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Measurement of nitrogen mineralization and immobilization fluxes in soil as a means of predicting net mineralization

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Abstract

The usual methods proposed to predict net mineral N available to crops, i.e. chemical and biological methods and long-term incubations, are analyzed. The failure in the extrapolation of laboratory data and models to predict true N fluxes *in situ* mainly results from gross mineralization and immobilization. The processes determining gross fluxes are discussed. Many methodological and theoretical problems are posed by the measurements of true N fluxes under field conditions. First estimations of these fluxes in different crop systems show that the net mineralization rate results from high rates of gross mineralization and immobilization.

Key-words : gross/net N-transformation processes, N-immobilization, N-mineralization, soil mineral N.

INTRODUCTION

There has been considerable research over the last thirty years into the factors and conditions determining net mineralization of nitrogen in soil. The main practical application of this research was the development of methods for predicting the soil nitrogen supply to a crop, on a year or a half-year basis, in order to improve fertilizer recommendations. Such methods are still needed, but the new environmental constraints placed on agricultural production, e.g. minimizing nitrate leaching, also make it necessary to predict nitrogen availability in soil over a shorter time scale. According to Johnston and Jenkinson (1989) 'we need to know more about the amount and time at which nitrate is supplied from soil reserves, organic inputs and the atmosphere'. This paper analyzes the methods used to assess net mineralization in soil, discusses the processes determining net mineralization, and presents some results on the gross mineralization and immobilization fluxes under field conditions.

EVALUATION OF METHODS FOR ASSESSING NET MINERALIZATION

Two types of methods are used to assess net mineralization in soils : i) methods providing 'N availability indexes', and ii) methods defining 'potentially mineralizable N'.

A great number and variety of methods for defining N availability indexes have been suggested. These indexes are used as reference values of soil mineralization capacities. The methods, which include chemical and biological tests, have been reviewed by Stanford (1982). Gianello and Bremner (1986b) have compared different tests : the chemical methods vary in the nature of the extractant used (neutral, acidic or alkaline), and the temperature and time of extraction ; the biological methods are incubation tests, under aerobic or anaerobic conditions, with or without leaching.

The validation of chemical tests is checked by reference to one or more incubation tests. Table 1 shows the correlation between the chemical and biological methods. All chemical methods showed a good correlation with all biological methods, except for method 11 (alkaline permanganate extractant). Method 3 (NH₄ extraction in hot KCl) proposed by Gianello and Bremner (1986a) correlated best with incubation tests and is therefore claimed to be the best index of N availability. However, the incubation tests do not necessarily reflect the actual N mineralization capacity of the soil, as pointed out by Harmsen and Van Schreven as early as 1955. Fox and Piekielek (1984) found a very poor correlation between N mineralized in incubation tests and 'field-measured N availability'.

Another chemical test has recently been developed in Austria by Nemeth (1979) ; this is the electro-

Table 1. Correlation coefficients for the relationships between the results of the chemical and biological methods for defining N availability indices (Giannelo and Bremner 1986b).

		Biological methods				
		13	14	15	16	17
Chemical method		Correlation coefficient (r)*				
1	Organic C wet oxidation	0.75	0.62	0.77	0.71	0.82
2	Total N Kjeldahl	0.79	0.65	0.80	0.73	0.86
3	Soil-KCl mixture, 100 °C, 4 h	0.95	0.88	0.94	0.94	0.95
4	Soil-KCl mixture, 95 °C, 16 h	0.94	0.84	0.93	0.90	0.96
5	Soil-KCl mixture, 80 °C, 20 h	0.91	0.84	0.88	0.87	0.93
6	Soil-KCl mixture, boil, 1 h	0.83	0.76	0.83	0.79	0.81
7	Soil-KCl mixture, 100 °C, 1 h	0.83	0.79	0.85	0.81	0.83
8	Phosphate-borate buffer	0.93	0.84	0.95	0.91	0.95
9	CaCl ₂ -autoclave	0.87	0.70	0.82	0.77	0.92
10	Acid KMnO ₄	0.84	0.77	0.89	0.82	0.85
11	Alkaline KMnO ₄	0.48	0.31	0.52	0.36	0.48
12	NaHCO ₃ UV	0.69	0.76	0.76	0.74	0.69
Biological method		Correlation coefficient (r)**				
13	Anaerobic incub., 40 °C, 7 days	=	0.85	0.95	0.91	0.96
14	Aerobic incub., 30 °C, 14 days	=	=	0.89	0.95	0.81
15	Aerobic incub., 35 °C, 12 weeks	=	=	=	0.96	0.96
16	Method 15 only during 2 weeks	=	=	=	=	0.90
17	N mineralization potential	=	=	=	=	=
	Calculated from method 15	=	=	=	=	=

* *r*-values between 0.47 and 0.61 are significant at the 1 per cent level; *r*-values above 0.61 are significant at the 0.1 per cent level.

** All *r*-values reported are significant at the 0.1 per cent level.

ultrafiltration (EUF) technique. The method yields the nitrate N and organic N extracted, usually at two temperatures and electrical potentials. These values have been combined in different ways to obtain a N index that is believed to represent the whole soil N supply to a crop (Mengel, 1991; Appel and Mengel, 1992). The date of soil sampling may also vary, from harvest time of the previous crop until time of fertilizer application. In an experiment reported by Nemeth *et al.* (1987), the grain yield of winter wheat in fertilized and unfertilized plots was compared to the total EUF (NO₃-N + organic N) measured in the soil in March, a few weeks after fertilizer application (Figure 1). The results showed that the grain yield was dependent on the EUF-N present in the soil in March. However, variations in the EUF-N were mainly due to variations in NO₃-N, so that the correlation resulted from the grouping of two populations (fertilized and unfertilized; Figure 1). This does not demonstrate that EUF-extractable N is a valuable indicator of mineralizable N. More generally, the major criticism of most studies on indexes of N availability is that they have not been properly checked. If the index value is a measure of

the nitrogen mineralization capacity, it must be correlated with net N mineralization obtained under field conditions. Very few studies have tried to quantify net mineralization *in situ*. The N index has often been compared to crop yield or to plant N uptake in unfertilized plots. The problem is that this uptake depends not only on N mineralization, but also on the amount of mineral N present in the rooting zone in soil when significant crop N uptake begins, and these two factors are largely independent. Machet (1991) showed that the main source of variation in the yield of unfertilized winter wheat was not soil mineralization, but the residual inorganic N in soil at the end of the winter (Figure 2).

Stanford and Smith (1972) used another approach for determining N availability in soil, which received considerable attention in the 80's. These authors used a long-incubation technique at a rather high temperature (35 °C), with periodic leaching of the soil to remove N mineralized. The N mineralization kinetics obtained by this technique show that the amounts of N mineralized are important and that the mineralization

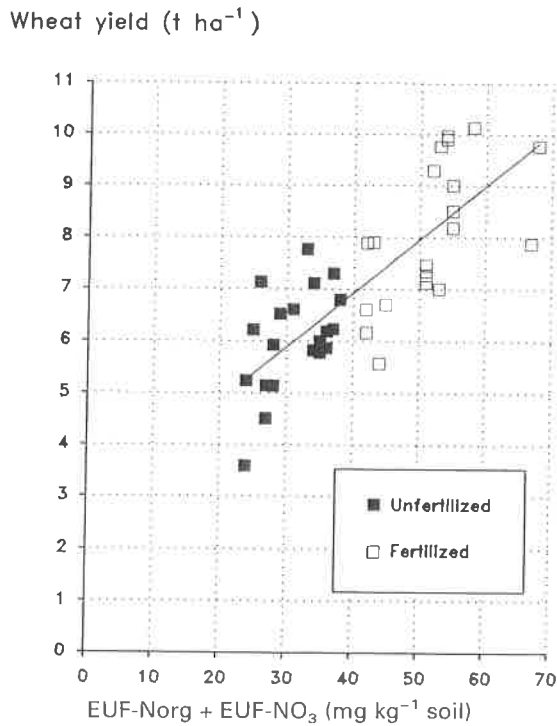


Figure 1. Relationships between grain yield of winter wheat (fertilized and unfertilized plots) and the index value of soil N supply EUF (measured in March). Data from Nemeth *et al.* (1987).

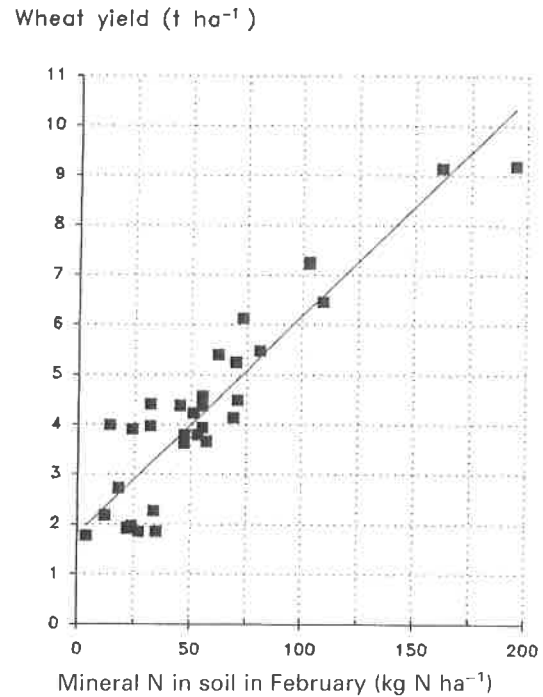


Figure 2. Relationships between winter wheat yield and residual mineral-N in soil at the end of winter in various fields, without fertilizer-N. Data from Machet (1991).

rates decrease smoothly and continuously with time. The kinetics fit relatively well with a single exponential model, given by the equation :

$$N = N_0 (1 - e^{-kt})$$

The method has been used to define the 'potentially mineralizable nitrogen' (N_0) and calculate this value from the incubation data. The effects of soil temperature (T) and moisture (θ) on the rate constant k have been investigated (Stanford and Epstein, 1974 ; Stanford *et al.*, 1973, 1975 ; Oyanedel and Rodriguez, 1977). Stanford *et al.* (1977) suggested that the actual mineralization under field conditions could be estimated versus time from the parameters N_0 and $k(T, \theta)$. This approach is attractive, and it is not surprising that many have tried to use it. Cabrera and Kissel (1988) first determined N_0 and k in their soils. They monitored soil temperature and moisture for 2-4 months in the field and were able to predict N mineralization from the above equation. However, they calculated mineralized N, under field conditions from the following mineral N balance :

$$N \text{ mineralized} = N_2 - N_1 + N_u - N_g + N_l$$

where N_1 and N_2 are the amounts of inorganic N in soil (1.2 or 1.5 m depth) at the beginning and the end of the period ; N_u is plant N uptake ; N_g is the N gain (atmospheric and seed inputs) and N_l the loss (volatilization, denitrification and leaching). In their calculation, N_g and N_l were minor corrective terms.

Their results are shown in Figure 3. The measured mineralization rates on the cropped plots varied little between plots, around $0.3 \text{ kg N ha}^{-1} \text{ day}^{-1}$. The predicted values were much higher : $0.7\text{-}1.2 \text{ kg N ha}^{-1} \text{ day}^{-1}$. The model also overestimated the net mineralization in the fallow plots, but the difference was smaller. Indeed, the mineralization rate was markedly higher in fallow soils than in cropped soils. The model therefore appears to overestimate net mineralization.

The concept of N_0 has been criticized with good reason. Even if there is a very good fit of the model to the data, the N_0 value cannot be determined accurately. The optimized parameters N_0 and k are strongly dependent on the incubation time ; this is clearly shown by results of Dendooven (1990) and Dendooven *et al.* (1990). Figure 4 is taken from this study. It indicates that the two parameters were strongly correlated : each couple (k, N_0) of the curve

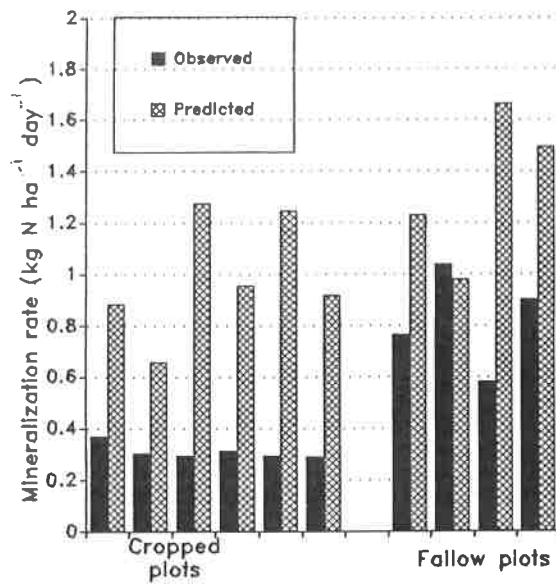


Figure 3. Observed and predicted values of N mineralization rates in different soils, cropped or fallow. Data from Cabrera and Kissel (1988).

defined approximately the same mineralization kinetics. The correlation can be decreased only if N mineralized approaches the asymptote N_0 , which requires very long incubation times. Then the method of Stanford and Smith (1972) may be valuable for practical applications, but it is impossible to assign any definite value to the 'mineralizable pool'.

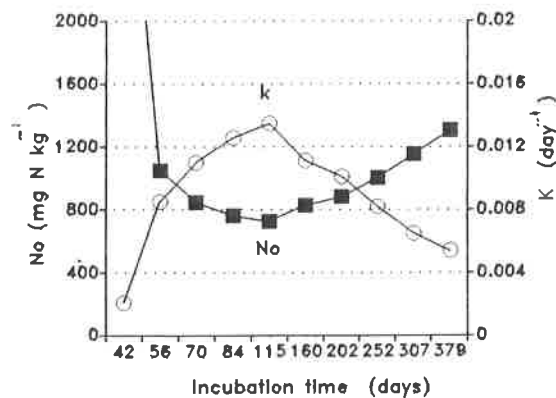


Figure 4. Influence of the incubation time on the calculated parameters N_0 and k of the single exponential mineralization model. Data from Dendooven (1990).

We believe that the leaching test may be useful for estimating gross mineralization. Figure 5 shows the results obtained by two incubation methods. Graph a shows the N mineralization kinetics obtained with the leaching incubation test by Nordmeyer and Richter (1985); graph b is from Muller and Mary (1981) using an incubation method without leaching. The mineralization kinetics in the control soils were comparable, but were very different when sugar-beet tops were added. The decomposition of sugar-beet tops resulted in net immobilization with the second method, whereas it produced continuous net mineralization with the leaching incubation test. This is probably due to leaching of soluble C compounds, reducing or even blocking N immobilization. This could be the main reason for the overestimation of net mineralization by Cabrera and Kissel (1988) using the leaching test.

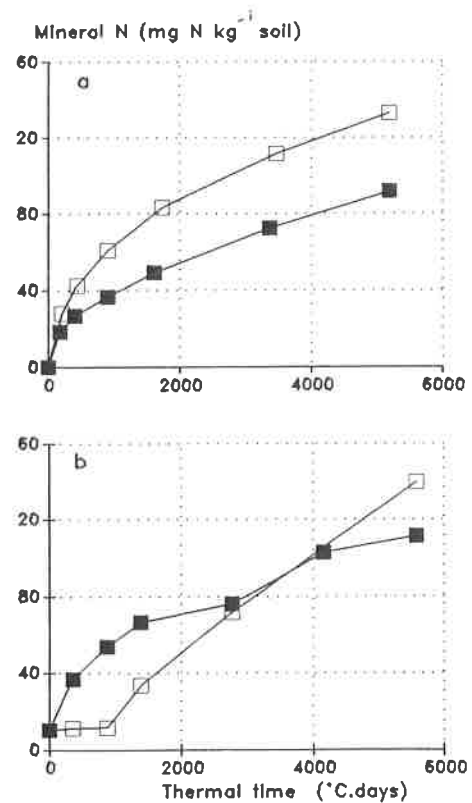


Figure 5. N mineralization kinetics in soils incubated with (open symbols) or without (closed symbols) sugar-beet tops. N accumulation is expressed versus a thermal time. Graph a: incubations made with periodic leaching. Data from Nordmeyer and Richter (1985); Graph b: incubations made without leaching. Data from Muller and Mary (1981).

PROCESSES DETERMINING NET MINERALIZATION

Net mineralization can be described as the result of four different processes : flush effects, basal mineralization, remineralization (these three fluxes constituting gross mineralization) and biological immobilization.

The *flush effects* likely to occur under field conditions are caused by sequences of soil drying-rewetting or freezing-thawing. Figure 6 shows the change in mineral N in soil incubated fresh or dried and rewetted every two weeks (Van Schreven, 1968). A marked flush effect occurred during the first two cycles. The size of the flush decreased in the third cycle and became negligible thereafter. The flush is caused partly by microbial death and subsequent decomposition of microbial cells. It probably also results from physical disturbance of the soil, decreasing physical protection of soil organic matter. The flush effect might be the main source of N mineralization in dry areas, but it probably occurs only in the first 2-3 cm of the soil in wet Northern Europe where the water potential reaches high values in summer.

The three other processes determining net mineralization are illustrated in Figure 7.

Basal mineralization can be defined as the gross mineralization of the soil organic matter in a soil that has not received crop residues recently, and where N

immobilization, measured by ¹⁵N, is negligible. This was the case in an incubation reported by Mary *et al.* (1993) : basal mineralization rate decreased from 0.30 to 0.19 mg N kg⁻¹ day⁻¹ during incubation for 6 months at 25 °C, and was very highly correlated with carbon mineralization.

Biological N immobilization corresponds to the assimilation of mineral nitrogen by soil heterotrophic microflora. It is closely related to carbon decomposition in soil and occurs particularly during decomposition of crop residues. Gross immobilization can be only estimated with ¹⁵N techniques whereas net immobilization can be calculated from the difference in mineral N contents of amended and unamended soils.

Remineralization takes place after the main decomposition phase, due to recycling of biomass N during microbial death and predation. Remineralization kinetics usually consists of a rapid phase, followed by a much slower phase : only a small part of the N is recycled over a short term.

These processes do not have the same kinetics. Flush effects due to drying and freezing are threshold events, basal mineralization is a rather continuous process, immobilization and remineralization vary with time because the return of crop residues to soil is discontinuous. These processes may also respond differently to environmental conditions. This especially applies to the soil inorganic N concentration, which strongly affects immobilization and remineralization

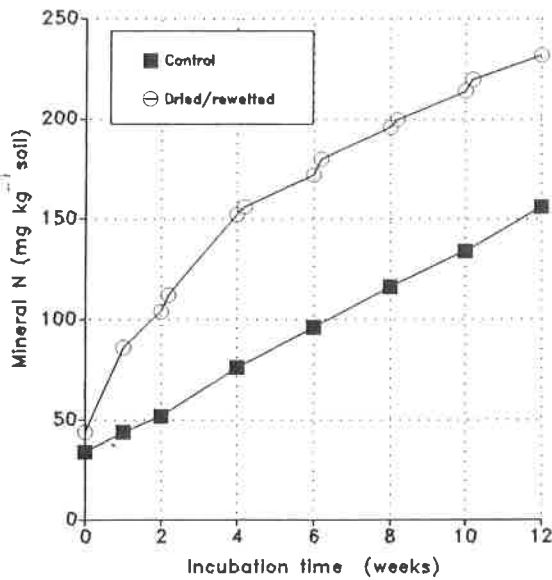


Figure 6. Effect of soil drying and rewetting on N mineralization after subsequent incubation at 29 °C. The soil was dried at 35 °C at weeks 0, 2, 4, 6, 8 and 10. Data from Van Schreven (1968).

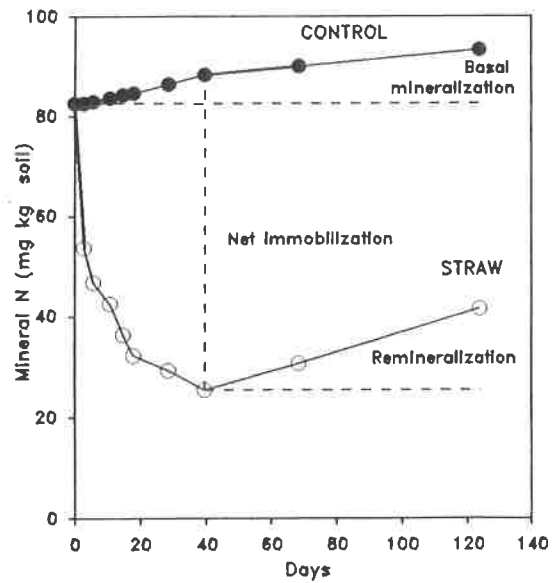


Figure 7. Evolution of mineral N in soil incubated at 15 °C with addition of straw at rate 1.75 g C kg⁻¹ soil (open symbols) or without straw (closed symbols). Data from Robin *et al.* (1992).

(Fog, 1988), but not gross mineralization (Hart *et al.*, 1986). When the microbial needs for mineral N ($\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$) in soil are large, this pool is rapidly depleted and the decomposition rate of organic compounds is reduced. In return, N immobilization is affected and remineralization is delayed.

The intensity and the kinetics of net immobilization and remineralization are also very dependent on the biochemical composition and nitrogen content of organic residues decomposing in soil. We found that the decomposition of root mucilage resulted in much more N immobilization and remineralization than did glucose decomposition. Roots that were rich in N decomposed more slowly than these two substrates and induced a lower net immobilization; the remineralization rate was comparable to that of glucose (Mary *et al.*, 1993).

ESTIMATION OF GROSS MINERALIZATION AND IMMOBILIZATION FLUXES *IN SITU*

Mineralization and immobilization at the year scale

We have attempted to estimate the order of magnitude of gross mineralization and immobilization fluxes in a continuous wheat rotation on a loamy soil with the usual organic restitutions in Northern Europe (Table 2). Rhizodeposition was estimated on the basis of 10-15 per cent of the carbon fixed by photosynthesis being returned to the soil via the root system (Keith *et al.*, 1986), and was assumed to be mainly root mucilage. We used the immobilization ratio obtained under laboratory conditions, i.e. $34 \text{ g N kg}^{-1} \text{ C}$ for straw and roots (Nommik, 1962; Robin *et al.*, 1992) and $72 \text{ g N kg}^{-1} \text{ C}$ for root mucilage (Mary *et al.*, 1993). Total immobilization potential calculated over the year was 250 kg N ha^{-1} . The annual net mineralization flux in this soil was estimated at around 120 kg N ha^{-1} (Hofman, 1988; Machet *et al.*, 1990). The remineralization was estimated to be between 20 and 50 per cent of immobilized N during a year, depending on the residue. It included all of the nitrogen contained in crop residues (considering that fresh organic matter content in the soil is constant). The nitrogen flush was estimated at 20 kg N ha^{-1} , half of it due to drying/rewetting in summer and half due to freezing/thawing during winter. The basal mineralization was the result of the balance between the four other fluxes, and amounted to $205 \text{ kg N ha}^{-1} \text{ year}^{-1}$. Net mineralization, gross immobilization and gross mineralization would then be: 0.33, 0.68 and $1.02 \text{ kg N ha}^{-1} \text{ day}^{-1}$ respectively, corresponding to a 1 : 2 : 3 ratio (Table 3).

The actual quantification of N fluxes *in situ* is difficult and poses both theoretical and methodological problems. Immobilization has often been measured at

Table 2. Estimation of annual organic restitutions and potential N immobilization in a simulated continuous wheat rotation.

Residue addition	Dry matter (kg ha^{-1})	N (kg ha^{-1})	C (kg ha^{-1})	Potential N immobilization (kg ha^{-1})
Straw	8000	35	3500	120
Roots	1500	10	600	20
Rhizodeposits	3500	20	1500	110
Total	—	65	5600	250

harvest in field experiments done with ^{15}N -labelled fertilizers. This kind of experiment gives estimations of the proportion or the quantity of fertilizer-N immobilized in the soil. Data have been obtained with different experimental procedures and N pools (Table 4), so that comparisons are difficult. The measurements made at short intervals after labelled-N application can be used to calculate N immobilization rates until mineral ^{15}N has disappeared in soil. The mean rates observed under winter wheat during the two weeks following fertilizer application were 0.25 at the tillering stage and $1.5 \text{ kg N ha}^{-1} \text{ day}^{-1}$ at the stem elongation stage (Recous *et al.*, 1988).

Table 3. Estimation of potential gross mineralization, gross immobilization and net mineralization in a continuous wheat rotation on a loamy soil (Northern France) receiving usual organic restitutions.

N flux	N ($\text{kg ha}^{-1} \text{ year}^{-1}$)		N ($\text{kg ha}^{-1} \text{ day}^{-1}$)	
Immobilization	- 250		- 0.68	
Remineralization	+ 145	} + 370	+ 0.22	} + 1.02
Flush mineralization	+ 20		+ 0.18	
Basal mineralization	+ 205		+ 0.62	
Balance : net mineralization	+ 120		+ 0.33	

Quantification of gross fluxes by the isotope dilution technique

There have been several recent attempts to calculate *in situ* gross immobilization and mineralization fluxes using the isotope dilution technique. The N fluxes which enter a N pool (production) or deplete it (con-

sumption) can be estimated from differential equations describing the rate of change of the N and ¹⁵N pools and solving these analytically or numerically (Kirkham and Bartholomew, 1954; Myrold and Tiedje, 1986; Bjarnason, 1988, Barraclough, 1991; Davidson *et al.*, 1991; Tietema and Wessel, 1992). The methods may differ, but they all assume that throughout the period of measurements :

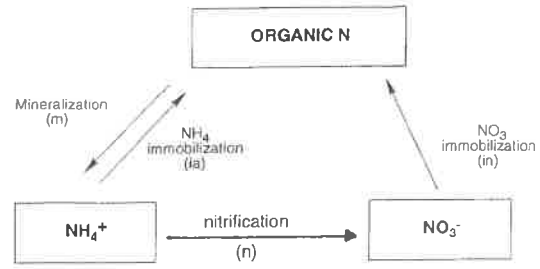
- (1) the N pools involved are isotopically homogeneous,
- (2) the N transformation rates are constant,
- (3) the recycling of biomass-N is negligible.

Experiments in which ¹⁵NH₄⁺ tracer is added to the soil allow calculation of mineralization and ammonium consumption (nitrification + ammonium immobilization + crop uptake + possible losses). Parallel ¹⁵NO₃⁻ tracer experiments enable the calculation of nitrification and nitrate consumption (nitrate immobilization + crop uptake + possible losses) (Figure 8). Most authors use the difference between NH₄⁺ consumption fluxes, calculated with ¹⁵NH₄⁺ and nitrification flux, calculated with ¹⁵NO₃⁻, to calculate gross immobilization. It is assumed that no ammonium is lost and that immobilization of nitrate is negligible. These two assumptions are often nonvalid, at least *in situ* (Recous *et al.*, 1988, 1992a; Schimel *et al.*, 1989). The calculation of gross immobilization using biomass ¹⁵N measurements (Davidson *et al.*, 1991) or organic ¹⁵N measurements (Recous *et al.*, 1992b) eliminates such assumptions.

The search for suitable conditions in which to apply the isotopic dilution method has led many to make injections of highly enriched ¹⁵N solutions into the soil (to satisfy assumption (1)) and to measure isotopic dilution over a short time scale of 1, 2 or 7 days (Schimel *et al.*, 1989; Davidson *et al.*, 1991; Davies *et al.*, 1992; Watkins, 1992; Recous *et al.*, 1992b), to satisfy assumptions (2) and (3). In fact, in the conditions of short-term experiments, homogenous distribution and uniform mixing of soil N and added ¹⁵N are difficult to obtain.

Some authors have used very small amounts of labelled nitrogen in soil so as not to disturb true fluxes of mineralization and immobilization. Tietema and Wessel (1992) determined N transformation rates in the upper soil layers of coniferous and deciduous forests at several sampling times. They observed very high rates of mineralization and immobilization, with fluctuations throughout the year, although the net resulting mineralization flux was rather low (Table 5). Jackson *et al.* (1989) measured smaller, but still important immobilization fluxes from both ammonium and nitrate pools in annual grassland.

The two major difficulties encountered with this approach are (i) obtaining homogenous distribution in soil, and (ii) that concurrent processes like NH₄⁺ fixation or NH₃ volatilization can become dominant in ¹⁵NH₄⁺ depletion.



- Estimation of gross mineralization ¹⁵NH₄ enrichment experiment

$$m = - \frac{\Delta A}{\Delta t} \frac{\ln \left(\frac{e_{a2}}{e_{a1}} \right)}{\ln \left(\frac{A_2}{A_1} \right)}$$

- Estimation of gross immobilization

$$\left\{ \begin{array}{l} i_a = \frac{\Delta^{15}N_{org}}{\bar{e}_a \cdot \Delta t} \\ i_c + i_n = \frac{\Delta^{15}N_{org}}{\bar{e}_i \cdot \Delta t} \end{array} \right. \quad (1) \text{ } ^{15}\text{NH}_4 \text{ enrichment experiment}$$

$$i_n = \frac{\Delta^{15}N_{org}}{\bar{e}_n \cdot \Delta t} \quad (2) \text{ } ^{15}\text{NO}_3 \text{ enrichment experiment}$$

Figure 8. Quantification of N transformation rates by isotope dilution techniques during a time interval $\Delta t = t_2 - t_1$. *m* : gross mineralization ; *n* : nitrification ; *ia* : immobilization from ammonium ; *in* : immobilization from nitrate. *A* = NH₄ pool, *e_a* = ¹⁵N isotopic excess of NH₄ pool, \bar{e}_a mean isotopic excess of NH₄ pool between *t*₂-*t*₁ time interval ; *e_n* = mean isotopic excess of NO₃ pool between *t*₁-*t*₂ time interval ; *e_i* = mean isotopic excess of (NH₄ + NO₃) pool between *t*₂-*t*₁ time interval.

Another approach is to apply much larger amounts of labelled N to obtain better distribution of ¹⁵N and minimize the concurrent processes (Recous and Mary, 1990; Recous *et al.*, 1992b). We used Barraclough's procedure (Barraclough, 1988) and measurements of mineral and organic ¹⁵N to calculate N fluxes after eight ¹⁵N pulses applied to winter wheat between March and June (Table 5). The immobilization fluxes calculated during one week after N applications were 0.6-0.8 kg N ha⁻¹ day⁻¹ for the top 5 cm soil. The mineralization rate was estimated with less precision at 0.15-0.77 kg N ha⁻¹ day⁻¹, with a mean rate of 0.34 kg N ha⁻¹ day⁻¹ during the same period. Extrapolation to the arable layer gives a mean rate of 1.70 kg N ha⁻¹ day⁻¹. A direct comparison of immobilization and mineralization rates would lead to the conclusion that net immobilization has occurred. However, we

Table 4. Estimation of fertilizer-N net immobilization at harvest time using ^{15}N .

Authors	Crop	N pool measured	N added (kg ha ⁻¹)	Net immobilization	
				% N applied	kg N ha ⁻¹
Balabane and Balesdent (1992)	Maize	Organic N associated with particle size fraction	160	25.6	41
Bristow <i>et al.</i> (1987)	Perennial ryegrass	Organic N < 200 μm (microbial biomass)	60	37.0	22
Powlson <i>et al.</i> (1992)	W. Wheat	Organic N (microbial biomass + roots)	100-200	16-21	16-40
Recous <i>et al.</i> (1988)	W. Wheat	Organic N (roots eliminated)	80	20-25	16-20
Stevens and Laughlin (1989)	Ryegrass	Organic N (microbial biomass + roots)	100	14.5	14

Table 5. Estimation of gross mineralization (*m*) and immobilization fluxes (*i*) in various ecosystems. *ia* = immobilization from NH_4 pool; *in* = immobilization from NO_3 pool.

	N fluxes (kg ha ⁻¹ day ⁻¹)			Experimental conditions
	except for Tietema and Wessel (mg kg ⁻¹ day ⁻¹)			
	<i>m</i>	<i>ia</i>	<i>in</i>	
Tietema and Wessel (1992)				
Feb. 90	78	60	0	Soils from deciduous forest
Nov. 90	48	36	0	$^{15}\text{NH}_4$ and $^{15}\text{NO}_3$ exp. 2 days
Schimel <i>et al.</i> (1989)				
Day	14.9	16.4	4.1	Annual grass top 9 cm
Night	14.0	8.0	3.3	$^{15}\text{NH}_4$ and $^{15}\text{NO}_3$ exp. 1 day (night/day)
Recous and Mary (1990)				
8 dates tillering-flowering (7/03 -14/06)	0.15-0.77	0.58-0.81 ^a		W. wheat; top 5 cm $\text{CO}(^{15}\text{NH}_2)_2$ exp. 7 days

^a *ia* + *in*.

believe that the immobilization rates measured were in fact potential rates. They were not limited by N deficiency since plenty of mineral N was present. The actual immobilization rates without addition of N would probably have been much lower. In contrast, the mineralization rates were correctly estimated, at least if we accept the hypothesis of no real added nitrogen interaction due to N application (Jenkinson *et al.*, 1985).

CONCLUSIONS

Techniques such as ^{15}N analysis (Preston, 1992) and isotope tracing (Myrold and Tiedje, 1986; Wessel

and Tietema, 1992) have greatly improved recently, allowing the accurate determination of N fluxes in soil under laboratory conditions. But estimating the actual gross mineralization and immobilization fluxes under field conditions is more difficult, and will require very detailed studies. Nevertheless, the first estimations obtained *in situ*, together with extrapolations from laboratory experiments, indicate that gross N mineralization and immobilization fluxes *in situ* are probably much greater than net mineralization.

The two processes are not determined by the same factors. Gross mineralization is the sum of very transient processes such as the flush effect, the fairly rapid recycling of microbial biomass-N (remineralization) and the slow process by which humified organic mate-

rial is mineralized. Gross immobilization is essentially due to the biological assimilation of N by microorganisms and is driven by the C dynamics of recent inputs of organic matter to soil. Its importance and kinetics strongly depend, in the short term, on the nature and the input rate of crop residues (including rhizodeposits); it is also affected by soil inorganic N concentration in decomposition zones.

This is why the recent history of soil plays a major role in the 'N availability index' or the 'potentially mineralizable N' values obtained, whatever the method employed, and is probably the cause of most of the failures in the extrapolation of laboratory data. The prediction models of net mineralization should take into account at least two functions: the first defines the basal mineralization as a function of soil texture and long-term C and N inputs; the second one describes immobilization-remineralization as a function of the amount and nature of recently added organic residues and mineral N.

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