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A simple model for estimating the contribution of nitrogen mineralization to the nitrogen supply of crops from a stabilized pool of soil organic matter and recent organic input

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Abstract

A simple model was developed to estimate the contribution of nitrogen (N) mineralization to the N supply of crops. In this model the soil organic matter is divided into active and passive pools. Annual soil mineralization of N is derived from the active pool. The active pool comprises stabilized and labile soil organic N. The stabilized N is built up from accumulated inputs of fresh organic N during a crop rotation but the labile N is a fraction of total N added, which mineralizes faster than the stabilized N. The passive pool is considered to have no participation in the mineralization process. Mineralization rates of labile and stabilized soil organic N from different crop residues decomposing in soil were derived from the literature and were described by the first-order rate equation $dN/dt = -K*N$, where N is the mineralizable organic N from crop residues and K is a constant. The data were grouped K_1 by short-term (0–1 year) and K_2 by long-term (0–10 years) incubation. Because the range of variation in K_2 was smaller than in K_1 we felt justified in using an average value to derive N mineralization from the stabilized pool. The use of a constant rate of K_1 was avoided so net N mineralization during the first year after addition is derived directly from the labile N in the crop residues. The model was applied to four Chilean agro-ecosystems, using daily averages of soil temperature and moisture. The N losses by leaching were also calculated. The N mineralization varied between 30 and 130 kg N ha^{-1} yr^{-1} depending on organic N inputs. Nitrogen losses by leaching in a poorly structured soil were estimated to be about 10% of total N mineralized. The model could explain the large differences in N- mineralization as measured by the potential N mineralization at the four sites studied. However, when grassland was present in the crop rotation, the model underestimated the results obtained from potential mineralization.

Introduction

In Chile, N fertilizer recommendations for arable crops are based on measurement of the amount of soil mineral N in early spring. Such investigations, provide little information because (i) the soil mineral N is measured in the top layer only (0–20 cm) as a starting point to establish different response curves with increasing rates of application of N fertilizer, and (ii) there is little differentiation between agro-ecological zones. Since 1977, estimates of N-mineralization in alluvial and volcanic ash derived soil (allophanic soil) have been made in Chile. Annual N mineralization was calculated from potentially mineralizable N after Stanford and Smith (1972) and used as input to a N balance-sheet equation to obtain the optimum N application rate (Oyanedel and Rodríguez, 1977; Rodríguez and Silva, 1984a). The weak point of this approach has been the estimation of the potentially mineralizable N. Potentially mineralizable N may be overestimated by drying and sieving the samples before incubation (Cabrera and Kissel, 1988) or by the bias introduced

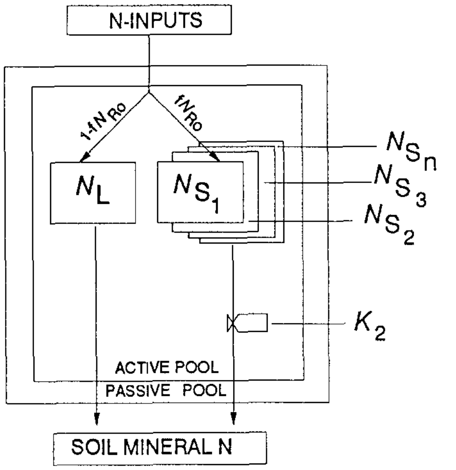

Fig. 1. Fate of N input from crop residues applied to the soil: N_L, N labile; N_{S1} .. N_{Sn} stabilized pool of soil organic N accumulated from the resistant N fraction fN_{Ro} from recent organic inputs, after *n* years of crop rotation; K_2 rates of N mineralization from N_S

into the estimation of the parameters as the time of incubation increases (Dendooven, 1990).

Nitrogen mineralization during a growing season comes from soil organic matter and recent organic inputs. Attempts to relate N mineralization to the total soil organic N content failed, especially where allophanic soils are involved, because a large part of soil organic matter is bound to the mineral part of soil (Zunino et al., 1982).

We have developed a practical model that predicts the release of N from a range of soils in different agricultural zones with large variation in fresh organic inputs, weather conditions and soil types; the model avoids the use of the potentially mineralizable N of Stanford and Smith (1972).

In this paper we describe the model, and its application to four Chilean agro-ecosystems.

Methods

Model description

Figure 1 shows the fate of crop residues decomposing in soil. The N input in crop residues is divided into resistant (fN_{Ro}) and labile (fN_L= 1–fN_{Ro}) N fractions which enter the active pool of soil organic N. The fractions fN_L and fN_{Ro} contribute to the formation of the labile (N_L) and stabilized (N_S) pool of soil organic N, respectively. By definition, the labile N mineralizes rapidly within the first year after the addition and N_S mineralizes slowly. Annual N decomposition from the resistant N input, N_{Ro} (kg N ha^{-1} yr^{-1}), may be described by the equation:

$$dN_{Ro}/dt = -K_2 * N_{Ro} \qquad (1)$$

where N_{Ro} is fN_{Ro}*N_{Rs}, N_{RS} fresh organic N inputs (kg N ha^{-1} yr^{-1}), K_2 is the rate constant of N mineralization (years $^{-1}$) and t time (years).

The N_S pool is accumulated from N_{Ro} and comprises organic materials resistant to decomposition (e.g. lignin), and presumably physically protected localized soil organic matter in soil aggregates which are not penetrated by microflora and fauna (Van Veen et al., 1985). The accumulation rate and size of the N_S pool depend on K_2 and N inputs from crop residues during a crop rotation. In this study the passive pool in Figure 1 is assumed not to increase or decrease during a growing season. However in the long term, particularly in grassland soil, the release of N from the passive pool may be significant. In the model the N losses by denitrification and N gain by mineralization from the passive pool, were not considered, so the N quantities gained or lost were regarded to be roughly in balance.

Estimation of rate constants (K_1, K_2) and N fractions (fN_{Ro}, fN_L)

Tables 1 and 2 show the rates, K_1 and K_2 and the resistant N fraction, fN_{Ro}, respectively. The data were derived from published N mineralization experiments using ^{15}N-labelled materials (Amato et al., 1987; Broadbent and Nakashima, 1974; Fox et al., 1990; Janzen and Kucey, 1988; Jensen, 1992; Ladd et al., 1981b; Müller et al., 1988; Voroney et al., 1989; Amato et al., 1984; Ladd et al., 1985). Nitrogen mineralization was assumed to proceed by two independent reactions following to first-order kinetics. Table 1 shows two groups of rates: K_1 for short- (0–1 year) and K_2 for long-term (0–10 years) incubations. The rates K_2 were obtained from the long-term data (i.e. > 1 year). The residual ^{15}N was plotted on a logarithmic scale against time in order to use the linear regression technique (Stanford and Smith, 1972). A example of long-term N mineralization (Ladd et al., 1981b; 1985) is shown in Figure 2. The slope of the regression line provides the rate K_2 and its intercept on the *Y*-axis, the resistant N fraction fN_{Ro}. The labile N fraction, fN_L, is calculated as 1-fN_{Ro}, and mineralizes rapidly with rate K_1. The rates K_1 were derived from a regression, using a one pool from the residual organic ^{15}N found in the the short-term (i.e. < 1 year) (Fig. 2). The straight line

Table 1. Rates of N mineralization K_1 and K_2 from several ^{15}N-labelled organic materials decomposing in soil in short-term (< 52 weeks) or long-term (0–10 years) incubation

Decomp. period	Lab. or field	Plant materials	C:N	Incub. temp (°C)	K adjusted 16°C (yr^{-1})	References[c]
K_1, undisturbed soils (weeks)						
0– 2	field	mustard	15.1	7.0[a]	18.09	1
0– 2	lab.	lentil	24.0	21.0	1.41	2
0– 4	field	legume	15.3	16.2	1.85	3
0–12	lab.	vigna	18.5	24.3	0.79	4
0–12	lab.	medic	18.5	24.3	0.65	4
0–43	field	white clover leaflets	11.0	11.0	2.67	5
0–43	field	red clover leaflets	11.0	11.0	2.16	5
0–43	field	timothy leaflets	16.0	11.0	2.11	5
0–43	field	timothy roots	29.0	11.0	1.25	5
0–43	field	field beans stems+petioles	28.0	11.0	1.22	5
0–43	field	field beans roots	28.0	11.0	0.37	5
0–52	lab.	barley root	35.7	22.5	0.71	6
All rates K_1 (mean)					2.77	
K_2, cultivated soils (years)						
0–4	field	wheat straw	20.4	12.0[b]	1.66	7
4–10	field	wheat straw	20.4	12.0[b]	0.14	7
K_2, undisturbed soils						
0.6–2	field	wheat straw	73.1	14.4	0.14	8
1 –2.7	field	mustard	15.0	7.0[a]	0.52	1
1 –2.7	field	ryegrass	33.7	7.0[a]	0.50	1
0.1–4	field	legume	13.1	16.0	0.24	9
1 –4	field	legume	15.3	16.2	0.07	3
1 –8	field	legume	15.3	16.2	0.06	10
1 –5	lab.	barley root	17.1	22.5	0.03	6
1 –5	lab.	barley top	35.7	22.5	0.04	6
All rates K_2 (mean of undisturbed soils)					0.20	

Incub.: incubation.
Decomp.: decomposition.
Lab.: laboratory.
[a] Assumed temperature; [b]Mean temperature only considered in months with temperature over 0° C;
[c]1, Jensen (1992); 2, Janzen and Kucey (1988); 3, Ladd et al. (1981b); 4, Fox et al. (1990); 5, Müller et al. (1988); 6, Broadbent and Nakashima (1974); 7, Voroney et al. (1989); 8, Amato et al. (1987); 9, Amato et al. (1984); 10, Ladd et al. (1985).

Table 2. Resistant N fraction (fN_{Ro}) from several ^{15}N-labelled crop residues decomposing in soil

Crop residues	C:N ratio	Resistant fN^{a}_{Ro}	Reference[b]
Mature wheat straw	73.1	0.91	8**
Field beans	27.5	0.82[c]	11
Subterranean clover	20.9	0.77[c]	11
Red clover	21.0	0.74[c]	11
Barley-root	35.7	0.72	6**
Timothy grass	18.9	0.69[c]	11
Rye grass	33.7	0.68	1**
White clover	19.3	0.65[c]	11
Barley-top	17.1	0.62	6**
Legume	15.3	0.58	10**
White mustard	15.1	0.53	1**
Young wheat straw	20.4	0.47	7**
Mean		0.68	

[a] Values derived from intercept on y axis from Eq. (4) fitted to the long-term ($\geq$ year) data points.
[b] 11: Müller and Sundman (1988)
**: references, see Table 1.
[c] Residual organic ^{15}N in soil 10 months after addition.

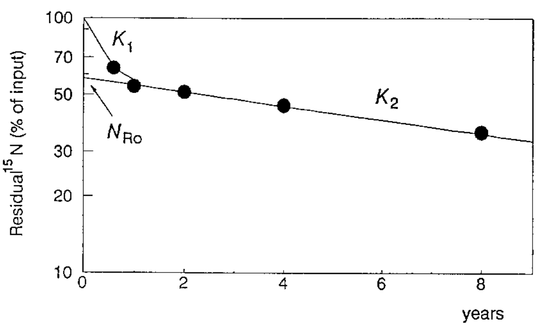

Fig. 2. Fit by first-order equations on the rapid and slow mineralization phase from long-term incubation experiments of ^{15}N-labelled legume residues decomposing in undisturbed soil under field conditions (Ladd et al., 1981b; 1985). Note logarithmic scale on *Y* axis.

obtained in short-term and long-term data points, indicated, whether a one- or two-pool model was appropriate to describe the N mineralization process (Voroney et al., 1989).

Effect of soil temperature and moisture content

The N mineralization heavily depends on environmental factors such as soil temperature and moisture content. The effect of temperature on N mineralization is given by:

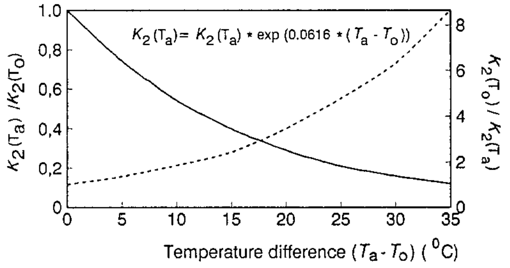

Fig. 3. Soil temperature function; $K_2(T_o)$ = constant decay of N mineralization K_2 at temperature T_o; $K_2(T_a)$ = K_2 adjusted by temperature T_a

$$K_2(T_a) = K_2(T_o) * \exp(0.0616 * (T_a - T_o) \quad (2)$$

where $K_2(T_a)$ is the constant decay rate K_2 adjusted to the temperature T_a ($5 \leq T_a \leq 35$°C) and $K_2(T_o)$ is the rate K_2 at temperature T_o ($5 \leq T_o \leq 35$°C). It follows from (2) if T_a is $\leq T_o$ the ratio $K_2(T_a)/K_2(T_o)$ is ≤ 1. Eq.(2) was derived from first-order rates K estimated at 5, 15, 25 and 35°C by Stanford et al. (1973). The K values obtained between 5 and 35°C were plotted on a semilog scale against temperature. Eq. (2) is the regression line obtained from plotted data with R^2 = 0.99 and slope 0.0616. From (2) it follows that a 10°C change in temperature leads to a change of $K_2(T_a)$ by a factor of approximately two (Fig. 3).

Cavalli and Rodríguez (1975) indicated that the relationship between soil moisture and N mineralization is linear between field capacity (33 k Pa) and permanent wilting point (1500 k Pa). Thus

$$K_2(W_a) = K_2(W_o) * (1.11 * (W_a/W_o) - 0.138) \quad (3)$$

where K_2 (W_a) is the rate constant K_2 adjusted to the soil moisture W_a (g g^{-1}) and $K_2(W_o)$ is the rate K_2 at soil moisture W_o (g g^{-1}). The variation in soil moisture was calculated on a daily basis from precipitation, class A pan evaporation and from the physical soil parameters such as: bulk density, soil moisture at field capacity and permanent wilting point.

Table 1 shows the N mineralization rates adjusted to 16°C assuming that the rate of mineralization doubles for every 10°C increase in temperature.

Estimation of stabilized pool of soil organic N

The integrated form of equation (1) is:

$$\ln N_{\mathrm{Ro}} = \ln N_{\mathrm{Ro_i}} - K_2 * t \tag{4}$$

Eq. (4) is the logarithmic form of:

$$N_{\mathrm{Ro}} = N_{\mathrm{Ro_i}} * \exp(-K_2 * t) \tag{5}$$

where $N_{\mathrm{Ro_i}}$ is the resistant N input. After n years of crop rotation, the size of the stabilized pool of soil organic N, N_{S} can be calculated for each resistant N input from t = 1 as:

$$\begin{aligned} N_{\mathrm{Sn}} &= N_{\mathrm{Ro_t}} * \exp(-K_2)^n \\ &\quad + N_{\mathrm{Ro_{t+1}}} * \exp(-K_2)^{n-t} \\ &\quad + N_{\mathrm{Ro_{t+2}}} * \exp(-K_2)^{n-(t+1)} \\ &\quad + \ldots + N_{\mathrm{Ro_n}} * \exp(-K_2)^t \\ &= \sum_{t=1}^{n} N_{\mathrm{Ro_t}} * \exp(-K_2)^{n-t+1} \end{aligned} \tag{6}$$

from (6) it follows that the equilibrium of N_s (when $n \rightarrow \infty$) after several years of crop rotation may be approximated by:

$$\begin{aligned} N_{\mathrm{S}_\infty} &= \frac{\frac{\sum_{t=1}^{n} N_{\mathrm{Ro_t}}}{n}}{1-\exp(-K_2)} - \frac{\sum_{t=1}^{n} N_{\mathrm{Ro_t}}}{n} \\ &= \frac{\frac{\sum_{t=1}^{n} N_{\mathrm{Ro_t}}}{n}}{\exp(K_2)-1} \end{aligned} \tag{7}$$

and (7) is approximated by:

$$N_{\mathrm{S}\infty} = \frac{\sum_{t=1}^{n} N_{\mathrm{Rot}}}{n * K_2} \tag{8}$$

The time when equilibrium is reached (t_{eq}), is defined as 95% of N_{S} at steady state:

$$t_{\mathrm{eq}} = \frac{-\ln 0.05}{K_2} \tag{9}$$

Nitrogen mineralization in the soil

The total N mineralization in soil is calculated from the N_{L} and N_{S} pools. The total soil mineral N in year n (N_{min}, kg N ha^{-1} yr^{-1}) is given by:

$$N_{\mathrm{min_n}} = N_{\mathrm{Ln}} + N_{\mathrm{Sn}} * (1 - \exp(-K_2 * t)) \tag{10}$$

where N_{L} is N_{Rs}*(1-fN_{Ro}). From Table 1 it appears that K_1 is so large that all N_{L} is mineralized within a year.

Nitrate leaching

The nitrate movement in soil was calculated according to a modified equation of Burns (1980):

$$L = A * (P/(P + (W_a * b_d)))^z \tag{11}$$

where L is the amount of N leached (kg N ha^{-1}) below the rooting depth z (cm), A the amount of N-NO_3^- (kg N ha^{-1}) present to depth z, W_a soil moisture content (g g^{-1}), b_d soil bulk density (g cm^{-3}) and P percolation below depth z. The percolation can be estimated as function of the surplus of precipitation (P_p, cm) over class A pan evaporation (E_v, cm) and the amount of water (h, cm) present between field capacity (W_{fc}, g g^{-1}) and permanent wilting point (W_{wp}, g g^{-1}) up to depth z:

$$P = P_p - E_v, \quad \text{if} \quad P_p - E_v > \mathrm{h} \tag{12}$$

$$P = 0, \quad \text{if} \quad P_p - E_v \leq \mathrm{h} \tag{13}$$

Field sites used to evaluate the model

The model was evaluated in four Chilean agro-ecosystems: Osorno, Temuco, Cauquenes and Rancagua. These sites are representative of agriculture in Southern and Central Chile. Tables 3 and 4 show some soil characteristics and the N inputs from crop rotations at each site. Cauquenes is a dryland area and the N input varies, depending on the amount and distribution of rainfall in winter. The soil of Cauquenes is highly eroded with a shallow rooting depth. Osorno and Temuco are soils derived from volcanic ash. In the last two sites the amount and distribution of rainfall within the year result in intermediate levels of productivity. Rancagua is an irrigated area with well structured soils which allow the highest grain yields in the country to be obtained.

The crop rotations in Osorno and Temuco have been approximately the same for more than 80 years and in Cauquenes and Rancagua for more than 100 years and reflect the time since colonization. The yields of maize and wheat have increased in Rancagua during the last 25 years as a result of the use of fertilizer and the introduction of new cultivars; the low input of N (Table 4) from wheat management is caused by residues being burned after harvest. In Osorno, although the mixed grassland (clover + ryegrass) can be maintained for between 6 and 20 years, pasture of 8 years duration is usual. The crop rotation and annual N inputs were estimated by Sierra and Rodríguez (1986), Matus and

Table 3. Precipitation, air temperatures and soil characteristics of the top soil layer (0–20 cm) for the four Chilean agro-ecosystems

	Osorno	Temuco	Cauquenes	Rancagua
Soil properties				
Soil Order (Soil Taxonomy)	Andisols	Ultisols	Alfisols	Inceptisols
Clay content (%)	23.0	44.1	19.0	26.5
Allophane (%)	21.0	0.0	0.0	0.0
pH (1:2.5, water)	5.3	5.1	6.0	6.8
soil org. C (t ha^{-1})	145.0	66.2	18.0	34.2
TOTAL. N (t ha^{-1})	12.8	6.3	1.8	2.9
C:N ratio	11.3	10.5	10.0	11.8
Physical parameters				
Bulk density (g cm^{-3})	0.8	1.0	1.2	1.2
Water holding capacity (%)	22.0	9.0	8.0	10.0
Temperature (°C)				
Sept.-March (spring-summer)	12.6	13.2	18.0	17.3
April-Aug. (autumn-winter)	8.0	8.6	11.4	11.9
Annual air temperature	10.7	11.2	15.3	15.1
Precipitation (mm)				
Sept.-March (spring-summer)	380.0	352.0	100.1	78.4
March-Spet. (autumn-winter)	810.0	862.0	532.5	516.1
Annual precipitation	1190.0	1214.0	632.6	594.5

Table 4. Nitrogen inputs (N_{Rs}) from crop residues in a crop rotation at four Chilean agro-ecosystems

Agro-eco-system	Crop rotation	N input (N_{Rs}) (kg N ha yr^{-1})
Osorno	sugar beat	50
	wheat	39
	grassland ryegrass + clover, 6 or 20 years)	150
Temuco	rapeseed	72
	wheat	30
	clover (2 years)	150
Cauquenes	wheat	19
	grass (5 years)	36
Rancagua	maize	98
	wheat	43

Rodríguez (1989), and Rodríguez (1990). The N inputs were obtained from the dry matter yield and by measurement of the N concentrations in above-and below-ground (0–20 cm) residues after harvest. The input of N from roots and dead plant material that enter the soil during a growing season were also considered (Matus and Rodríguez, 1989). From Osorno, Temuco and Rancagua, a total of 29 soil samples (0–20 cm) were taken and the potentially mineralizable soil N was measured by the method of Stanford and Smith (1972) (Rodríguez and Silva, 1984b; Rodríguez and Sierra, 1987). In the Cauquenes soil mineral N was estimated by the uptake of wheat in control field experiments without added N (García, 1973).

Results

Accumulation of stabilized pool of soil organic N

The two components required to build up the N_S pool are the constant decay rate K_2 (Table 1) and the resistant N fraction, fN_{Ro} (Table 2). Table 1 shows that (i) the constant decay rates K_2 in the long-term (0–10 years incubations) vary less than K_1 in the short-term (0–52 weeks) incubations, (ii) K_1 and K_2 decrease as the time of incubation increases and (iii) K_2 diminishes little in incubations longer than three years. The rates K_2 in undisturbed soil were about 7 times lower than K_1 (the highest value of K_1, was excluded) and the range of variation between the highest and lowest K_2 values from undisturbed soil incubations between 1 to 8 years was 2 times compared to 50 times for the range of variation of K_1. The relatively low variation in K_2 for several organic inputs decomposing in different soil and weather conditions has already been observed by Kolenbrander (1974). Experiments with ^{15}N- and ^{14}C-labelled plant materials have confirmed this finding (Ladd et al., 1985; Voroney et al., 1989). The constant rates K_2 for N may be compared with those for carbon in long-term incubation (Jenkinson, 1981). Table 5 shows the K_2 values adjusted to 16°C from several organic materials. These figures vary between 0.07 and 0.18 yr^{-1} and agree well with the observed data of N mineralization from Table 1.

Table 6 shows an example of the calculation of the N_S pool in a crop rotation, of maize-wheat in Rancagua. Annual average values of K_2 were obtained after adjusting for soil temperature (Eq. 2) and moisture (Eq. 3) on daily basis. Annual N inputs were obtained from Table 4 and fN_{Ro} was taken as the value 70% as obtained from Table 2. The accumulation curve started from the beginning of land cultivation. After several years of crop rotation an equilibrium of N_S pool, estimated by Eq. 8, is reached. The time of equilibrium, t_{eq}, was 81 years as calculated by Eq. 9.

Figure 4 shows an accumulation curve of the N_S pool for Rancagua and Osorno. Both agro-ecosystems approach equilibrium. In Osorno grassland contributed most to the size of N_S pool; however, the slower rate K_2 in this sites means that the equilibrium is reached later as the crop rotation continues. Rancagua has been cultivated longer than Osorno and its higher mean annual soil temperature (Table 3) raises the value of decomposition (K_2) and thus equilibrium is reached more quickly.

Table 7 shows the N_S pools and t_{eq} at the four field sites as calculated by the model. The N_S pools were predicted for 80 years of crop rotation in Osorno and Temuco and 100 years for Cauquenes and Rancagua. The N_S pools at equilibrium varied between 600 and 3000 kg N ha^{-1} and were greatest where the N inputs came from grassland. The constant rates K_2 ranged from 0.031 to 0.038 yr^{-1}; this variation was also mainly caused by differences in temperature amongst sites (Table 3). The predicted time of equilibrium has already been reached at Cauquenes and Rancagua but Osorno and Temuco have not yet achieved this level.

Annual net N-mineralization

Table 8 shows the contribution of annual net N mineralization to the N supply of crops as calculated by the model. Nitrogen supply was estimated from the amount of N mineralized according to Eq. (10) minus the nitrate leaching obtained with Eq. (11). For example, in Osorno the N supply for sugar beet was calculated from the mineralization of N_L and N_S for the last year of grassland minus the N leached below the rooting depth of 20 cm. The N supply ranged over-all sites from 29 to 130 kg N ha^{-1} yr^{-1}. The most important contribution of N_L and N_S to the total soil mineral N was in the agro-ecosystem of Osorno. The lowest N supply and the largest N leaching were predicted in the eroded soils of Cauquenes.

Model evaluation

Figure 5 shows the plot of net N mineralization estimated by the model and the potential N mineralization estimated by the method of Stanford and Smith (1972). The total soil mineral N calculated by the model was

Table 5. Decay rates K_2 of ^{14}C-labelled organic materials decomposing in soil in long-term incubation

Decomp. period (years)	Incubation lab. or field	Plant materials	Incub. temp. (°C)	K_2 Incub. temp. (yr^{-1})	K_2 Adjusted 16°C (yr^{-1})	References[a]
1–10	lab.	wheat straw	9.0	0.12	0.18	16
1–10	field	rye grass	9.1	0.09	0.14	12
1–3	lab.	glucose	20.0	0.17	0.13	14
0–6	lab.	glucose	20.0	0.14	0.11	13
1–3	lab.	hemicellulose	20.0	0.13	0.10	14
2–10	field	wheat straw	12.0[b]	0.08	0.10	7**
1–3	lab.	barley straw	20.0	0.11	0.09	14
12–20	field	barley straw	7.0	0.05	0.09	15
1–3	lab.	cellulose	20.0	0.10	0.08	14
1–4	field	legume	16.2	0.08	0.08	3**
1–3	lab.	maize straw	20.0	0.10	0.08	14
0–6	lab.	cellulose	20.0	0.09	0.07	13
mean					0.10	

Decomp.: decomposition.
Incub.: incubation.
Lab.: laboratory.
**: References, see Table 1.
[a]12; Jenkinson (1977); 13, Sørensen (1972); 14, Sørensen (1983); 15, Sørensen (1987); 16, Sauberbeck and Gonzalez (1977).
[b] Mean temperature only considered in months with temperature over 0°C.

Table 6. Example of accumulation (Janssen, 1984) of N_S pool (rounded figures) in Rancagua as calculated for addition of 98 and 43 kg N ha^{-1} $year^{-1}$ (N_{RS} from crop residues in a crop rotation of maize-wheat. The fN_{Ro} was taken 0.7 and K_2, 0.037 yr^{-1}

Crop residues added in the rotation	Years after addition 1	2	3	4..	..81
Maize	66	64	62	59..	..3[a]
Wheat		29	28	27..	..2[b]
Maize			66	64..	..4
Wheat				29..	..2
.	.	.	.	.	.
.	.	.	.	.	.
Total	66	93	156	179..	..1334

[a]3=98*0.7*exp(-0.037*81)
[b]2=43*0.7*exp(-0.037*80)

Table 7. Stabilized pool of soil organic N (N_S), rates K_2 and time of equilibrium (t_{eq}) at four Chilean agro-ecosystems as estimated by the model

Agro-eco systems	Crop rotation	Constant rate K_2^a (yr^{-1})	Equilib time t_{eq} (years)	Stabilized organic N (N_S) 80 or 100 yr (kg N ha^{-1})	steady-state
Osorno		0.031	97		
	sugar beet-			2303	2755
	wheat-			2416	2699
	6 years grassland			2571	2806
Osorno		0.031	97		
	sugar beet-			2725	3120
	wheat-			2744	3053
	20 years grassland			2974	3182
Temuco		0.034	88		
	rapeseed-			1894	2064
	wheat-			1850	1996
	2 years clover			1928	2064
Cauquenes		0.038	79		
	wheat-			569	583
	5 years native grass			578	590
Rancagua		0.037	81		
	maize-			1294	1327
	wheat			1277	1303

[a]Annual average adjusted by soil temperature and moisture.

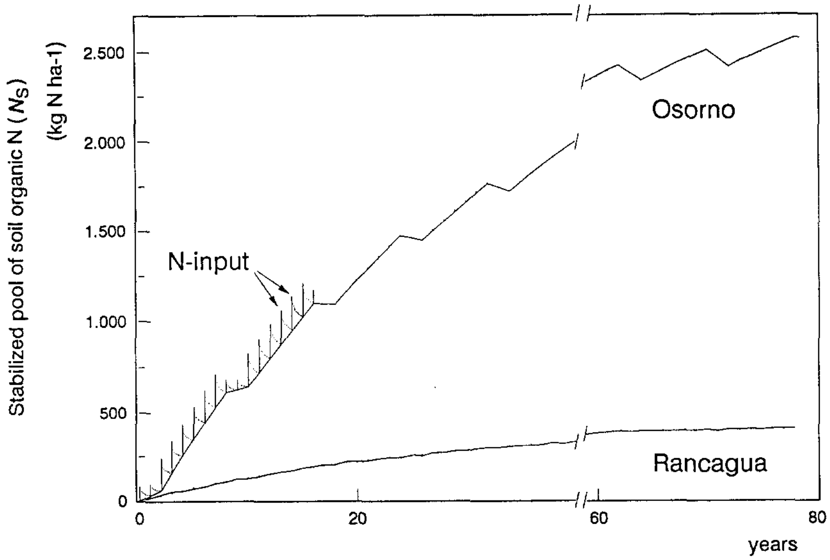

Fig. 4. Accumulation of stabilized pool of soil organic N, N_S, as shown for two crop rotations in the agro-ecosystems of Osorno and Rancagua.

Table 8. Contribution of net N mineralization to the N supply of crops as estimated by the model at four Chilean agro-ecosystem

Agro-eco systems	Crop rotation	Preceding crop	Mineralization (N_{min}) N_L^a	N_S^b	N–leaching	N–supply
			(kg N ha^1)			
Osorno	sugar beet-	grassland[c]	45	71	0	116
	wheat-	sugar beet	14	75	0	89
	6 years grassland					
Osorno	sugar beet-	grassland[c]	45	85	0	130
	wheat-	sugar beet	14	85	0	99
	20 years grassland					
Temuco	rape seed-	clover[c]	46	64	<2	110
	wheat-	rape seed	22	63	<2	85
	2 years clover					
Cauquenes	wheat-	grass[c]	10	22	3	29
	5 years native grass					
Rancagua	maize-	wheat	19	47	<2	66
	wheat	maize	12	48	<2	60

[a]N_L = labile N
[b]N_S = stabilized pool of soil organic N
[c]ploughed in the last year of grassland

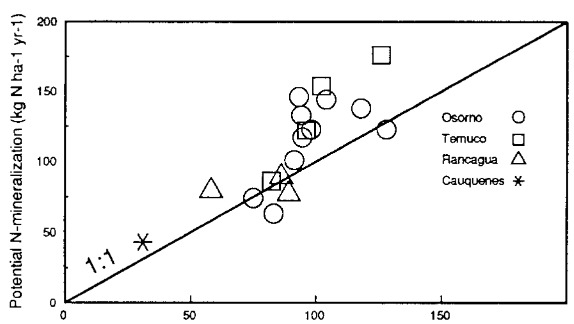

Fig. 5. Plot 1:1 of soil mineral N as predicted by the model at the four sites studied and potential mineralization estimated by the method of Stanford and Smith (1972).

less than predicted as shown by the 1:1 line. The under-prediction was worse in the agro-ecosystems where pasture was present. The quantity and quality of organic input in grassland soils may be the cause of an increase in N mineralization in the field (Nordmeyer and Richter, 1985).

Discussion

Model parameter estimation: rate constant K_2 and resistant N fraction fN_{Ro}

Plant materials decay with different rates depending on their C:N ratio and lignin content. In the early stages of decomposition a rapid N mineralization (high K value) is expected in crop residues with low C:N ratio and low lignin content (Parton et al., 1987). As the time of incubation increases, lower rates are observed (Hunt, 1977) (Table 1). The decay rate K_1 represents the easily decomposable fractions (e.g. amino-sugars, proteins, hemicellulose, cellulose and microbial products) followed by a slow constant decay rate K_2, which was assumed to reflect supply from the stabilized N_S pool.

It can be argued that the use of empirical values of K_2 is not possible because they decrease as the incubation time increases (Janssen, 1984). The turnover time of soil organic matter has been considered as the resultant of a series of first-order kinetic reactions from intermediate pools (Van Veen et al., 1981). An oversimplification may be made by assuming that K_2 represents the N mineralization of a homogeneous stabilized pool of soil organic N. Evidence for the existence of an N_S pool can be found indirectly from radiocarbon dating and the fractionation of soil organic matter. Complete turnover of apparently very humic organic material (passive pool) requires between 600 to 1400 years. These figures are 50–100 times lower than the mineralization of young soil organic matter (active pool) derived from recent organic input (Fig. 1). The turnover rates for young soil organic matter have been found to range between 0.047 and 0.069 yr^{-1} (Balesdent et al., 1987, 1988; Schwartz et al., 1986), close to the rates K_2 between 1 and 8 years of incubation studies (Table 1).

Table 2 shows a positive and significant (p<0.05) correlation (r = 0.70) between fN_{Ro} and C:N ratios of different plant materials. The mature crop residues showed the largest fN_{Ro} values, suggesting a greater resistance to decomposition as indicated by their high C:N ratios as well.

Stabilized pool of soil organic N

Table 7 shows that the grassland soil, generally accumulated more soil organic N in the stabilized pool. Cauquenes, even when grassland was present in the crop rotation, exhibited the lowest accumulation in N_S pool because of the quantity and presumably the quality of the N input, incorporated every year (Table 4). No large differences in the size of the N_S pool calculated from short or long periods of grassland in Osorno were predicted. Averaged over the crop rotation, 20 years of grassland resulted in a N_S pool 16% greater than 6 years of grassland. There were little differences between sites and managements in times of equilibrium (Table 7). The values ranged from 79 years in Cauquenes to 97 years in Osorno. The time of equilibrium were obtained according to Eq. 9 with the rates K_2 corrected for soil temperature and moisture. Neither soil moisture nor soil temperature at each site were limiting factors to the decomposition in spring. A small range of soil moisture and temperature amongst sites were observed, this little differences may have accounted for similar time of equilibrium. It seems probable that the agro-ecosystem approaches equilibrium (Fig. 4) (Martel and Paul, 1974) and that the N_S pool originates from the accumulation of humified fraction (N_{Ro}) or stabilized soil matter (Balesdent et al., 1988) or because of the accumulation of "young" soil organic matter (Janssen, 1984) with faster turnover rates than a passive pool.

Soil disruption by cultivation is another factor that can affect the size of N_S pool. The empirical parameters used in the model were obtained from undisturbed soil, but soil tillage enhances the rate K_2 of N mineralization. Evidence of this has been observed in short-term incubation experiments (Gregorich et al., 1989; Nordmeyer and Richter, 1985) and in disturbed grassland soils with an increasing number of years of cultivation (Lathwell and Bouldin, 1981). Soil tillage can not have a long-term effect on N mineralization, as outputs from the N_S pool may equal the inputs in the long run. In the first years, however, (and for the duration of most agronomic experiments), N mineralization will be increased if starting from a relatively large N_S pool of undisturbed soil, e.g. grassland soils.

Annual net N mineralization and model evaluation

Table 8 shows substantial differences in the calculated net N mineralization at the four sites. In agro-ecosystems with several years of grassland, greater N mineralization is expected. Leaching losses in winter months predicted by the model were smaller than 2.4 kg N ha^{-1} yr^{-1}, except in the poorly structured soil of Cauquenes where the N losses were between 10 and 13% of the total amount mineralized. About 60–90% of the N mineralized originated from the N_S pool. The remaining N came from the labile N pool, derived from the N input from the immediately preceding crop. In the literature, an average of 17% of the inputs from ^{15}N-labelled plant material is accounted for as N losses by denitrification and leaching (Ladd et al., 1981a; 1983; Müller and Sundman, 1988; Müller, 1988; 1987; Wagger et al., 1985). If this figure is subtracted from the mineralization N_L in Table 8, the total soil mineral N (N_L+N_S) must be decreased by 2–7%. These losses are small and therefore were not considered in the annual estimation. However, in Temuco the denitrification losses may have been greater than the other sites because of its higher rainfall and heavy clay soils (Table 3).

Annual N mineralization in Osorno was about 0.7–1.0% from the total soil organic N compared to 1.7–2.3% in the other agro-ecosystems. In this soil the higher soil organic matter content may have a large passive pool compared with an elevated amount of humic compounds. The allophanic soils have a high anion-adsorption capacity favoring the stabilization of organic polymers and microbial substances formed during decomposition (Zunino et al., 1982). In general the model output corresponded well with the potential N mineralization (Fig. 5). A double exponential model has been used to describe N mineralization in disturbed soils according to first-order kinetics (Cabrera and Kissel, 1988) but the results are variable when the parameter values are compared from different incubation times (Dendooven, 1990).

Conclusions

The purpose of our model was to simulate a range of N mineralization in different field sites where little information was available. The estimated release of N by mineralization was close to the soil mineral N observed at the four sites studied and any differences were explained on the basis of N input from crop rotations. The model estimates a dynamic equilibrium after several cycles of crop rotation. When this equilibrium is achieved the variation in the N_S pool depends on the N input from individual crops. The model suggests that the contribution to the N supply of the crop is determined more by cropping history reflected in the accumulation of a stabilized pool of soil organic matter. The model has the advantage that it is simple, however it does not consider the short-term dynamics of N mineralization within a growing season (e.g N immobilization), and must therefore be used on an annual basis.

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