Increased proportion of active soil N in Breton loam under cropping systems with forages and green manures

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Wani, S. P., McGill, W. B., Haugen-Kozyra, K. L. and Juma, N. G. 1994. **Increased proportion of active soil N in Breton loam under cropping systems with forages and green manures.** Can. J. Soil Sci. **74**: 67–74. Total soil N and N mineralization rate partially characterize the influence of various cropping systems on the growth of sequent crops in a rotation. The objectives of this study were to (1) quantify the relationship among cropping system, total N and mineralizable N; and (2) compare amount of N mineralized under controlled laboratory conditions with plant N uptake under greenhouse conditions. Three cropping systems that have been in operation between 9 and 60 yr on a Gray Luvisol (Breton loam) were selected. They included: (1) an **agro-ecological (AER) 8-yr rotation** involving fababeans as green manure (AER1 sampled after the first fababean crop and AER2 sampled after 3 yr of continuous forage); (2) **continuous grain system (CG)**, with fertilizer N at 90 kg ha^{-1} yr^{-1}; initiated in 1980 and considered established in 1981; (3) a **classicial Breton rotation (CBR)** involving a long-term (ca. 1930) 5-yr rotation with forages and cereals and no return of crop residues (CBR1 fertilized with P-K-S and CBR2 unfertilized). We caution that not all phases of each rotation were sampled; our conclusions pertain to N-mineralization potential in soil samples immediately preceding barley as sequent crop in each rotation. The rate of N mineralization declined with time, but it remained greater than zero after 20 wk of incubation in all soils. Mineral-N accumulation at 20 wk followed the order AER1 > AER2 >> CBR1 > CBR2 = CG. Mineralizable soil N, following one cycle of the AER rotation, was almost double that following 60 yr of the CBR rotation. Data for mineral-N accumulation under laboratory conditions were described best by a single-component exponential model. Legume-based rotations were associated with increased total soil N and a greater proportional increase in active N than in total soil N. Active N was least in soil under the CG system. The incubation–extraction procedure resulted in higher estimates of mineralizable N than did the plant-uptake method; however, the ranking of N-supplying power of soils was the same.

Key words: Cropping systems, Gray Luvisol, N mineralization, soil quality, Typic Cryoboralf

Wani, S. P., McGill, W. B., Haugen-Kozyra, K. L. et Juma, N. G. 1994. **Accroissement de la proportion de N actif dans un loam Breton conduit selon divers assolements comportant des cultues fourragères et des cultures engrais vert.** Can. J. Soil Sci. **74**: 67–74. La concentration de N total et le taux de minéralisation de N déterminent en partie l'influence des divers systèmes culturaux sur la croissance des cultures successives dans une rotation. Les objectifs de l'étude étaient (1) de quantifier les rapports entre les systèmes de culture, l'azote total et le N minéralisable et (2) de comparer les quantités de N minéralisable en laboratoire ainsi que l'absorption de N par les plantes en serre. On a choisi à cet effet le sol de trois assolements pratiqués dans une période allant de 9 à soixante ans sur un luvisol gris (loam Breton). Il s'agissait d'une rotation agroécologique de 8 ans (AER), comportant une culture engrais vert de féverole (AER 1), échantillonnée après la première récolte de féverole et après trois années de cultures fourragères continues (AER 2); d'un assolement de céréales en continu (CC), recevant un apport de 90 kg N ha^{-1} par année, installé en 1981 et d'une rotation Breton classique (RBC), c.-à-id. une rotation de 5 ans répétée depuis environ 30 ans, comprenant des cultures fourragères et des céréales sans restitution des restes de culture (RBC avec fumure PKS et RBC 2 non fertilisée). Les phases de chaque rotation n'étaient pas toutes échantillonnées. Nos conclusions portent sur les potentialités de minéralisation de N mesurées sur des échantillons prélevés avant la sole d'orge dans chaque rotation. Le taux de minéralisation de N diminuait graduellement, mais demeurait supérieur à zéro dans tous les sols après 20 semaines d'incubation. Au bout de ce temps, l'accumulation de N minéralisable s'établissait dans l'ordre suivant: RAE 1 > RAE 2 >> RBC 1 > RBC 2 = CC. Le N du sol minéralisable après un cycle de RAE était près du double des quantités récupérées après 60 années de RBC. C'est un modèle exponentiel à composante unique qui décrivait le mieux l'accumulation de N minéralisable en laboratoire. Les rotations comportant des légumineuses produisaient un accroissement du N total dans le sol et une augmentation proportionnellement plus forte du N actif que du N total. C'est dans l'assolement CC qu'on retrouvait le moins de N actif. Le processus d'incubation-extraction donnait des valeurs plus élevées de N minéralisable que la méthode par absortion par les plantes, bien que le classement des sols pour la disponibilité de N demeurait le même.

Mots clés: Assolement, luvisol gris, minéralisation de N, qualité fu sol, cryoboralf typique

The quality of soil organic matter present in a soil is affected by the type and quantity of residues added, the cropping sequence, the climate and the soil type (Juma and McGill 1986). Some increases in soil organic matter content of Gray Luvisols and Black soils in western Canada have been attributed to perennial forages grown in rotations with cereals (Campbell et al. 1991). Crop rotations that include legumes increase the amount of total soil N (Campbell et al. 1991) and often increase the yield of cereals subsequently grown on the same soil (Hoyt 1990).

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The relation between cropping systems and quantity and quality of soil organic matter has been inferred from studies of chemical and biological soil indices. Measurements of potentially mineralizable N (N_0) and mineralizable C (Bonde et al. 1988; Campbell et al. 1991) have been used to monitor biologically meaningful changes in quantity and quality of soil organic matter. Although some studies report improved soil organic matter resulting from perennial forages grown in rotations with cereals in the Black Chernozems of western Canada (Poyser et al. 1957; Khan 1971; Campbell et al. 1991), Janzen (1987) observed no difference in organic matter content and N-mineralization potential of an unfertilized Dark Brown Chernozemic soil following alfalfa and crested wheat grass in rotation with wheat or continuous wheat cropping. In contrast, potentially mineralizable N and total N were significantly lower in rotations containing fallow.

The total quantity of organic N / total N changes more slowly than do the most active components. Microbial biomass and N_0 may serve as indices of the active N fraction. Consequently, McGill (1983) reasoned that until the active fraction reached steady state, a direct relation would exist between total soil organic N and N_0 / total N; thereafter the trend would reverse. McGill et al. (1988) extended this to show an inverse relation between N_0 / total N using published data of Campbell and Souster (1982) for virgin prairie soils.

The long-term rotations established in 1930 and a new 8 yr rotation consisting of annual legumes, cereals and forages established in 1980 at the University of Alberta plots near Breton, Alberta, provide an opportunity to assess changes in total N and rates of N mineralization. Previous studies on these rotational systems have shown that a 5-yr grain–legume–manure rotation had twice as much microbial N and a slower biomass turnover rate than a 2-yr grain–fallow rotation (McGill et al. 1986). A comprehensive study of barley growth, soil-N status, soil fertility, crop-residue decomposition and soil biological properties was undertaken on these systems in 1989 (Wani et al. 1991a,b, 1994). It was shown that the N effect in the new 8-yr rotation was only partially responsible for increased soil fertility and barley yields (Wani et al. 1991a); additional attributes were greater vesicular–arbuscular mycorrhizae colonization and higher nutrient accumulation and translocation to grains when compared with a continuous monoculture wheat system (Wani et al. 1991b).

The objectives of this study were (1) to test the hypothesis that the quality of active soil N as determined by a plant bioassay, under controlled conditions, varies with previous cropping practice, and if this hypothesis is confirmed, to document the nature of the relationship among cropping system, total N and mineralizable N; and (2) to compare the amount of N mineralized under controlled laboratory conditions with plant N uptake in greenhouse conditions.

MATERIALS AND METHODS

Site Description and Cropping Systems

The soils used in this study were from the long-term crop rotations near the town of Breton, Alberta (53°07′N, 114°28′W), 110 km southwest of Edmonton. The dominant soils in the region are Orthic Gray Luvisols (Lindsay et al. 1968). Three cropping systems were compared: (1) an agro-ecological 8-yr rotation (AER) (barley, fababean, barley, fababean, barley underseeded to clover, forage, forage, forage) and (2) continuous grain system (CG), both established in 1981; and (3) a 5-yr classical Breton rotation (CBR) (wheat, oat, barley, forage, forage), established in 1930.

The Breton plots are set out in series (A-F, running east to west) and ranges (1–26, running north to south). Plot size for each treatment was 269.5 m^2 (31.6 m × 8.53 m). A detailed plot plan and description of agronomic practices, are given in Wani et al. (1994). The AER is within the Hendrigan plot area and comprises A-14, A-16, A-17, B-13, B-16, C-13, C-15 and C-16. The CG system comprises plots A-13, B-15 and C-17. The remainder of the Hendrigan plot area is a set of continuous forage plots. The AER and CG plot areas were in a crop rotation from 1940 to 1964, after which it was used for general annual grain production with little or no added fertilizer until 1980. The CBR plots are A-1 to D-11 and F-1 to F-11. Slope varies from 0 to 3% over the plot area used for this study. Aspect is southwest for the AER, CG and much of the CBR plot area; otherwise, it is northeast.

The forage crop in AER system was red clover bromegrass mix and alfalfa bromegrass mix in the CBR system. Where used, fertilizers were applied at seeding: P with the seed and N, K and elemental S were broadcast and incorporated. Herbicides were used for weed control in all plots. Soils were disked (weather and time permitting) in spring and fall. The only treatment plots that were replicated in the field were those of the CG system (three replicates).

In the CG system barley was grown annually from 1981 and received N-P-K-S at 90-22-46-5.5 kg ha^{-1} yr^{-1}. All crop residues were returned to the soil.

The AER plots received no chemical fertilizer N, but P-K-S was added annually at 22-46-5.5 kg ha^{-1}. The quantity of manure applied was equivalent to 70% of the N removed as forages and harvested grain, to simulate return of manure from feeding forages and harvestd barley to livestock. Cereal straw was returned to the plots; the fababean crop remaining after removing several square-metre samples for yield determination was ploughed down as green manure. On completion of the rotation, the forage stubble was ploughed into the soil. Two plots were selected from the AER rotation: (1) following fababean (AER1; plot A-14) and (2) following 3 yr of forage (AER2; plot C-16). Fababean plough down, as green manure on plot A-14 under the AER1 rotational schedule, occurred in 1981 (204 kg N ha^{-1} return), 1983 (245 kg N ha^{-1} return) and 1989 (276 kg N ha^{-1} return). The AER2 rotational schedule on plot C-16 had fababean green-manure treatment in 1983 (245 kg N ha^{-1} return) and 1985 (289 kg N ha^{-1} return).

Two fertilizer treatments from the CBR were used in this study: (1) P-K-S (CBR1; plot D-8E) and (2) control (CBR2; plot D-1E,-5E,-11E), each following oats. In the CBR rotation, straw was not returned to the plots. Forage stubble was ploughed down after the first cut in the second year of forage. No commercial N was added to the plots used in this study.

Nitrogen was supplied by biological fixation and atmospheric deposition only. The P-K-S treatment plots received 9 kg P ha^{-1} yr^{-1} between 1930 and 1979 and from 1980 on received P-K-S at 22-46-5.5 kg ha^{-1} yr^{-1}. The control plot (CBR2) received no amendments since 1930, other than lime (to pH 6.5 in 1972).

Soil samples were collected in early October 1989. Each plot was divided into quadrants and 10 cores (5-cm diameter) 15 cm deep were taken from each quadrant and pooled to form a composite sample. Thus, four such replicates were obtained from each plot and, depending on the analysis, were either pooled to form one bulk sample (mineralizable N) or remained as four distinct replicates (plant bioassay). Properties of the soil samples used for greenhouse and laboratory studies are given in Table 1.

Potentially Mineralizable N

Three subsamples were obtained from each of the five treatment plots by splitting the bulk sample. The subsamples were air dried and undecomposed, and coarse plant residues were removed. Mineralizable N was determined for each treatment using a leaching incubation procedure (Stanford and Smith 1972). Unsieved soil (50 g) and acid-washed sand (50 g) mixture was incubated in plastic Buchner funnels. The soils were leached with 0.01 *M* $CaCl_2$ and nutrient solution (Stanford and Smith 1972) at 0 (leachate discarded), 1, 2, 3, 4, 6, 8, 11, 14, 17 and 20 wk. The soils were incubated at 30°C and the moisture content was maintained at 70% water-holding capacity (WHC). The leachates were analyzed for NO_3^- content using automated cadmium reduction (Technicon 1977) and for NH_4^+ content using the automated indophenol procedure (Technicon 1973).

To analyze the data for accumulated mineral N over the 20-wk period, a linear regression package was used for the linear model and a nonlinear least-squares fitting procedure of the Statistical Analysis System Institute, Inc. (SAS) (1987) was used for the exponential model.

The linear model was

$$N_t = X \bullet t \quad (1)$$

where N_t is the quantity of N mineralized (mg kg^{-1}); X is the zero-order rate constant (mg kg^{-1} wk^{-1}); and t is time (wk).

The exponential model describing net accumulation of mineral N during first-order decomposition of N from a potentially mineralizable source was

$$N_t = N_0\ [1 - \exp\ (-k \bullet t)] \quad (2)$$

where N_t is the cumulative net N mineralized (mg kg^{-1}) to time t (wk); k is the first-order mineralization-rate constant (wk^{-1}); and N_0 (mg kg^{-1}) is the potentially mineralizable quantity of N at $t = 0$.

Plant Bioassay of N Mineralization

Net N mineralization in the presence of growing barley plants was determined in a greenhouse pot experiment. Four replicates, one from each quadrant of each treatment plot, were collected from the field. Coarse, undecomposed plant residues were separated and weighed, and the soil was mixed. Plastic pots (22 cm i.d.), without drainage holes, each received 5.5 kg soil. Plant residues, equivalent to the quantity removed, were returned to and mixed with the soil in each pot. The pots were arranged in the greenhouse in a completely randomized design. Prior to sowing, superphosphate and K_2SO_4 were applied to provide P and S equivalent to 10 and 4 kg ha^{-1}, respectively. Barley (*Hordeum vulgare* L. 'Heartland') was seeded and thinned to four plants per pot 12 d after sowing. At the time of thinning, N, as ammonium sulfate, was applied in solution at 10 kg ha^{-1} equivalent (55 mg pot^{-1}). The moisture content of the pots was maintained at 70% WHC with distilled water. The temperature in the greenhouse was maintained at 21° ± 1°C throughout the plant growth period. The plants were grown with a 12-h day–night cycle. Supplementary light was provided by 400 W Son/T high-pressure sodium lamps. The **photon flux density** (**PAR**) in the greenhouse varied from 500 to 1680 μmol m^{-2} s^{-1}, depending on cloud cover. Plants were harvested 15 wk after sowing. The plant samples were separated into grain, stems, leaves and roots and oven dried at 70°C; then their mass was recorded.

Total N content in finely ground plant samples was determined using a Carlo Erba NA-1500 nitrogen carbon sulphur analyzer. Mineral N in soil samples (<2 mm) prior to sowing and after harvesting was determined following extraction with 2*M* KCl (25 g soil : 125 mL solution) for 1 h and

Table 1. Properties of the soil samples used for greenhouse and laboratory studies

Treatment[z]	pH	pH change during 20-wk incubation	Total C	Total N	Clay	Silt	Cation exchange capacity
			(g kg^{-1} soil)				(cmol kg^{-1})
AER1	6.91	−0.88	30.9	2.5	191	385	19.4
AER2	6.30	−0.58	24.1	2.1	198	397	16.8
CBR1	6.15	−0.49	18.9	1.6	160	386	11.9
CBR2	6.45	−0.45	16.9	1.4	161	411	13.3
CG	6.34	−0.42	19.4	1.6	183	396	14.5
SE	0.02	—	0.4	<0.1	8	7	0.2

[z]AER, agro-ecosystem rotation: 1, following fababean; 2, following 3-yr forages. CBR, classical Breton rotation: 1, P-K-S treatment following oat; 2, control treatment (no fertilizer) following oat. CG, continuous grain system.
SE, standard error of the mean.

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filtration through Whatman No. 42 filter paper. The extracts were stored frozen prior to analysis. Net amount of N mineralized was calculated as

$$\text{net N mineralized} = (\text{total plant N uptake from soil} + \text{mineral N in soil at harvest}) - (\text{mineral N in soil prior to sowing} + \text{fertilizer N}) \quad (3)$$

Nitrogen loss by leaching, denitrification and volatilization was assumed to be negligible under controlled conditions.

Net N mineralization from the soils during the 15-wk growing period of the greenhouse bioassay was compared with that calculated using the linear and exponential models. The rate-constant values were corrected for the difference in temperature between the greenhouse and laboratory assays (21°C vs. 30°C) by using a value of $Q_{10} = 2$ (Stanford et al. 1973; Fyles et al. 1990).

Statistical Analyses

Analysis of variance was used to test for significant treatment effects. For the plant bioassay, a completely randomized design was used, whereas for the N mineralization incubation study, treatments were compared and analyzed at each sampling interval. Treatment means were separated using the least-significant-difference method (SAS 1987). The exponential model was compared with the linear model using the F ratio (Robinson 1985) to determine if the reduction in the **residual sum of squares** (**RSS**) justified the increased model complexity. The F ratio was the quotient of the difference between the RSS of the two models divided by the **residual mean square** (**RMS**) of the exponential model. The result was compared with an F value at $P \leq 0.05$ with 1 and n $- p$ degrees of freedom, where n is number of data points and p is the number of parameters. The slopes obtained with the linear model for cumulative N mineralization (i.e., AER1 vs. AER2, AER1 vs. CBR1, and so on) were tested using an F test, with homogeneity of slope as the null hypothesis.

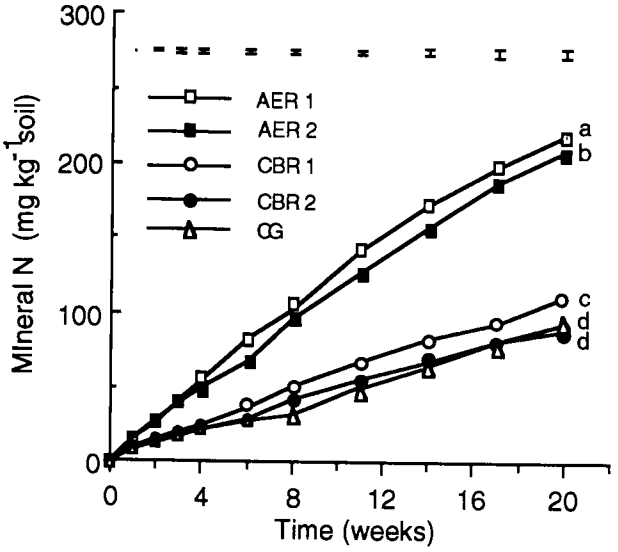

Fig. 1. Cumulative mineral N extracted over the 20-wk incubation of soil from a Gray Luvisol under three cropping systems. Lines followed by different letters indicate that slopes (linear model) varied significantly between treatments ($P \leq 0.05$).

RESULTS

Potentially Mineralizable N

The rate of N mineralization declined with time in a slightly curvilinear fashion, but it remained greater than zero after 20 wk of incubation in all soils (Fig. 1). Mineral-N accumulation was greater from soils of the AER system than from those of the CBR or CG systems. Mineral-N accumulation at 20 wk was CG = CBR2 < CBR1 << AER2 < AER1.

The first-order exponential model yielded N_0 values between 204 and 557 mg kg^{-1} soil and k values between 0.024 and 0.034 wk^{-1}, for the various treatments (Table 2). Analysis of the CG treatment did not converge within 50 iterations. The maximum N_0 of 557 mg kg^{-1} was estimated for the AER2 soil (sampled after 3-yr forage); the highest k value (0.034 wk^{-1}) for the AER1 soil (sampled after fababean plough down). The active N fraction, calculated as the quotient of N_0 / total N and expressed as a percentage, varied from 12 to 27% (Fig. 2), with the highest proportion in AER soils. The RSS were significantly reduced by Eq. 2, indicating that mineral-N accumulation curves were described more closely by the exponential than the linear model (Table 3) in those soils where the nonlinear model converged.

The soils studied were ranked according to the time required to mineralize fixed quantities (10–50 mg kg^{-1}) of N using linear and exponential models. These values were

Table 2. Equation parameters for the exponential and linear models, based on mineralization data from soil samples of three cropping systems at the Breton plots (incubated at 30°C): nitrogen mineralization potential (N_0), first-order mineralization-rate constnat (k), and zero-order mineralization-rate constant (X)

Treatment[z]	Exponential model N_0 (mg N kg^{-1})	SE	k (wk^{-1})	SE	Linear model X (mg N kg^{-1} wk^{-1})
AER1	451	69	0.034	0.007	11.86
AER2	557	85	0.024	0.004	11.04
CBR1	272	43	0.026	0.005	5.81
CBR2	204	30	0.029	0.005	4.80
CG	NC	NC	NC	NC	4.71

[z]AER, agro-ecosystem rotation: 1, following fababean; 2, following 3-yr forages. CBR, classical Breton rotation: 1, P-K-S treatment following oat; 2, control treatment (no fertilizer) following oat. CG, continuous grain system.
NC, convergence was not achieved in 50 iterations, so estimated parameter values are not reported.

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selected because they are within the range of plant N uptake. The time required to mineralize a fixed quantity of N uses both parameters of the exponential model (N_0 and k). This approach is superior to comparing the values of each parameter separately (El Gharous et al. 1990). The time required to mineralize 50 mg kg^{-1} estimated using the linear model ranged from 4.22 to 10.6 wk (data not shown); for the exponential model, 3.48 to 9.6 wk (Table 4). Although time required to mineralize a fixed quantity of N varied with the models, the rankings of the soils did not change. Regardless of the model used or the amount of N to be mineralized, soils from the AER system required the least time, followed by CBR1 (P-K-S treatment) and CBR2 (control) (Table 4); CG had the slowest rate of all using the linear model (Table 2).

The instantaneous rate of N mineralization [$N_0 \bullet k/\exp(k \bullet t)$; mg kg^{-1} wk^{-1}; $t = 0$] is the slope of cumulative N-mineralization curves. This parameter provides insight into the mineralization pattern over the incubation period (Table 4). When compared with the constant slope of the linear model, the instantaneous rate of N mineralization ($t = 0$) exceeded the linear rate but was lower than the linear rate from 8 wk onward (data not shown). The exponential model and the linear model yielded similar rankings of the soil up to 8 wk. The rankings of AER1 and AER2 were reversed after 16 wk using the exponential model.

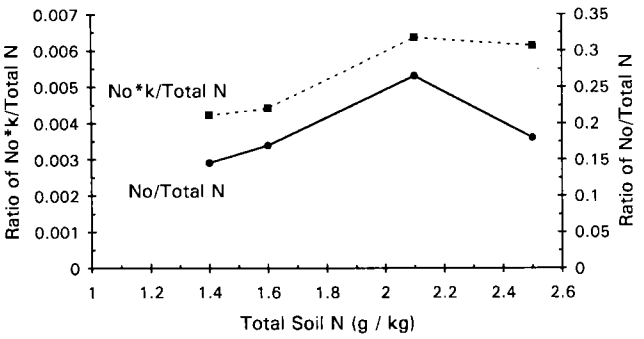

Fig. 2. Relationship between ($N_0 \bullet k$/total soil N) or (N_0 (active N)/total soil N) and total soil N.

Plant Bioassay of N Mineralization Compared with Model Estimates

Net N mineralization calculated from N uptake by barley grown for 15 wk varied significantly ($P \leq 0.05$) among soils from different cropping systems (Table 5). Net N mineralization in 15 wk calculated using the linear model, was 98–166% of that obtained by the barley-N yield method. Values from the exponential model were 112–184% of the barley-N yield values. Plant dry matter yields were described by Wani et al. (1991a).

DISCUSSION

Recent cropping history affected N-mineralization potential (N_0) and the mineralization-rate constants (k) of the soil samples under investigation. The higher N_0 values for AER treatments than CBR treatments indicate increases in mineralizable N associated mostly with different cropping systems. The short time (9 yr and only two fababean crops ploughed down as green manure in AER2; three in AER1) needed to observe this trend is notable. Similar increased N_0 values for Black Chernozemic samples were observed with a green-manuring wheat system without fertilizer addition (Campbell et al. 1991). The N_0 of CBR1 soil, which received P fertilizer for 50 yr followed by P-K-S for 9 yr, was only marginally higher than N_0 from CBR2, the control plot.

The values for the rate constant (k) varied only slightly among treatments (Table 2). Nonlinear regression analysis of data obtained for 39 different soils by Stanford and Smith (1972) yielded estimates of k that varied with soil types (Talpaz et al. 1981). Janzen (1987) found no effect of rotation treatments on k. On the contrary, k has been reported to be a functon of climate, soil type and the length of incubation (Juma et al. 1984; Paustian and Bonde 1987; Cabrera and Kissel 1988).

Several criteria, such as the amount of N mineralized during selected periods of time under controlled conditions (Stanford et al. 1973), the time required to mineralize a fixed amount of N (El Gharous et al. 1990), and the instantaneous rate of N mineralization (Campbell et al. 1991), have been used to compare N availability among soils. All the above criteria use both N_0 and k simultaneously and yield similar results (Tables 4 and 5). The instantaneous rate of mineralization

Table 3. Comparison of models to describe N mineralization potential (N_0) and the rate constant (k) with time (t)

Treatment[z]	Model	RSS[y]	RMS[y]	F ratio	% TSS[y]
AER1	Linear (Eq. 1)	5370	167		98.9
	Exponential (Eq. 2)	2775	90	28.8**	99.4
AER2	Linear	2190	68		99.4
	Exponential	1080	35	31.7**	99.5
CBR1	Linear	755	24		99.3
	Exponential	389	13	28.1**	99.7
CBR2	Linear	621	19		99.2
	Exponential	301	10	31.9**	99.6
CG	Linear	393	12		99.5
	Exponential[x]	—	—	—	—

[z] AER, agro-ecosystem rotation: 1, following fababean; 2, following 3-yr forages. CBR, classical Breton rotation: 1, P-K-S treatment following oat; 2, control treatment (no fertilizer) following oat. CG, continuous grain system.
[y] RSS, residual sum of squares; RMS, residual mean square; % TSS, % total sum of squares.
[x] Not calculated.
**Significant at $P \leq 0.01$.

Table 4. Time required to mineralize a fixed amount of N (10, 25 or 50 mg N kg^{-1}) and the instantaneous rate of N mineralization (t = 0) in soil samples of three cropping systems from the Breton plots incubated at 30°C (exponential model)

Treatment[z]	Rank	Time to mineralize (wk) (mg N kg^{-1}) 10	25	50	Instantaneous rate of N mineralization (mg N kg^{-1} wk^{-1})
AER1	1	0.66	1.69	3.48	15.22
AER2	2	0.76	1.94	3.97	13.19
CBR1	3	1.44	3.72	7.83	7.05
CBR2	4	1.72	4.46	9.60	5.98
CG	NC	NC	NC	NC	NC

[z]AER, agro-ecosystem rotation: 1, following fababean; 2, following 3-yr forages. CBR, classical Breton rotation: 1, P-K-S treatment following oat; 2, control treatment (no fertilizer) following oat. CG, continuous grain system.
NC, not calculated, as convergence was not achieved.

Table 5. Bioassay plant dry matter yields (above ground) and comparison of 15-wk net N-mineralization estimates by both the plant bioassay method (at 21°C) and the N-mineralization data (obtained from 30°C incubations and corrected to 21°C using Q_{10} = 2)

Treatment[z]	Plant DM yields (g pot^{-1})	Net N mineralized (mg pot^{-1}) Bioassay model	Linear model	Exponential model	% deviation from bioassay Linear model	Exponential model
AER1	51.3	503*a*	538	603	7	20
AER2	36.8	484*a*	501	544	24	12
CBR1	22.1	185*bc*	263	288	42	56
CBR2	17.7	131*c*	218	241	66	84
CG	24.5	218*b*	214	NC	−2	NC

[z]AER, agro-ecosystem rotation: 1, following fababean; 2, following 3-yr forages. CBR, classical Breton rotation: 1, P-K-S treatment following oat; 2, control treatment (no fertilizer) following oat. CG, continuous grain system.
a–c Values followed by different letters within a column varied significantly ($P \leq 0.05$); means of four replicates; SE = 22 mg pot^{-1}.
NC, not calculated.

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contains no requirement for arbitrary selection of time or quantity of N mineralized and is consistent with the amount of N mineralized over a certain period, usually 12–20 wk to simulate a field season (Campbell et al. 1991). It is a useful, convenient parameter to assess the N-supplying ability of different soils. In this study, the instantaneous rates of N mineralization at the t = 20 interval in the AER exceed those of CBR at t = 0 (data not shown).

The active fraction calculated from the ratio N_0 / total N constituted 12–27% of soil N in the present study and was affected by the cropping history of the soil (Fig. 2). Recalculation of data from Campbell and Souster (1982) for virgin prairie soils yielded values of 4–20%. The AER1 (following fababean), AER2 (following 3-yr forage) and CBR1 (P-K-S) treatments had a higher active-N fraction than CBR2 (control), suggesting that green manuring, straw application, manure and P application increased the proportion of soil N in the active-N fraction as well as in total N. Consequently, a plot of N_0 / total N or of ($N_0 \bullet k$/total N) versus total N has a positive slope (Fig. 2), although with only four data points the relationship must be interpreted with caution. Increased proportions of active N in soils due to fertilizers, manures and straw addition have been reported from Sweden (Bonde et al. 1988). Our findings are consistent with the hypothesis of McGill et al. (1988), which stated that until the active fraction reached steady state, during transitions of soil to more organic matter, a direct relation would exist between the proportion that is active (using N_0 as an index) and total soil organic N.

Models that used parameter values from laboratory incubations normally generated higher estimates of net N mineralization than did a plant bioassay (Table 5). Similarly, Fyles et al. (1990) reported that although results from the two methods correlated, estimates of net N mineralization from forest-floor materials, using laboratory incubations, were higher than those by a plant-N bioassay. Lower estimates of plant-N bioassay resulted from either more immobilization or less mineralization than occurred during laboratory incubations at the same temperature. Immobilization may have been increased by the return of coarse plant residues to soils used for growing barley plants in pots, whereas in the laboratory incubation, the residues were removed from the soils. Immobilization may also be enhanced if plant growth is limited by something other than N (Wani et al. 1991a).

Plants may also influence N transformations in soils. Reduced rates of ^{14}C loss from labeled plant residue (Jenkinson 1977; Reid and Goss 1982), labeled soil organic matter (Reid and Goss 1983) and labeled amino acids (Burton 1989) have been observed in the presence of growing plants. Drying of soils by growing plants would be expected to decrease N mineralization (Jenkinson 1977; Burton 1989). Alternatively, input of root exudates and sloughed cells with a wide C/N ratio may increase immobilization of N (Reid and Goss 1982). Although the mechanisms by which growing plants influence the microbial metabolism of organic substrates in soils is not clear, our results showed that the net N mineralized in a laboratory incubation exceeded plant N

uptake under greenhouse conditions. However, the ranking of soils according to net N mineralized remained the same regardless of method used.

This study has shown that within 9 yr, AER increased N availability over the continuous barley system, which received N at 90 kg ha^{-1} yr^{-1}. Mineralizable soil N, following one cycle of the AER rotation involving fababeans as green manure, was approximately double that following 60 yr of a 5-yr CBR rotation involving forages and cereals but with no return of crop residues. We caution that not all phases of each rotation were sampled; these conclusions pertain to N-mineralization potential in soil samples immediately preceding barley as the sequent crop in each rotation. It may be that the N-mineralization potential from the CBR system if sampled after forage plough down would have been closer to that observed in the AER system after forage or fababeans. The trend toward high N availability in the AER system raises this question: How much build-up in mineralizable soil N should we aim for when we are developing cropping or farming systems that are self-sufficient in N? If export of N from the farming system is not balanced by input through fixation, then either soil N will be depleted or the soil will accumulate organic and mineral N. Excess mineral N is prone to leaching and (or) denitrification, resulting in environmental degradation. Depletion of soil N reduces the quality of soil resources and efficiency of their use. Both these contrasting outcomes must be balanced while we develop cropping systems for sustainable agriculture.

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