

$$\mathbf{N_m = N_1\,[1 - exp(-k_1\,t)] + N_r\,[1 - exp\,(- k_r\,t)]} \qquad \mathbf{[2]}$$

where N_1 and Nr are the amounts of organic N initially present as the labile and resistant N pools, respectively, and k_1 and k_r are the corresponding first order rate constants for the two pools.

Pedotransfer functions, PIF, have been used to define the parameters of models such as Eq. [2] as functions of bulk soil properties (Bouma, et al., 1987). These functions enable the computation of values for the parameters which could be used for modelling N-mineralization.

The objectives of this study were to determine how N mineralization dynamics vary with bulk soil properties and tillage by investigating how the N-mineralization parameters; N_0, N_1, N_r k_o, k_1, and k_r are correlated with bulk soil properties, variations in bulk density, and pore characteristics.

2.0 MATERIALS AND METHODS

2.1 Site Description

A laboratory incubation experiment was carried out to determine N-mineralization from 7 soils with contrasting properties (Table 1). The soils used in this study were collected from Mr. Don Lobb's farm near Clinton, Ontario. This site has been used for several years for studies in contrasting tillage practices. These studies have been funded by Agriculture Canada Research Branch (National Soil Conservation program) and by the Ontario Ministry of Agriculture, Food and Rural Affairs (Land Stewardship Program). The site is a 500 m transect with two tillage systems imposed side by side. Each tillage system is about 9 m wide, i.e. 12 rows of corn 0.75 m apart. The two tillage systems are conventional till (ploughing in fall followed by secondary tillage in spring) and no-till. The site traversed a range of soil mapping units. Further details regarding site description are available in several reports (eg. Kay et al., 1993b).

2.2 Soil Sample Collection and Processing

Soil samples were collected from 7 locations, that represented a range in clay contents from 8 to 40%, along the conventionally tilled transect. About 10 kg of soil were collected, in early October 1993, from 4 to 5 randomly selected places from each location. A spade was used to collect samples to a depth between 10 and 15 cm. The samples collected from each location were bulked and transferred to labelled PVC bags and taken to the laboratory. The samples were air-dried to constant moisture content and large clods were manually broken to clods not greater than 2 to

3 cm in diameter. The samples were then passed through a sieve with mesh openings of 4 mm and all the material < 4.00 mm was collected. Plant residue and debris in this portion were manually removed. The < 4.00 mm soil was transferred to labelled bags to be used for incubation studies, soil characterization, and determination of water retention curves.

2.3 Soil Characterization

The textural characterization was carried out using the procedure described by Gee and Bauder (1986). Soil pH was determined using the procedure described by McLean (1986). Nelson's (1986) method was used for carbonate determination. Total carbon, organic carbon, and organic matter determination were carried out using procedure described by Nelson and Sommers (1986). The total-N determination was carried out using the Keeney and Nelson (1982) procedure. The cation exchange capacity of the soils was determined using the procedure described by Rhoades (1982). All determinations were repeated four times and the results of these analyses are summarized in Table 1.

The clay content of the soils ranged from 8.5 to 36.7% and the corresponding range in silt content was 18.4 to 52.5%. The CEC of the soils ranged from 18.5 to 33.4 meq/100 g. The range in organic matter content of the soils was from 2.3 to 4.3% and that of total-N was from 0.088 to 0.188%. The $CaCO_3$ content among the soils showed much wider variation than soil pH.

Table 1. Selected bulk properties of the soils

Selected properties									
Soil#	Clay	Silt	Sand	OM	TN	$CaCO_3$	pH	CN	CEC
	(......................... %........................)								Meq/100
1	8.5	18.4	73.1	2.3	0.088	5.7	7.2	15.0	21.0
2	24.1	50.8	25.1	3.3	0.158	1.1	7.2	12.0	18.5
3	25.7	49.7	24.6	3.7	0.130	3.7	7.3	11.7	21.1
4	25.8	54.5	19.7	3.2	0.153	2.3	7.3	12.3	21.2
5	27.6	52.5	19.9	2.7	0.100	5.7	7.4	15.7	22.0
6	35.3	47.3	17.4	4.3	0.188	1.7	7.5	13.4	33.4
7	36.7	50.4	12.9	3.7	0.180	1.4	7.4	11.8	30.0

OM =organic matter, CN = C:N ratio, TN = total-N, and CEC = cation exchange capacity.

2.4 Bulk density adjustments

Bulk density has been used as an index to characterize the state of soil compaction under reduced tillage. Because bulk density can vary with texture, it has limited value when different soils are compared. In order to remove this limitation, the concept of relative bulk density has been used (Carter, 1990; Kay et al., 1993b). The relative bulk density is calculated as the observed bulk density divided by the bulk density of that soil under a standard compaction treatment (200 kPa). Kay et al. (1993b) showed that, although there was wide variation in bulk density, the relative bulk density across this site was independent of texture and organic matter content and depended only on tillage treatment. The relative bulk densities along the zero till and conventional till transects were 0. 87 and 0.79 respectively. Each soil was packed to the two relative bulk densities that were found at the site under conventional (referred to as low density) and no-till (referred to as high density) conditions in the top 15 cm depth of the soil profile. The bulk densities for these soils under a standard compaction treatment were calculated using regression equations developed by Kay et al. (1993b) for the soils at this site. These equations were based on soil properties such as those listed in Table 1. The values of bulk densities, both low and high density conditions, for the 7 soils are reported in Table 2. The bulk density of the soils ranged from 1.288 to 1.327 g cm^{-3} for the low density condition and from 1.362 to 1.451 g cm^{-3} for the high density condition.

2.5 Characteristics of the red clover material

Red clover shoot biomass was collected in early September 1993. Christie et al. (1992) reported the total biomass (shoot plus root) production of red clover as 3200 kg ha^{-1} (dry weight basis) in some Ontario soils. We decided to incorporate 6000 kg ha^{-1} (only the shoot biomass) in the top 15 cm depth of soil. The shoot biomass was dried at 80°C for 2 to 3 d and ground to < 2.00 mm for subsequent studies.

The total N content in the ground material was 2.36% and the C content was 45.9%. The amount of red clover N added to the soil was equivalent to about 140 kg ha^{-1} (75 mg legume-N kg^{-1} soil).

Table 2 Soil water and aeration characteristics at two bulk densities.

Soil	Bulk density ($g\ cm^{-3}$)		Total porosity %		Air-filled porosity (%) at -15 kPa		Water content at -15 kPa ($cm^3\ cm^{-3}$)	
	l	h	l	h	l	h	l	h
1	1.288	1.451	0.514	0.452	0.316	0.217	0.198	0.235
2	1.288	1.433	0.514	0.476	0.203	0.130	0.311	0.346
3	1.327	1.433	0.499	0.459	0.241	0.170	0.258	0.289
4	1.311	1.415	0.505	0.466	0.208	0.135	0.297	0.331
5	1.327	1.433	0.499	0.459	0.264	0.196	0.235	0.263
6	1.264	1.362	0.523	0.486	0.170	0.095	0.353	0.391
7	1.288	1.362	0.514	0.486	0.161	0.041	0.401	0.446

The letters l and h refer to values of bulk density at low and high density conditions, respectively.

2.6 Establishment of water retention curves

Water retention curves were established for the 7 soils, using soil columns packed to two bulk densities for each soil (Table 2). Soil was packed in aluminum rings 4.8 cm internal diameter and 2.5 cm in height. Subsequent to adjustment for air-dry moisture content, the amount of soil required to pack a ring at a given bulk density for a given soil, was weighed out and the packing was carried out using the procedure described by Klute (1986). A cheese cloth was tied to one of the circular faces of the ring to hold the soil in the ring while packing and wetting. The packing was carried out with and without red clover in order to determine the influence of red clover incorporation on water retention. There were three replicates for each treatment of a given soil at a given bulk density. The packed rings were set on a tray containing 1 cm depth of distilled water. The soil in the ring was allowed to saturate for about 48 hr and then transferred to a 1 cm suction table and allowed to drain for 30 minutes. The rings were then transferred to a pressure plate apparatus and the water content was determined after equilibration at -5, -10, -30, -60, -100, and -200 kPa tension.

Using the water content-tension data, water retention curves were established for each soil at each bulk density, with and without red clover addition. Statistical analysis (not reported here) indicated that clover addition did not have a significant influence on water retention for any soil at either bulk density. However, water retention varied with soil and with variation in bulk density. Thus, the water content-tension data for the two clover treatments were pooled for a given soil and a given bulk density and the data fitted to Gardner's(1958) equation,

$$1_v = \mathbf{a}\, R^{-b} \qquad [3]$$

where a and b are regression constants, 1_v is volumetric water content, and R is tension in kPa. The best fits were significant at P # 0.05 for each soil and at each bulk density and the R^2 values for the best fits ranged from 0.91 to 0.99 (not shown here). The fitted equations were then used to compute the water content at -15 kPa for each soil and at each bulk density. The values of total porosity and the water content at -15 kPa were used to compute the air-filled porosity, AFP, at -15 kPa and the results are reported in Table 2. The AFP at -15 kPa ranged from 0.16 to 0.32% for the low density condition and from 0.04 to 0.22 for the high density condition. The AFP values suggests that aeration would not be a limiting factor during incubation with the possible exceptions of soils 6 and 7 under the high density condition.

2.7 Computation of volume fraction of pores

The water content-tension data were also used to compute volume fraction of pores, VFP, occupied by pores in a given size range. The following equation was used to compute the average effective pore diameter, d, in µm,

$$\mathbf{d = 300/}\, R \qquad \mathbf{[4]}$$

here R is tension in kPa. Using the water content-tension relation, the VFP, of a given size range was calculated. For, example the size of pores at -15 kPa is 20 µm and that at -30 kPa is 10 µm. The VFP in the size range from 20 to 10 µm is considered to be equal to the difference in the volumetric water content between -15 and -30 kPa. The VFP between 10 to 20 (S_1), 5 to 10 (S_2), 3 to 5 (S_3), 1.5 to 3 (S_4), and < 1.5 µm (S_7) were computed. The VFP in the size range 5 to 20 µm was abbreviated S_5 and those 1.5 to 5 µm as S_6.

2.8 The relation between bulk soil properties

Simple linear correlations between bulk soil properties, listed in Tables 1 and 2, were carried out and indicated (Table 3) that significant positive correlation existed between clay, and silt, organic matter, total-N, and CEC. The AFP at -15 kPa was negatively correlated with clay and organic matter content and positively with total-N and $CaCO_3$.

Table 3. Simple correlation between soil properties listed in Tables 1 and 2.

	Silt	OM	CN	TN	BD	AFP	CEC	pH	$CaCO_3$
Clay	* +	* +	ns	* +	ns	* -	* +	ns	* -
Silt		ns	ns	* +	ns	ns	ns	ns	ns
OM			ns	* +	ns	* -	* +	* +	* -
TN				* -	ns	ns	ns	* +	ns
BD					ns	* +	* +	ns	* -
AFP						ns	ns	ns	ns
CEC							ns	ns	* +
pH								* +	ns
$CaCO_3$									ns

OM =organic matter, CN = C: N ratio, TN = total N. CEC = cation exchange capacity, BD =bulk density, AFP = air filled porosity. * and us are significant and not significant, respectively, at P# 0.05 and the + or - sign indicate the relation was positive or negative.

2.9 Incubation Experiments

Soil columns for incubation were packed in the same size aluminum rings and at two bulk densities using the same procedure that was used for water retention measurements. Before packing, the required amount of red clover material was mixed with the soil for the treatments. The control in the experiment was no red clover incorporation. There were four replicates for each treatment. Subsequent to packing, the amount of water required to bring a given soil column to -15 kPa (Table 2) was applied. The soil column was then transferred to an zip-lock air-tight PVC bag in order to reduce evaporation during incubation. However, two to three pinprick holes were made on the bag to ensure sufficient aeration. There were 102 columns, i.e. 7 soil x 2 bulk density x 2 treatment x 4 replicates. Nitrate- and ammonium-N, biomass C and N and moisture content were measured after incubation periods of 14, 21, 32, 42, 56, and 70 d. The incubation was conducted in a room maintained at a temperature of 23 $\pm$ 1°C.

About of one-quarter of the soil from a column was used for N and biomass determination. Soil nitrate- and ammonium-N determinations were carried out using the procedure described by Keeney and Nelson (1982) and expressed as mg kg^{-1} soil on an oven-dry mass basis. The biomass N and C determinations were carried out using the procedure described by Vance et al. (l987) and also expressed as mg kg^{-1} soil. The biomass data are not extensively reported in this report, other than to substantiate any anomalies in nitrate-N data.

2.10 Statistical Analyses

The statistical analyses were carried out using the SAS and Statgraphics soft-ware packages (1991). The simple best fit procedure was used for correlation analysis. The simple correlation analysis between N-mineralization parameters and bulk soil properties provided information on the nature of the relation. Similar analyses were also carried out between N-mineralization parameters and VFP belonging to different size classes. The combined influence of bulk soil properties on N mineralization parameters was obtained using stepwise variable selection analysis, with forward force in force out technique. The empirical functions obtained in this analysis are called pedotransfer functions, PTF. Similarly, the combined influence of VFP belonging to different size classes was explored using the stepwise procedure. Finally, the influence of bulk soil properties and VFP on the N mineralization was explored using the stepwise procedure. Because the VFP was influenced by bulk properties, we decided to drop those bulk properties that had a significant correlation with VFP during the stepwise analysis. For example, if VFP in a given size range was linearly related only with clay and not with other soil properties, then clay content was excluded in the stepwise analysis relating N-mineralization parameters to bulk soil properties and VFP.

3.0 RESULTS AND DISCUSSION

3.1 N-mineralization

The temporal variation in inorganic-N (ammonium plus nitrate) for soil 1 with red clover addition and packed at low and high bulk densities are shown in Fig. la. The corresponding data for the control are shown Fig. lb. For comparison and contrast the data is shown in Fig. 2 for soil 6. Until day 21 the N-mineralization from the control was greater than that from the treatment (Figs. 1 & 2). The biomass-N data during this period indicated that biomass N in the treatment was twice much as that in the control (Fig. 3). Thus, until day 21, N-immobilization was greater than N-mineralization in the treatment, therefore the amount of inorganic-N in the treatment was less than that in the control. The increase in bulk density resulted in an increase in N-mineralization both in the treatment and in the control in soil 1 (Fig. la & b). An opposite trend was observed in soil 6 (Fig. 2 a & b). It is speculated that, since 61% of the pore space in soil 1 is air-filled at the low bulk density, the increase in bulk density increased the accessibility of the organic substrates to decomposers and their predators. In soil 6, on the other hand, only 32% of the pore space at the low bulk density was air-filled and the increase in bulk density may have contributed to either increased denitrification or increased protection of the organic substrates by increasing the volume fraction of small pores.

3.2 Fitting N-mineralization data to first order rate equations

The nitrate-N data obtained for the 7 soils during the 70 day incubation period was fitted to Eq. [2] using the Marquardt's (1963) non-linear fitting technique. The model converged to solution, i.e, produced estimates for the N-mineralization parameters, for the inorganic-N data obtained from the treatment, i.e., with red clover, (Fig. la) but not with that from the

Figure 1a. Inorganic-N mineralized from soil 1 at high and low bulk density subsequent to red clover incorporation (each data point is the mean of four measurements).

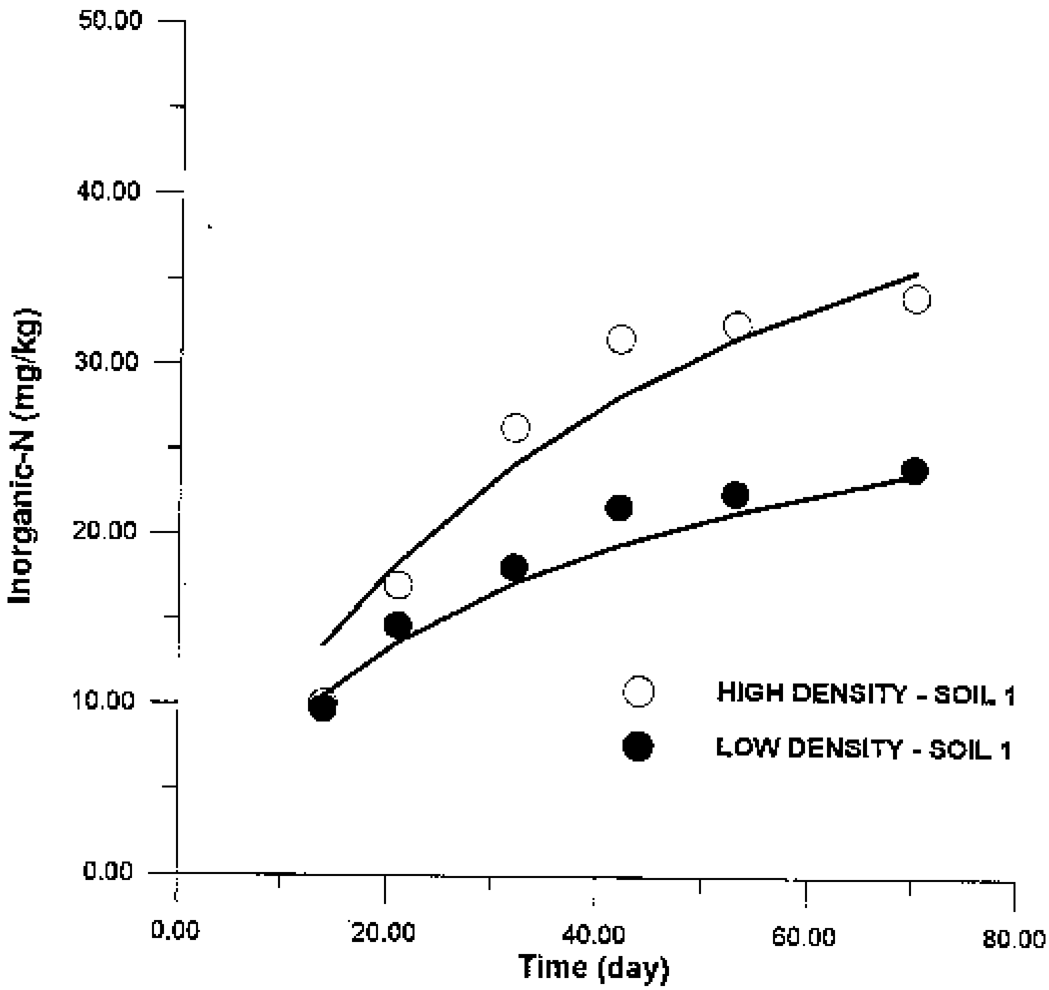


Figure 1b. Inorganic-N mineralized from soil 1 at high and low bulk density without red clover addition (each data point is the mean of four measurements).

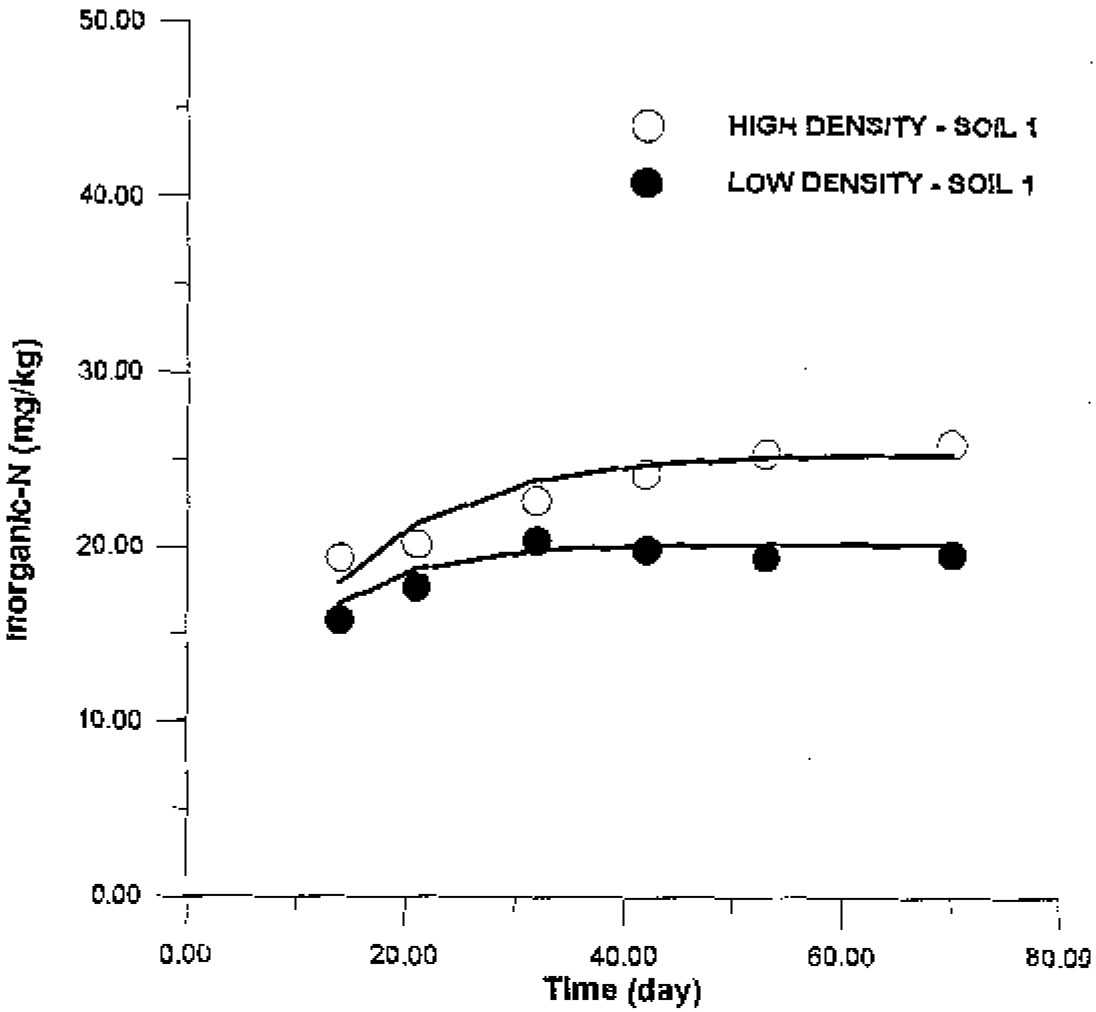


Figure 2a. Inorganic-N mineralized from soil 6 at high and low bulk density subsequent to red clover incorporation (each data point is the mean of four measurements).

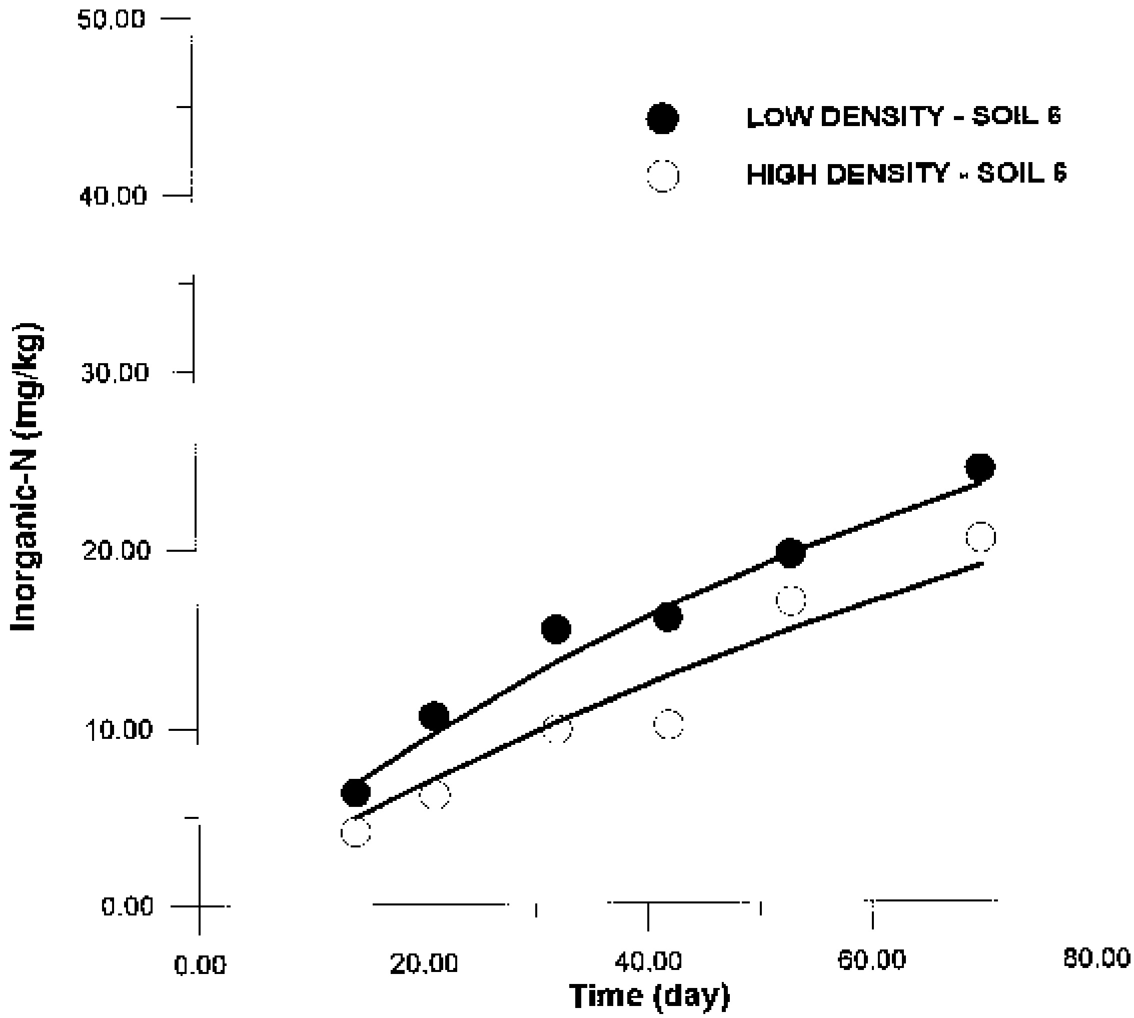


Figure 2b. Inorganic-N mineralized from soil 6 at high and low bulk density without red clover addition (each data point is the mean of four measurements).

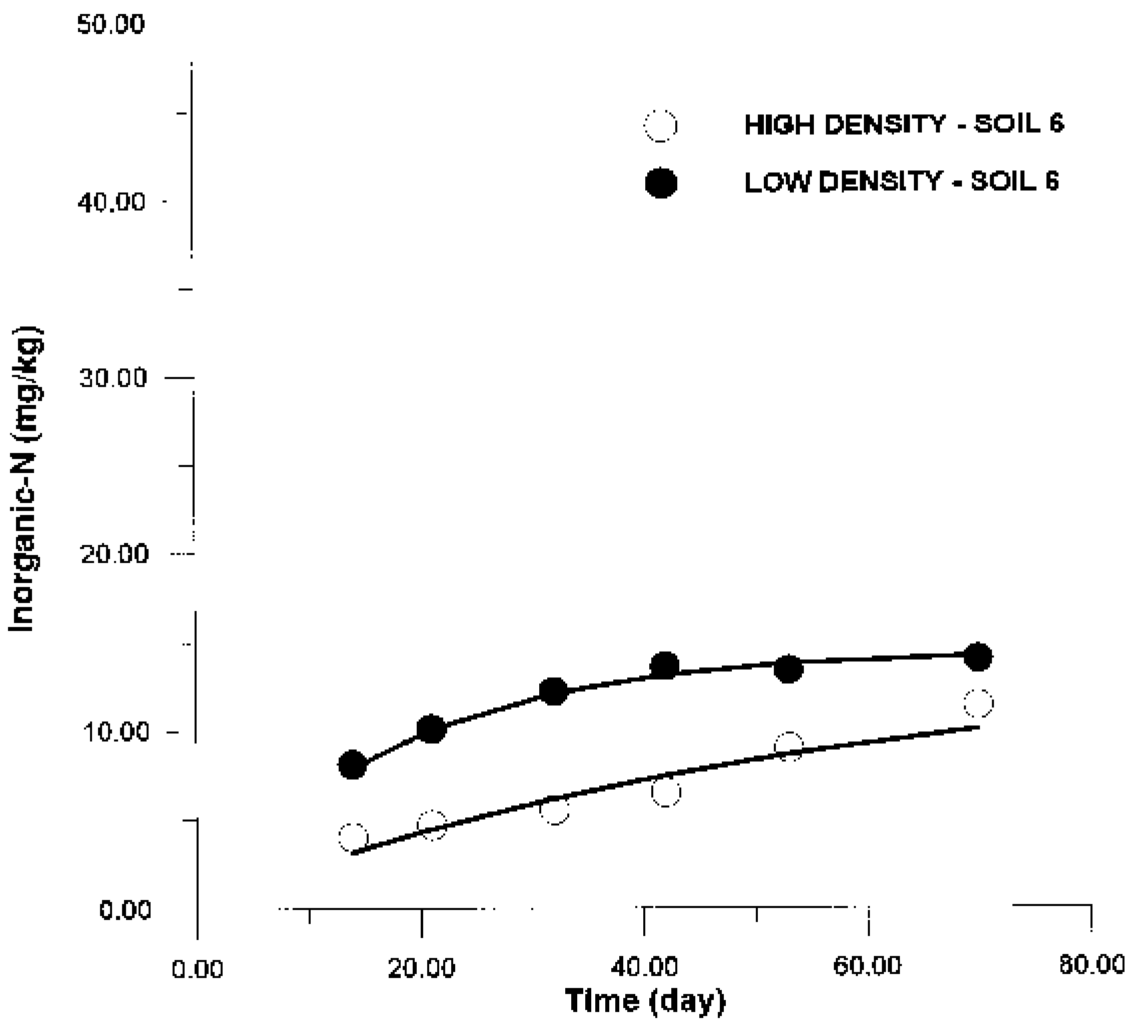
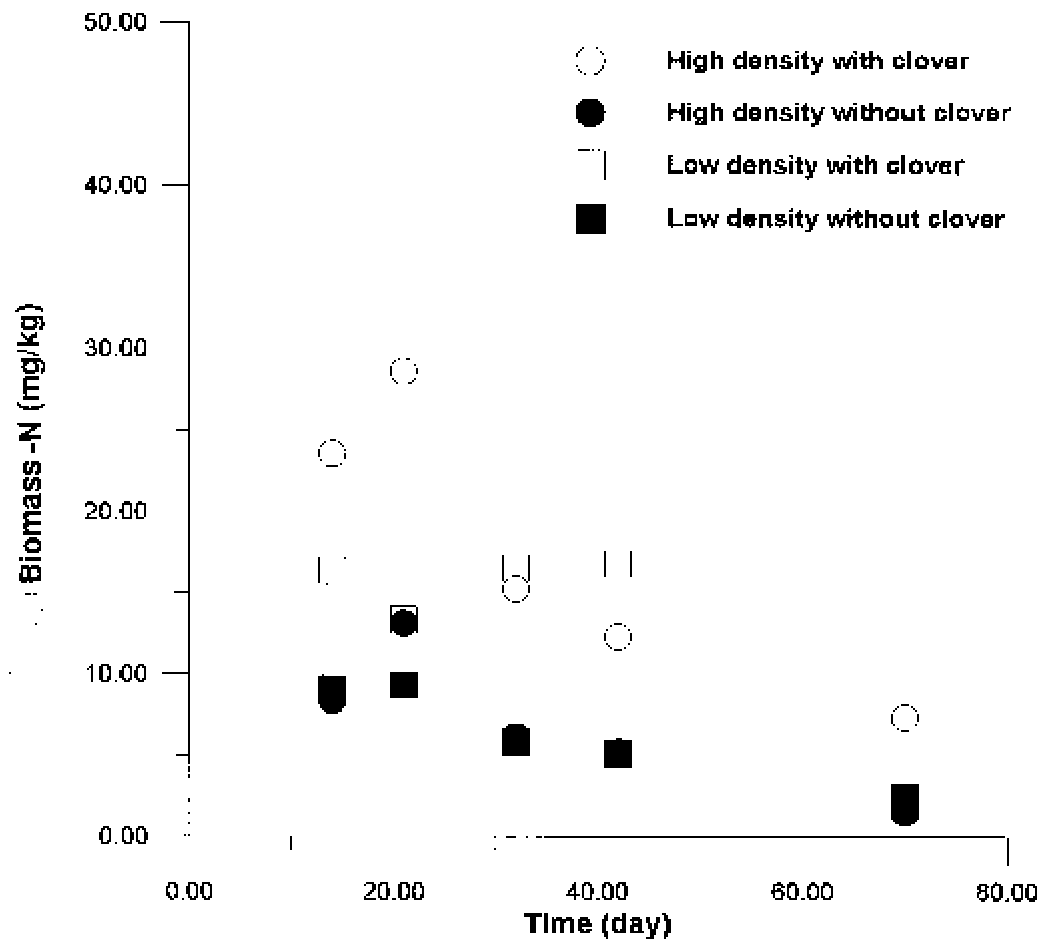


Figure 3. Biomass-N measured from soil 1 at high and low bulk density and with and without red clover (each data point is the mean of four measurements).



corresponding control, i.e., without clover. The N-mineralization data from the control was fitted to Eq. [1] using the same fitting procedure, as described previously, and the model converged to solution. Each non-linear best fit was significant at P # 0.05 and the R^2 values for the best fits ranged from 0.63 to 0.99 (Table 4).

Table 4. Values of N-mineralization parameters obtained for the 7 soils with and without red clover incorporation.

Soil	N_0	Nr	N_l	k_0	k_r	k_l	R^2_0	R^2_2
	Values at low bulk density							
1	22.21	33.69	14.93	0.1245	0.0044	0.0596	0.84	0.91
2	22.01	51.30	14.94	0.1313	0.0056	0.0176	0.63	0.99
3	22.63	33.43	20.34	0.1279	0.0038	0.0329	0.84	0.97
4	21.74	49.47	14.49	0.0987	0.0060	0.0165	0.96	0.99
5	25.41	31.25	20.55	0.0923	0.0040	0.0299	0.98	0.97
6	18.82	28.16	17.04	0.0693	0.0050	0.0243	0.85	0.89
7	14.42	43.68	14.34	0.0561	0.0044	0.0247	0.88	0.95
	Values at high bulk density							
1	25.41	34.71	27.11	0.0872	0.0051	0.0375	0.89	0.86
2	19.18	68.12	10.32	0.0414	0.0065	0.0112	0.99	0.92
3	20.72	54.40	16.42	0.0981	0.0050	0.0253	0.80	0.96
4	21.32	61.84	11.84	0.0626	0.0052	0.0149	0.71	0.98
5	23.87	35.83	20.62	0.0529	0.0063	0.0299	0.98	0.97
6	11.81	67.41	11.22	0.0614	0.0051	0.0081	0.79	0.89
7	13.97	46.66	8.32	0.0179	0.0045	0.0200	0.83	0.96

N= potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to N-mineralization parameters for the one pool model (control), r and 1 refer to the resistant and labile N-pools, respectively, of the two pool model (red clover treatment) and the corresponding rate constants. The subscript 2 refers to the two pool model.

The N-mineralization data were regressed with soil properties and time to determine whether a multiple regression could be used to predict nitrate-N instead of Eq. [2]. The best fit was not significant indicating that Eq. [2] was the most appropriate form to predict legume-N mineralization.

3.3 Estimates of N-mineralization parameters

The size of the potentially mineralizable resistant N-pool, N_r, obtained using Eq. [2], ranged from 28.16 to 51.30 mg kg^{-1} soil for the low density treatment, and that of the labile pool, N_l, ranged from 14.34 to 20.55 mg kg^{-1} (Table 4). The corresponding range in the rate constant of the resistant pool, k_r, was from 0.0038 to 0.0056 d^{-1} and that of the labile, k_l was from 0.0165 to 0.0596 d^{-1}. The ranges in values of N_r, N_l, k_r and k_l, obtained for the high density treatment were similar to that obtained for the low density condition. However, in general, the values of N_r obtained for high density treatment were greater than the corresponding values obtained for low density treatment and an opposite trend was observed for the values of N_l. Higher bulk densities decreased the values of k_l, to a larger extent than that of k_r.

The size of the potentially mineralizable N-pool, N_o, obtained for the control at low density ranged from 14.42 to 27.21 mg kg^{-1} and the corresponding range in rate constant, k_0, was from 0.0561 to 0.1245 d^{-1} (Table 4). The range in values of the N-pool size and the corresponding rate constant obtained for the high density treatment for the control was less than the corresponding range obtained for the low density treatment. A comparison of the values of N_r, plus N_l, for a given soil, with the corresponding value of N_o indicates the size of the potentially mineralizable N-pool substantially increased following the incorporation of red clover. Values of k_0, for a given soil and at a give bulk density, were greater than the corresponding values of k_r or k_l,. It appears that clover incorporation substantially altered the nature and size of the potentially mineralizable N-pool and the rate constant of these pools.

Limited information exists in the literature regarding the values of N-mineralization parameters for different soils. The values of N_l, reported in this study, in general, are similar to those reported by Cabrera and Kissel (1988), i.e., 17 to 30 mg kg^{-1}, for the mineralization of sorghum residue in soils with similar range in clay content. The values of N_r reported by them ranged from 137 to 207 mg kg^{-1} compared to 28 to 68 mg kg^{-1} in this study. Values of k_l and k_r showed an order of magnitude difference between them (Table

4) a trend which is similar to that observed by Cabrera and Kissel (1988). However, the range in values of k_l, 0.014 to 0.163 d^{-1}, reported by Cabrera and Kissel (1988) is greater than that obtained, 0.0165 to 0.0596 d^{-1}, in this study. The range in values of k_r obtained in this study is comparable to that reported by Cabrera and Kissel (1988).

The values of N_l, N_r, k_l, and k_r obtained for soil 1 and 6 and at two bulk densities were used to model the amount of inorganic-N produced from the labile and resistant pools individually (Fig. 4a & b). At high density, about 70% of the total inorganic-N produced from soil 1 in 70 d was from the labile N-pool compared to 37% from soil 6 (Fig. 4a). Under low density condition, a similar trend, 60%, was observed in soil 1, however, in soil 6 the amount of inorganic-N produced from the labile and resistant pools were approximately similar, i.e., 50:50. It should, however, be noticed that the total amount of inorganic-N produced under the high density condition was approximately twice that under the low density condition for either soil. It seems that reduced tillage (high bulk density) enhanced the amount of inorganic-N produced both in the coarse and fine textured soil.

3.4 Interrelation between the N-mineralization parameters

Aeration may have been limiting N-mineralization or contributing to denitrification in soil 6 and 7 under the high density condition since the air-filled porosity was less than 10%. Consequently we dropped the values of N_r, N_l, N_o, k_r, k_l, and k_0 for these two soils in all the regression analyses hereafter. The size of the potentially mineralizable N pool from the control, obtained using Eq. [1], i.e. N_o, was positively correlated with N_l, of the treatments, obtained using Eq. [2]. No significant relation existed between N_o and N_r (Table 5).

The source of N that underwent rapid mineralization from the control (Fig. lb & 2b) may have been similar to that of N_l and we suggest that it was the labile biomass from the previous summer's crop. Significant and positive correlations between k_0 and k_l and between N_o and k_l suggest the labile material that underwent mineralization in the control was similar to that found in the treatments.

The size of N_r decreased with increasing size of N_l and with increasing k_l (Table 6). If N_r and N_l, are largely determined by the material added, and since the amount of N added was relatively

Figure 4a. The amount of inorganic-N produced from the labile and resistant N-pools from soil 1 and 6 under high density conditions.

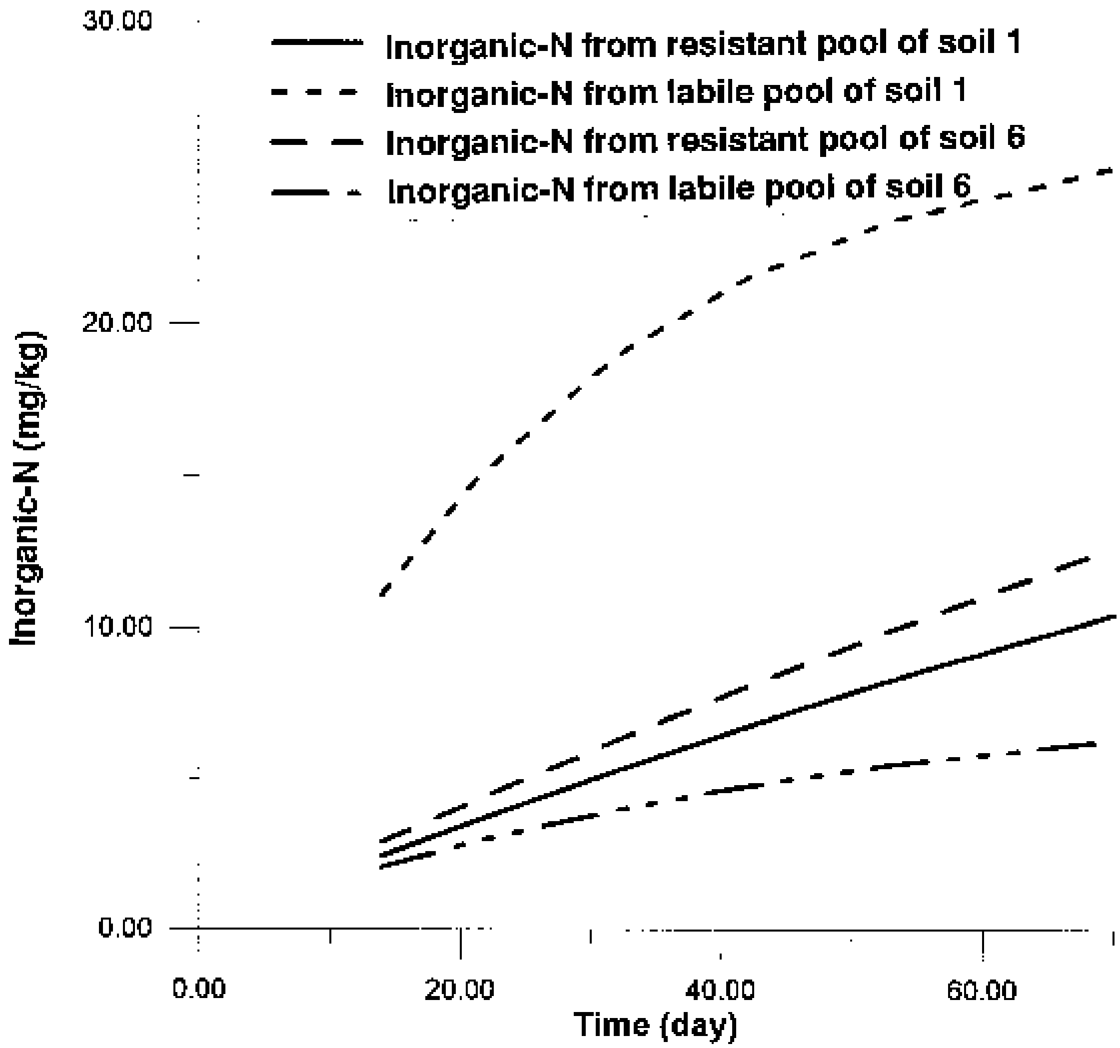
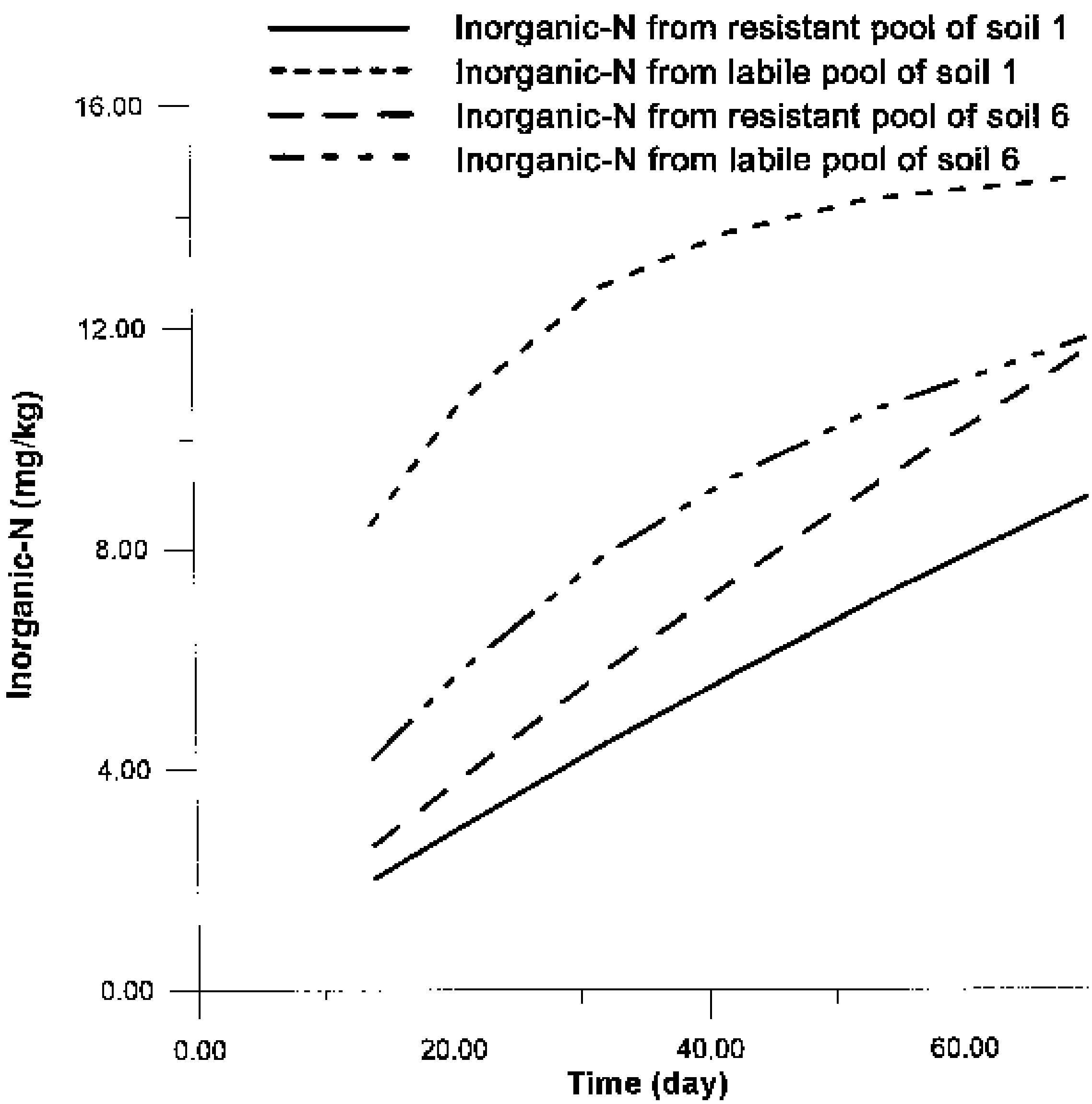


Figure 4b. The amount of inorganic-N produced from the labile and resistant N-pools from soil 1 and 6 under low density conditions.



constant, then an inverse relation between N_r and N_l would be expected. A significant positive correlation between N-pools and their corresponding rate constants suggests that the larger the size of the pool, the greater is the rate constant. The relations presented in Table 6 indicate that the rate constant increased in a power fashion with increasing pool size. This suggests the potential amount of N released increased rapidly with the amount of clover incorporated.

Table 5. The relations between N-mineralization parameters.

Parameters					
	N_r	N_l	k_0	k_r	k_l
N_o	ns	* +	ns	ns	* +
N_r		* -	ns	* +	* -
N_l			ns	ns	* +
k_0				ns	ns
k_r					ns

N = potentially mineralizable nitrogen, k = rate constant. The subscripts r and 1 refer to the resistant and labile N pools, respectively, of the two pool model and the corresponding rate constants and 0 refers to the one pool model. * = significant at P# 0.05, ns = not significant at P# 0.05. The - or + sign indicates the correlation was negative or positive.

Table 6. Simple best fit relation between the N-mineralization parameters of the one and two pool models.

Simple best fit equation	R^2
$N_r = 75.24 - 1.86\ N_l$	0.47
$N_r = 3.16 \times 10^8\ k_r^{\ 0.892}$	0.26
$N_r = 96.83\ k_l^{\ -0.473}$	0.67
$N_o = 11.03 + 0.603\ N_l$	0.43
$N_o = 14.63 + 237.60\ k_l$	0.45
$N_l = 1.66 \times 10^4\ k_l^{\ 0.394}$	0.41

N=potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N-pools, respectively, of the two pool model and the corresponding rate constants. The relations are significant at P # 0.05.

3.5 Influence of soil properties on N-mineralization parameters

The influence of each one of the soil properties listed in Table 1 and 2 on N-mineralization parameters and the corresponding significant simple best fit equations are provided in Tables 7 and 8, respectively. The striking features of these simple relations are that the rate constant of the resistant N pool, k_r, was not significantly influenced, individually, by any one of the soil properties listed in Table 1 and 2 and none of the N-mineralization parameters, obtained both for the treatment and control, were significantly influenced by soil pH or bulk density (Table 7). The R^2 values for the significant simple best fit relations ranged from 0.26 to 0.59 (Table 8). The rate constant of the labile pool, k_l, was sensitive to changes in most of the soil properties whereas N_l, N_o, and N_r correlated with fewer soil properties. The soil property that had a significant influence on all the N-mineralization parameters, exclusive of k_r, was AFP. This should not, however, be interpreted to mean that aeration was a major problem since, as indicated earlier in the text, the AFP was less than 10% on only soil 6 and 7 under the high density condition and these soils were excluded from the analyses. Similar information with regard to the influence of soil properties on N-mineralization parameters is practically nonexistent in the literature. However, Tabatabi and Al-Khafaji (1980) indicated that the cumulative amounts of N-mineralized from 12 soils were not significantly related to organic C or total-N, or soil pH. It should, however, be noted that their correlation analysis with soil properties was not carried out with the N-mineralization parameters as done in this study.

Table 7. Influence of soil properties on N-mineralization parameters.

	Soil Properties										
	Clay	Sand	Silt	OM	TN	CN	$CaCO_3$	pH	BD	AFP	CEC
N_r	ns	ns	ns	ns	*+	*-	*-	ns	ns	*-	ns
N_l	ns	ns	ns	*-	*-	*+	*+	ns	ns	*+	ns
k_r	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
k_l	*-	*+	*-	*-	*-	*+	*+	ns	ns	*+	ns
N_o	ns	ns	ns	*-	*-	ns	*+	ns	ns	*+	*-
k_0	ns	ns	ns	ns	ns	ns	ns	ns	ns	*+	ns

N=potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N-pools, respectively, of the two pool model and the corresponding rate constants. OM = organic matter, TN = total N, CN = carbon to nitrogen ratio, BD = bulk density, AFP = air filled porosity, CEC = cation exchange capacity. *= significant at P # 0.05. ns = not significant at P # 0.05. The + or - sign indicate the correlation was positive or negative.

Table 8. Significant simple best fit relations between the N-mineralization parameters and soil properties.

Simple best fit equation	R^2
$N_r = 7.05 \times 10^4\ TN^{0.54}$	0.26
$N_r = 2.69 \times 10^7\ CN^{-1.42}$	0.31
$N_r = 57.97 - 3.78\ CaCO_3$	0.36
$N_r = 67.36 - 118.97\ AFP$	0.38
$N_l = 6.03 \times 10^3\ OM^{-0.94}$	0.38
$N_l = 29.56 - 95.94\ TN$	0.50
$N_l = -8.49 + 1.86\ CN$	0.34
$N_l = 10.39 + 1.69\ CaCO_3$	0.53
$N_l = 3.72 \times 10^3\ AFP^{0.47}$	0.59
$k_l = 0.0116 + 4.94 \times 10^4$ sand	0.56
$k_l = 0.0627 - 8.13 \times 10^4$ silt	0.56
$k_l = 0.0504 - 9.63 \times 10^4$ clay	0.44
$k_l = 4.80 \times 10^{-5}\ CaCO_3^{\ 0.537}$	0.50
$k_l = 1.618 \times 10^{-2}\ OM^{-1.779}$	0.52
$k_l = 0.063 - 0.263\ TN$	0.55
$k_l = -0.0337 + 4.49 \times 10^{-3}\ CN$	0.29
$k_l = -4.24 \times 10^4 + 0.141\ AFP$	0.58
$N_o = 3.36 \times 10^5\ CEC^{-0.813}$	0.53
$N_o = 16.13 + 1.139\ CaCO^3$	0.35
$N_o = 33.07 - 4.20\ OM$	0.45
$N_o = 30.65 - 76.01\ TN$	0.45
$N_o = 2.95 \times 10^3\ AFP^{0.282}$	0.39
$ko = 0.09\ AFP^{0.839}$	0.58

N=potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N pools, respectively, of the two pool model and the corresponding rate constants. OM = organic matter, TN = total N, CN = carbon to nitrogen ratio, BD = bulk density, AFP = air filled porosity, CEC = cation exchange capacity.

The stepwise variable selection analysis indicated that from 58 to 93 % of the variability in the values of N- mineralization parameters was accounted for by bulk soil properties (Table 9). Based on the values of R^2 of the PTF's presented in Table 9, it seems that subsequent to red clover addition, soil properties had a greater influence on the values of k_l, N_l, and N_r than on k_r. In addition to bulk soil properties, values of N_l, N_r, k_l, and k_r, were significantly influenced by bulk density which may change subsequent to changes in management practices. However, simple correlation analysis indicated that none of these parameters were significantly influenced by bulk density (Table 7). Thus, it should be noted that simple correlation analyses alone are not sufficient to explore the influence of soil properties on N-mineralization parameters. Furthermore, the stepwise variable selection analyses also indicate that property or properties that do not have a simple significant relation with N-mineralization parameters can have an impact when several properties are involved simultaneously.

Table 9. The pedotransfer functions to predict N-mineralization parameters from soil properties

Equation	R^2
N_r = 79.03 BD - 2.20 CEC + 355.80 TN- 61.52	0.85
N_l = 6.27 clay + 106.29 BD + 1.72 $CaCO_3$ - 4.70 clay BD -131.75	0.88
k_r = 0.0014 OM + 0.0067 BD - 0.00014 CEC - 0.0051	0.58
k_l = 0.2113 + 0.0062 $CaCO_3$ - 0.0868 BD - 0.0045 CN - 0.00065 Silt	0.93
N_o = 148.81 BD + 225.56 TN - 192.37	0.77
k_o = 0.135 -0.00028 Silt- 0.181 TN - 0.0581 BD	0.90

N = potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N pools, respectively, of the two pool model and the corresponding rate constants. CN = carbon to nitrogen ratio, BD = bulk density (g cm^{-3}), TN = total N (%), AFP = air filled porosity at -15 kPa (%), $CaCO_3$ and clay contents in %, CEC = cation exchange capacity in meq/100 g, and clay in %. The equations are significant at P# 0.05.

The PTF presented in Table 9 for N_l indicate that it increased with increasing $CaCO_3$ content. A strong interaction involving clay and BD indicate that values of N_l increased with increasing clay, at constant density, at low clay content and the trend got reversed at high clay content. The interaction term also indicates the values of N_l increased with increasing bulk density at low clay content but the trend got reversed at high clay content. Thus, the influence of changes in bulk density caused by changes in tillage systems on the size of labile N-pool largely depends on the clay content. The increase in N_l with bulk density may, as noted earlier, be due to increased accessibility of the organic substrate to decomposers and their predators. At higher clay contents an increase in bulk density will lead to an increasing proportion of small pores that may physically protect the organic substrates from decomposition. Values of N_r increased with increasing bulk density and total-N and decreasing CEC. Unlike the labile N-pool, the resistant pool was not influenced by an interaction involving clay and bulk density. However, an increase in the size of the labile N-pool resulted in a decrease in the size of resistant N-pool (Table 6). Thus, an increase in clay content resulted in larger size of resistant N-pool. Increases in bulk density at high clay content also resulted in larger resistant N-pool.

The rate constant of the labile N-pool, k_l, was influenced by bulk characteristics: silt, C:N ratio, and $CaC0_3$, and by bulk density. Decreases in k_l, with increasing bulk density suggests the mineralization of legume-N under reduced till management system is slower than under conventional till.

The combined influence of soil properties on the rate constant of the resistant N-pool, k_r, showed a trend opposite to that of k_l, for changes in bulk density (Table 9). This suggests, that changes in tillage practices had the opposite impact in the amounts of legume-N released from the corresponding pools. It should, however, be noted that simple correlation analysis indicated that kr was not significantly influenced, individually, by soil properties (Table 6). The stepwise analysis again illustrates that researchers should not ignore the combined influence of soil properties on rate processes in soil even though no significant simple relations existed between them.

The size of the N-pool in the control, N_o was influenced by total-N and bulk density (Table 9). This sensitivity to bulk density suggests that management changes have an impact on the size of potentially mineralizable N even in the absence of substrate addition, i.e, without red clover. The rate constant k_o, was influenced by total-N, silt content, and bulk density. These soil factors accounted for 90% of the variability in k_o and it should also be noted that simple correlation analysis indicated that k_o was not significantly influenced, individually, by any one of the soil properties (Table 7).

Comparable information with regard to the combined influence of soil properties on N-mineralization parameters is practically non-existent in literature.

3.6 Influence of pore size characteristics on N mineralization

The stepwise variable selection analyses indicated that the N-mineralization parameters, N_r, N_l, k_r and k_l were significantly influenced by bulk density (Table 9). Changes in bulk density can have an impact on the volume fraction of pores, VFP, in a given size range, particularly on the larger size pores. Simple correlation analyses between VFP and soil properties indicated significant correlations between selected VFP and soil properties (Table 10). Recent studies (Kay et al. 1993b) showed that pore characteristics can be related to textural and other soil characteristics which change when tillage is reduced (organic matter content and bulk density). The influence of soil properties on VFP (Table 10) indicates that soil properties, exclusive of soil pH, had a significant influence on VFP in each size class. The VFP #1.5µm in diameter, S_7, were influenced by all of the soil properties listed in Table 1, except pH. This size class of pores is considered to be devoid of microbial grazers and most microorganisms (Hattori, 1988; Amato and Ladd, 1992; Killham et al., 1993; Juma et al., 1993). Simple organic exudates and small bacteria could, however, diffuse into these pores, thereby reducing their availability for further microbial degradation. The VFP in the size range 10 to 20 µm, S_1, are also influenced by several soil properties. These pores are probably accessible to microbial grazers (Juma et al., 1993). The VFP in the range 5 to 10 (S_2) and 3 to 5 (S_3) µm were not influenced by any of the soil properties (Table 1). The VFP in the size range 1.5 to 3 µm (S_4) are considered to be accessible to microorganisms but not to microbial grazers (Killham et al., 1993; Juma et al., 1993). The analyses presented in Table 10 suggest that VFP belonging to pores from 3 to 20 µm are negatively influenced by bulk density whereas pores smaller than 1.5 µm are positively correlated with B.D.

Correlations also exist between the VFP in different size classes (Table 11). As a generalization the VFP tend to be positively associated with nearest size classes and negatively correlated with those farthest away.

Table 10. Simple linear relation between volume fraction of pores belonging to different size classes and soil properties.

	Clay	Silt	OM	TN	$CaCO_3$	pH	CN	CEC	BD
				(.......... % ....)				meq /100g	g cm^{-3}
S_1	-	ns	* -	* -	* -	ns	*+	ns	* -
S_2	ns	ns	ns	ns	ns	ns	ns	ns	* -
S_3	ns	ns	ns	ns	ns	ns	ns	ns	* -
S_4	*+	*+	ns	*+	ns	ns	ns	ns	ns
S_5	ns	ns	* -	* -	*+	ns	*+	ns	* -
S_6	ns	*+	ns	ns	ns	ns	ns	ns	ns
S_7	*+	*+	*+	*+	* -	ns	* -	*+	*+

+ = positive, - = negative, ns = not significant at P #0.05, *= significant at P # 0.05.
The volume fraction of pores in the 10 to 20 µm is abbreviated S_l. Similarly, S_2 = 5 to 10 µm, S_3 = 3 to 5 µm, S_4 =1.5 to 3 µm, S_5 = 5 to20 µm, S_6 = 1.5 to 5 µm, S_7 < 1.5 µm.

Table 11. Correlation between the volume fraction of pores belonging different size classes.

Volume fraction of pores in different size classes						
	S_1	S_2	S_3	S_4	S_5	S_6
S_7	* -	ns	ns	* +	* -	ns
S_6	ns	* +	* +	* +	ns	
S_5	* +	ns	ns	* -		
S_4	* -	* +	* +			
S_3	ns	* +				
S_2	ns					

+ = positive , -= negative , ns= not significant at P # 0.05, * = significant at P #0.05 . The volume fraction of pores in the size range 10 to 20 µm is abbreviated S_1,. Similarly, S_2 = 5 to 10 µm, S_3 = 3 to 5 µm, S_4 = 1.5 to 3 µm, S_5 = 5 to 20 µm, S_6 = 1.5 to 5 µm, S_7 < 1.5 µm

Simple correlation analyses indicated the size of the labile N-pool, N,, increased with increasing A, or decreasing S_7 (Table 12). A larger proportion of the S_1 class of pores is related to greater opportunity for microbial predation. Thus, increases in N_l with increasing S_1 suggest microbially immobilized-N was released to the environment as S_1 increases. Decreases in N_l with increasing S_7 is attributed to physical protection of molecular sized fraction of the N-pool. Values of k_l, showed trends similar to those observed for N_l for changes in S_1, and S_7. Thus, the mineralization of labile N-pool increased with the VFP in which predation would occur and decreased with the VFP in which physical protection of molecular sized form of N is enhanced. In addition, k_l decreased with increasing S_4, suggesting that microbial immobilization of N reduced its availability for mineralization. Values of N_r showed trends opposite to that of N_l for changes in S_1 and S_7 suggesting that increases in predation reduced the accumulation of resistant N-pool, whereas increases in physical protection within smaller pores increased the size of resistant N-pool. Values of N_o decreased with increasing S_7, a trend similar to that observed for N_l. Values of k_r and k_o were not significantly influenced, individually by VFP.

The stepwise variable selection analysis on the influence of VFP on N-mineralization parameters indicated that 45 to 78 % of the variability in these parameters are accounted for VFP (Table 13). Seventy eight percent of the variability in N_l was accounted for by S_2 and S_7. The S_2 pores are also believed to be part of the habitat of microbial grazers (Juma et al., 1993), thus the size of labile N-pool was determined by pores that serve as habitat for microbial grazers and those that physically protect molecular form of N from microbial degradation. Values of k_l, were influenced by S_4 and S_7 pores and they accounted for 73% of the variability in k_l. The size of the resistant pool was influenced only by S_7 pores and it accounted for only 45% of the variability in N_r. The rate constant of the resistant N-pool was not influenced by VFP.

The regression analyses between N-mineralization parameters and VFP indicated that N_l and k_l, were more strongly influenced by VFP than N_r and k_r (Tables 12 and 13). A similar trend was observed for the influence of bulk soil properties (Tables 1 and 2) on N_l and k_l, compared to that of N_r and k_r (Tables 8 & 9). The results indicate the size of the labile N-pool and its rate constant are more strongly influenced by VFP and bulk soil properties than the resistant N-pool and its rate constant. The regression equations presented in Tables 9 and 13 for N_r and k_r indicate that bulk soil properties largely accounted for the variabilities in these parameters.

Table 12. Simple best fit relations between N-mineralization parameters and volume fraction of pores belonging to different size classes.

Simple best fit equations	R^2
$N_r = 55.91 - 500.15\ S_1$	0.44
$N_r = 66.\ 24 - 472.98\ S_5$	0.44
$N_r = 19.28 + 118.84\ S_7$	0.45
$N_l = 12.10 + 186.01\ S_l$	0.44
$N_l = 27.46 - 52.01\ S_7$	0.64
$k_l = 0.0136 + 0.565\ S_l$	0.61
$k_l = 0.0798 - 2.418\ S_4$	0.46
$k_l = 5.127 \times 10\text{-}3 + 0.462\ S_5$	0.46
$k_l = 0.0552 - 0.135\ S_7$	0.63
$N_o = 27.73 - 35.54\ S_7$	0.43

N = potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N pools, respectively, of the two pool model and the corresponding rate constants. The volume fraction of pores belonging to the 10 to 20 µm size range is abbreviated S_l. Similarly, S_2 = 5 to 10 µm, S_3 = 3 to 5 µm, S_4 = 1.5 to 3 µm, S_5 = 5 to 20 µm, S_6 = 1.5 to 5 µm, S_7 < 1.5 µm.

Table 13. Multiple regression equations relating N-mineralization parameters to volume fraction of pores belonging to different size classes.

Equation	R^2
$N_r = 19.28 + 118.84\ S_7$	0.45
$N_l = 20.36 + 363.49\ S_2 - 57.78\ S_7$	0.78
$N_o = 15.18 + 728.17\ S_4 - 53.20\ S_7$	0.73
$k_l = 0.0777 - 1.309\ S_4 - 0.103\ S_7$	0.73

N = potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N pools, respectively, of the two pool model and the corresponding rate constants. The volume fraction of pores in size range 10 to 20 µm is abbreviated S_1,. Similarly, S_2 = 5 to 10 µm, S_3 = 3 to 5 µm, S_4 = 1.5 to 3 µm, S_5 = 5 to 20 µm, S_6 = 1.5 to 5 µm, S_7 < 1.5 µm.

In order to reduce the number of variables involved in the stepwise selection analysis to determine the combined influence of bulk soil properties and VFP on N-mineralization parameters the following procedure was followed. Based on the simple correlation between bulk soil properties and VFP (Table 10), the bulk soil properties that had significant correlation with VFP were disregarded in further analyses. For example, N_l was influenced both by S_2 and S_7 (Table 13) and the only bulk soil property that did not have significant relation with S_2 and S_7 was pH (Table 10). Thus, the influence of soil pH in conjunction with that of S_2 and S_7 was explored using the stepwise variable selection (Table 14). These analyses indicate that inclusion of pH along with S_7 substantially increased the R^2 values of the PTF's for N_r (Tables 13 and 14). On the other hand, the values of N_l, and k_l, (Tables 13 and 14) were not influenced by inherent soil properties.

A comparison of the R^2 values of predictive equations presented on Table 9 and 14 for N_r, k_r, N_l and k_l, indicates PTF's developed using the information only on bulk soil properties have higher R^2 than those obtained using the information on VFP and soil properties. Furthermore, k_r couldn't be defined as a function of soil properties and VFP. Thus, the information on inherent soil properties alone seem to be sufficient to predict values for the N-mineralization parameters. The analyses involving VFP are of greatest value in understanding the mechanisms whereby bulk soil properties influence mineralization. For instance, incubation studies in which pores larger than 5 µm are drained (R = 60 kPa) would not be expected to involve predation of microorganisms thereby reflecting smaller values of N_l (Table 14). At this potential the influence of B.D. on mineralization would also be different (Table 10).

Table 14. Equations relating N-mineralization parameters to inherent soil properties and volume fraction of pores belonging to different size classes.

Equation	R^2
$N_r = 520.14 - 69.26\ pH + 145.84\ S_7$	0.71
$N_l = 382.36\ S_2 - 57.20\ S_7 - 2.66$	0.82
$k_l = 0.0777 - 1.3091\ S_4 - 0.1031\ S_7$	0.73
$N_o = 94.66 + 796.77\ S_4 - 16.66\ S_7 - 11.20\ pH$	0.80

N = potentially mineralizable nitrogen, k = rate constant. The subscript 0 refers to one pool model and r and 1 refer to the resistant and labile N pools, respectively, of the two pool model and the corresponding rate constants. The volume fraction of pores in size range 10 to 20 µm is abbreviated S_1,. Similarly, S_2 = 5 to 10 µm, S_3 = 3 to 5 µm, S_4 = 1.5 to 3 µm, S_5 = 5 to 20 µm, S_6 = 1.5 to 5 µm, S_7 < 1.5 µm.

4.0 CONCLUSIONS

The following conclusions relate to the influence of soil properties and soil management changes on the production of nitrate-N from legumes:

C Clay and $CaCO_3$ contents, bulk density, and an interaction term involving clay and bulk density determined the size of the labile-N pool, N_l, ie. the readily available legume-N, subsequent to red clover incorporation. The rate constant of this pool, k_l, was influenced, in addition to bulk density and $CaCO_3$, by C:N ratio and silt content.

C The size of the resistant N-pool, N_r, was determined by bulk density, CEC and total-N. In addition to bulk density and CEC, organic matter content determined the rate constant, k_r, of the resistant pool.

C The influence of reduced tillage on N-mineralization, as characterized by differences in bulk density, is attributed to differences in volume fraction of pores, VFP, belonging to different size classes. The size of N_l decreased with a decrease in the VFP in the size range from 5 to 20 µm and the VFP of these pores decreased with increasing bulk density. The size of N_l also decreased with increasing VFP # 1.5 µm in size and the VFP of these pores increased with increasing bulk density, clay, silt, organic matter, and total-N contents. The decrease in N_l with a decrease in the VFP 5 to 20 µm in diameter is attributed to a decrease in predation, that releases microbial-N to the labile N-pool. The decrease in N_l with increasing VFP # 1.5 µm is attributed to physical protection, of simple molecular fractions of N.

- Even though both bulk soil properties and the VFP belonging to different size classes had significant influences on the N-mineralization parameters, values for these parameters can be predicted from information on bulk soil properties alone.

- The source of approximately two-thirds of the nitrate-N that was produced in a coarse textured soil originated from the labile N-pool. On the other hand, approximately equivalent amounts of nitrate-N were produced from the labile and resistant N-pools in a fine textured soil.

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