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A comparison of different indices for nitrogen mineralization

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Abstract Indices of N mineralization in soils of contrasting texture, pH, and organic matter contents were compared at different dates during the growing season. The indices were derived from a 12-week aerobic incubation, determination of the amount of microbial biomass at the start of the incubation, determination of the increase in NH_4^+ after boiling with 2 *M* KCl for 2 h, and extraction of total soluble N with 0.01 *M* $CaCl_2$. Cumulative mineral N increased linearly with time in the course of the incubations. Rates of mineralization in soil samples taken in March 1989 and 1990 were significantly correlated with soluble organic N, while correlations between the mineralization rate and the increase in NH_4^+ after boiling with 2 *M* KCl for 2 h were poor for sandy soils and absent for loamy soils. Correlations between NH_4^+ after boiling with 2 *M* KCl for 2 h and the soil N concentration were highly significant, but no general relationship was found between the mineralization rate and the soil N concentration. Neither biomass N nor biomass C was significantly correlated with the mineralization rate or with one of the chemical indices. Among the methods tested, soluble organic N extracted with 0.01 *M* $CaCl_2$ was the only method with any promise for routine measurement of the mineralization capacity of the individual sites.

Key words Mineralization · Soil organic matter · Aerobic incubation · $CaCl_2$ extraction · Soluble organic nitrogen · Microbial biomass

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Introduction

Fertilizer recommendations for arable crops are usually based on soil mineral N (NH_4^+-N+NO_3^--N) before the growing season, or on a combination of soil mineral N, mineralizable soil N, and the expected yield of the crop (Prins et al. 1988). Recommendations originally developed for economically optimum fertilizer rates have led to increasing problems of groundwater pollution caused by leaching of NO_3^- from agricultural land, making it necessary to find a compromise between the economic optimum and the ecological optimum, where leaching losses are minimal. Thus, accurate prediction of seasonal N mineralization is of major importance.

The spatial variability in mineralization is very large. In 61 field experiments with potatoes in the Netherlands, Neeteson et al. (1987) found apparent rates of mineralization ranging from 0.4 to 2.0 kg ha^{-1} day^{-1}, with an average of 1.0 kg ha^{-1} day^{-1}; these data were derived from the N uptake on unfertilized plots. Attempts have been made to estimate N fertilizer requirements using simulation models. In a comparison of 14 models of N dynamics in crops and soils, De Willigen (1991) concluded that while the crop response to available soil mineral N was generally satisfactorily simulated, the simulated dynamics of soil mineral N were inaccurate. This was mainly a result of inadequate understanding of soil organic matter dynamics.

Stanford and Smith (1972) assumed that net mineralization proceeded according to first-order kinetics, and derived potentially mineralizable N and the mineralization rate constant k from a rate analysis of N mineralization during soil incubation. In these experiments, the soils were dried after sampling and rewetted before being incubated. In incubation experiments using fresh soils, Verstraeten et al. (1969) also found that net mineralization followed first-order kinetics. In other incubation experiments with field-moist soils, however, mineralized N increased linearly with time (Tabatabai and Al-Khafaji 1980; Addiscott 1983). The apparent first-order behavior

described by Stanford and Smith (1972) was attributed to a flush of mineral N upon rewetting (Birch 1958).

Soil incubation is laborious and time-consuming, and therefore unsuitable for routine determinations of mineralization capacity in agricultural practice. Various simple chemical extraction methods giving results that have been correlated with those of incubation experiments have been proposed. In a series of widely differing Brazilian soils Gianello and Bremner (1986) showed that the potentially mineralizable N, determined according to Stanford and Smith (1972), was closely correlated with NH_4^+ extracted after boiling with 2 *M* KCl for 4 h. A significant correlation was observed between N mineralization, as reflected in the uptake of N by rape, and soluble organic N extracted by 0.01 *M* $CaCl_2$ (Appel and Mengel 1990). Soluble organic N has been considered an indicator of the size of the soil microbial biomass, as a significant correlation between the two has been found (Olfs and Werner 1989).

In the present study, field-moist soil from different locations, different depths, and sampled at different times was incubated aerobically for 12 weeks and mineralization rates were determined. These rates were compared with the results of chemical methods and with the size of the microbial biomass.

Materials and methods

Sites and soils

In 1989, soil samples were taken in March, June, and October from depths of 0–30 and 30–60 cm at eight locations in The Netherlands differing in soil type. At two locations samples were taken from 60–90 cm, also. Winter wheat was grown at all sites during the 1989 season. In 1990 samples were taken in March, from depths of 0–10, 10–20, and 20–30 cm at three locations, and from 0–10, 10–30, and 30–60 cm at a fourth location. In both years at each location, one or more additional fields with a different cropping history were sampled. The sampling sites were chosen to cover a wide range in texture, organic matter content, C : N ratio, and pH (Table 1). Each sample consisted of 40 soil cores (total fresh weight about 10 kg) taken randomly from 1 ha.

Determination of extraction, incubation, and microbial biomass

Between sampling and the start of incubation (2–4 weeks), the samples were stored at 2° C and subsequently sieved over a 4-mm mesh, and thoroughly hand-mixed. From each sieved field-moist sample, subsamples were taken for the following analyses.

NH_4^+ and NO_3^- were determined in 200 g field-moist soil which was shaken with 500 ml 1 *M* KCl for 1 h. NH_4^+ and NO_3^- concentrations were measured using a Kjeltech autoanalyzer. The dry matter content of the soil was determined after drying it at 105° C overnight, and the concentrations of NH_4^+ and NO_3^- were expressed per unit dry weight.

For the incubation, 10 glass jars (370 ml) for each sample were loosely filled with 300 g soil each, covered with oxygen-permeable polyethylene foil to prevent the soil from drying, and maintained at 20° C and 80% relative humidity. NH_4^+ and NO_3^- were measured in duplicate (two separate glass jars) after 1, 3, 6, 9, and 12 weeks, using the KCl extraction described above.

The microbial biomass was determined in triplicate in the 1989 soil samples by the fumigation–incubation method (Jenkinson and Powlson 1976). Soils with a pH of less than 5.0 were omitted, as the fumigation–incubation method gives reliable results for pH 5.0–8.5 only (Goûteaux et al. 1989; Jenkinson 1988). Two 50-ml beakers were filled with 20 g moist soil brought to 60% water-holding capacity. One beaker was exposed for 24 h at room temperature to $CHCl_3$ in a desiccator, and then the fumigant was removed by repeated evacuation. The fumigated soil and an untreated control were then each placed in a 1.5-liter stoppered bottle containing a small beaker with 10 ml 1 *M* NaOH to absorb respired CO_2, and were incubated at 25° C. After 10 days, carbonate in the NaOH was precipitated with excess $BaCl_2$, and NaOH was titrated with 0.05 *M* HCl to determine the difference in CO_2 production between the fumigated and unfumigated soils. NH_4^+ and NO_3^- were measured after extraction with KCl to determine the difference in N production between the fumigated and unfumigated soils.

Chemical analysis

The remainder of each soil sample was oven-dried at 30° C for 24 h, and subsamples were taken for the following analyses.

Soil pH was measured in a suspension of soil with 1 *M* KCl. The particle-size distribution was measured using the pipette method (Gee and Bauder 1986). The C content was determined according to Mebius (1960), and the organic matter content was estimated by dividing the C content by 0.58. The Kjeldahl method was used to determine total soil N (Bremner and Mulvaney 1982).

Soluble organic N was measured after extraction with 0.01 *M* $CaCl_2$, as described by Houba et al. (1987), in soil samples taken from a depth of 0–30 cm in March and June 1989 and in all soil samples taken in October 1989 and March 1990. In the soil samples taken in October 1989, organic N was also measured in the course of aerobic incubation (see previous section), after 1, 3, 6, 9, and 12 weeks.

NH_4^+, extracted after boiling with 2 *M* KCl, was determined according to Gianello and Bremner (1986), except that the soils were boiled for 2 h instead of 4 h. This analysis was applied to soil samples taken in March and June 1989, and to all soil samples taken in 1990.

Results

Soil properties

Some major properties of the soils at the sampling sites are summarized in Tables 1 and 2. The soils were classified according to particle-size distribution (Soil Science Society of America 1987). The characteristics of the selected soil samples varied widely, including 0–37% clay, 7–73% silt, 0–93% sand, pH ranging from 3.5 to 8.0, 1.1–21.6% organic matter, and C : N ratios ranging from 7.3 to 43.1.

Incubations

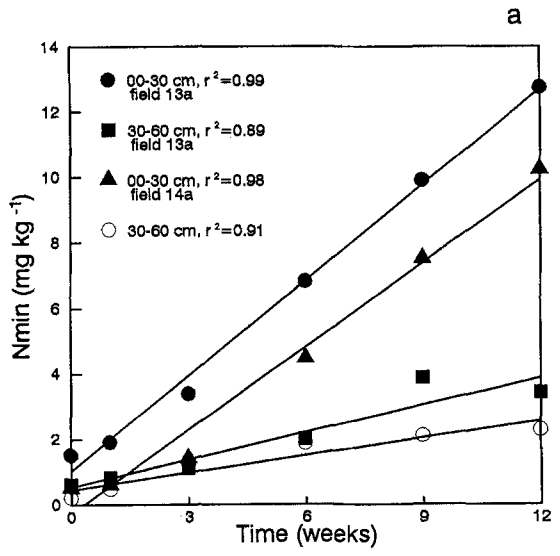
Some results of the incubation experiments are given in Fig. 1. Mineral N generally increased linearly during the 12-week incubation period, due to an increase in NO_3^-. Some soil samples taken in March contained small amounts of NH_4^+, but virtually all NH_4^+ disappeared during the incubation. In all incubation experiments, dif-

Table 1 Soil characteristics of sampling sites in 1989 experiments

Depth and location	Description	Texture	Particle size (%)			pH (KCl)	Organic matter (%)	C (%)	N (%)	C:N	$CaCO_3$ (%)
			<2 μm	2–50 μm	>50 μm						
0–30 cm											
Lovinkhoeve	Polder soil, reclaimed in 1942	Silty loam	21.1	68.9	10.0	7.5	2.4	1.33	0.12	11.2	9.0
OBS	Polder soil, reclaimed in 1942	Loam	20.0	46.5	33.5	7.5	2.1	1.19	0.11	10.8	8.9
RIJP-Lelystad	Polder soil, reclaimed in 1957	Sandy loam	9.0	23.3	67.7	7.6	2.3	1.30	0.09	14.4	5.5
RIJP-Almere	Polder soil, reclaimed in 1968	Silty clay loam	36.9	43.7	19.5	7.3	3.6	2.02	0.16	12.6	8.2
Bouwing	Alluvial clay deposit	Silty clay loam	36.0	54.9	9.1	7.1	1.8	0.99	0.14	7.3	0.2
Borgerswold	Reclaimed peat soil	Sand	0.0	12.0	88.0	5.0	16.2	9.07	0.36	25.5	0.0
IB-Haren	Glacial sand deposit	Loamy sand	0.0	30.8	69.2	5.7	3.1	1.73	0.12	14.4	0.0
Nieuwlande	Reclaimed peat soil	Loamy sand	0.0	14.7	85.3	4.8	8.1	4.56	0.15	30.4	0.0
30–60 and 60–100 cm[a]											
Lovinkhoeve	Polder soil, reclaimed in 1942	Silty loam	13.6	72.9	13.5	7.7	1.8	1.02	0.08	12.3	8.3
OBS	Polder soil, reclaimed in 1942	Silty loam	10.3	64.9	24.8	7.7	2.0	1.09	0.08	13.7	8.6
RIJP-Lelystad	Polder soil, reclaimed in 1957	Sandy loam	5.7	18.3	75.9	7.9	1.4	0.79	0.05	15.7	4.3
RIJP-Lelystad[a]	Polder soil, reclaimed in 1957	Sandy loam	4.7	21.0	74.3	8.0	1.1	0.60	0.04	14.9	4.6
RIJP-Almere	Polder soil, reclaimed in 1968	Silty clay loam	33.0	56.6	10.4	7.4	5.0	2.82	0.21	13.4	7.7
RIJP-Almere[a]	Polder soil, reclaimed in 1968	Silty clay loam	30.6	62.3	7.1	7.4	8.7	4.89	0.32	15.3	5.9
Bouwing	Alluvial clay deposit	Silty clay loam	36.0	54.6	9.4	7.1	1.3	0.72	0.10	7.3	0.1
Borgerswold	Reclaimed peat soil	Sand	0.0	7.2	92.8	4.0	6.8	3.81	0.13	29.5	0.0
IB-Haren	Glacial sand deposit	Loamy sand	0.0	26.9	73.1	4.9	2.3	1.29	0.09	14.3	0.0
Nieuwlande	Reclaimed peat soil	Loamy sand	0.0	17.9	82.1	3.9	6.9	3.88	0.09	43.1	0.0

Table 2 Soil characteristics of sampling sites in 1990 experiments

Location and depth	Description	Texture	Particle size (%)			pH (KCl)	Organic matter (%)	C (%)	N (%)	C:N	$CaCO_3$ (%)
			<2 μm	2–50 μm	>50 μm						
OBS	Polder soil, reclaimed in 1942										
0–10		Silty loam	22.0	55.5	22.5	7.4	2.4	1.36	0.12	11.7	9.3
10–30		Loam	21.1	48.6	30.3	7.4	2.3	1.34	0.12	11.5	9.3
30–60		Silty loam	11.2	71.8	17.0	7.6	1.9	1.10	0.07	15.7	9.0
Nieuwlande	Reclaimed peat soil										
0–10		Loamy sand	0.0	15.5	84.5	4.3–6.2	7.0–17.6	4.1–10.2	0.12–0.39	26.1–34.0	0.0
10–20		Loamy sand	0.0	15.2	84.8	4.3–5.1	6.5–17.2	3.8–10.0	0.12–0.46	21.7–33.2	0.0
20–30		Loamy sand	0.0	14.3	85.7	4.1–5.0	6.5–21.6	3.8–12.5	0.11–0.38	29.0–34.2	0.0
30–60		Loamy sand	0.0	14.2	85.8	3.5–4.2	5.7–9.7	3.3–5.6	0.09–0.16	33.3–43.4	0.0
Borgerswold	Reclaimed peat soil										
0–10		Sand	0.0	12.9	87.1	4.9	20.6	11.94	0.45	26.4	0.0
10–30		Sand	0.0	12.2	87.8	4.7	18.5	10.72	0.40	26.8	0.0
30–60		Sand	0.0	9.5	90.5	4.0	4.6	2.70	0.09	29.5	0.0
IB-Haren	Glacial sand deposit										
0–10		Sandy loam	0.0	32.6	67.4	5.3	4.1	2.41	0.12	21.0	0.0
10–30		Loamy sand	0.0	27.4	72.6	5.2	4.2	2.45	0.12	21.3	0.0
30–60		Sandy loam	0.0	32.6	67.4	4.6	3.9	2.25	0.10	22.7	0.0



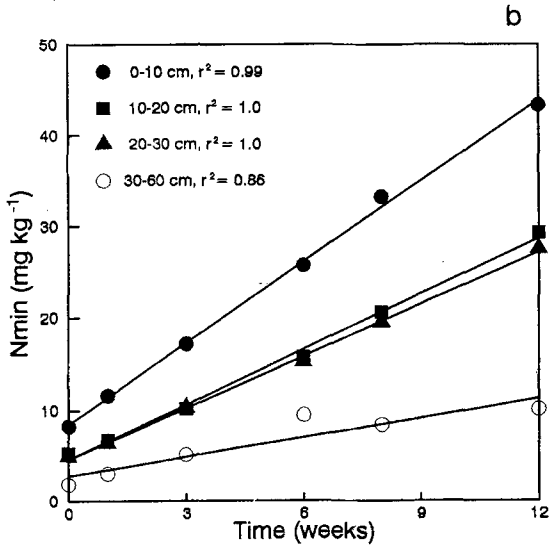


Fig. 1 a, b Cumulative mineral N (*Nmin*) during a 12-week incubation in two polder soils (Lovinkhoeve, Table 1) sampled in June 1989 (**a**) and a loamy sand (Nieuwlande, Table 1) sampled in 1990 (**b**)

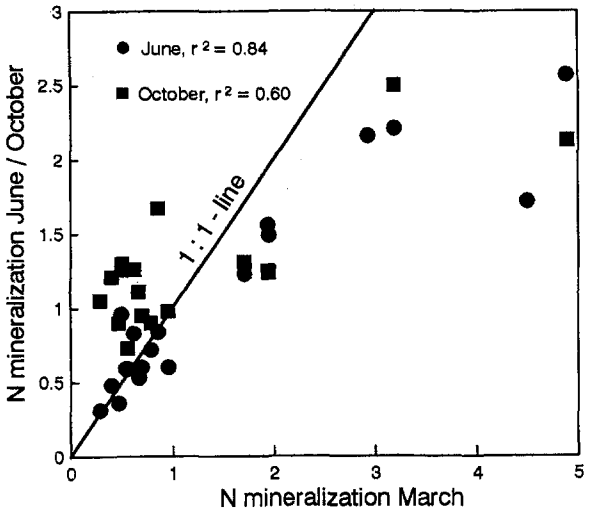


Fig. 2 Relationship between mineralization rates measured in March and mineralization rates measured in June or October in topsoil samples (0–30 cm)

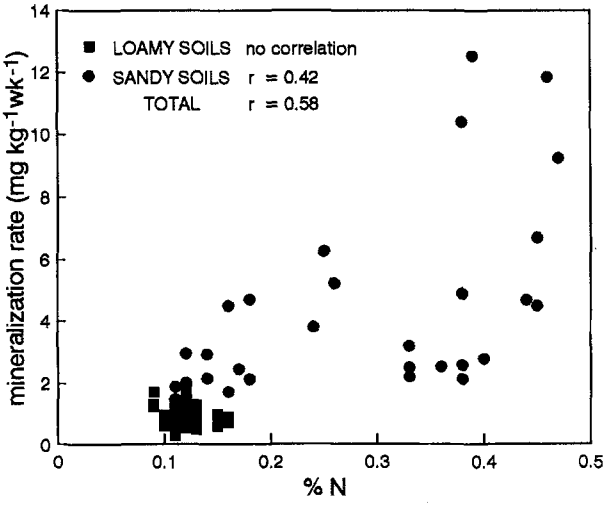


Fig. 3 Rate of N mineralization (mg kg^{-1} $week^{-1}$) as a function of soil N content (%) for all soil samples (1989 and 1990) from 0–30 cm

ferences between replicates were small (<5%). A linear regression of mineral N over time showed that for 12 out of 160 incubation experiments, r^2 was less than 0.90, and these results were omitted from further analysis.

Rates of mineralization (expressed as mg N kg^{-1} soil) in the samples taken from 0–30 cm in March and June 1989 were closely correlated (Fig. 2, $r^2 = 0.84$), but the correlation between the March and October samples was considerably weaker (Fig. 2, $r^2 = 0.60$). In the subsoil (30–60 cm), correlations between rates of mineralization measured in the March and June samples and between those in the March and October samples were not significant (Table 3).

To determine whether mineralization could be expressed as a function of soil N, rates of mineralization for all soil samples taken from 0–30 cm (both 1989 and 1990) were plotted against the N concentration (Fig. 3). The relatively high r^2 value (0.58) was mainly due to high rates of mineralization in the sandy soils; when data from the sandy and loamy soils were analyzed separately, no correlation between the soil N content and mineralization was found in the loamy soils, but in the sandy soils r^2 was 0.42 (Table 3).

Table 3 Coefficients of determination (r^2) of regressions between different soil characteristics [mineralization rate (*MR*), increase in NH_4^+ after boiling with 2 *M* KCl for 2 h, soluble organic N (N_{org}), N content (% N)] versus the mineralization rate measured at different times of the year or NH_4^+ measured after boiling with 2 *M* KCl for 2 h or the N content

Soil characteristic	Regressed on:	Depth (cm)	*n*	r^2
MR March 1989	MR June 1989	0–30	19	0.84
MR March 1989	MR June 1989	30–60	19	0.25
MR March 1989	MR October 1989	0–30	17	0.60
MR March 1989	MR October 1989	30–60	17	0.25
% N all soils 1989/90	MR 1989/90	0–30	83	0.58
% N loamy soils 1989/90	MR 1989/90	0–30	45	0.11
% N sandy soils 1989/90	MR 1989/90	0–30	38	0.42
N_{org} March 1989	MR March 1989	0–30	19	0.78
N_{org} June 1989	MR June 1989	0–30	19	0.46
N_{org} October 1989	MR October 1989	0–30	17	0.52
N_{org} October 1989	MR October 1989	30–60	18	0.33
N_{org} March 1990	MR March 1990	0–30	28	0.69
N_{org} March 1990	MR March 1990	30–60	8	0.05
NH_4^+ (2 *M* KCl) loamy soils	MR 1989/90	0–30	31	0.00
NH_4^+ (2 *M* KCl) sandy soils	MR 1989/90	0–30	33	0.52
NH_4^+ (2 *M* KCl) all soils	MR 1989/90	0–60	110	0.67
NH_4^+ (2 *M* KCl) March 1989	NH_4^+ (2 *M* KCl) June 1989	0–30	19	0.61
NH_4^+ (2 *M* KCl) March 1989	NH_4^+ (2 *M* KCl) Oct. 1989	0–30	17	0.58
% N all soils 1989/90	NH_4^+ (2 *M* KCl)	0–60	116	0.94
N_{org} March 1989	NH_4^+ (2 *M* KCl) March 1990	0–30	17	0.84
N_{org} March 1989	% N March 1989	0–30	19	0.79
N_{org} March 1990	NH_4^+ (2 *M* KCl) March 1990	0–30	28	0.81
N_{org} March 1990	% N March 1990	0–30	28	0.81

Soluble organic N

When the rate of mineralization measured by incubation was related to the organic N content in samples taken in March 1989 (Fig. 4) a significant correlation ($r^2 = 0.78$) was again found, mainly due to data from the sandy soils. Mineralization rates in the samples taken from 0–30 cm in March 1990 were also significantly correlated with organic N ($r^2 = 0.67$). However, in soil samples taken in June and October 1989, the correlation was weaker ($r^2 = 0.46$ and 0.51, respectively). In subsoil samples (30–60 cm) taken in October 1989 and March 1990 no significant correlation was found ($r^2 = 0.33$ and 0.05, respectively).

In both years, in the March samples taken from 0–30 cm, organic N was significantly correlated with the increase in NH_4^+ after boiling with 2 *M* KCl ($r^2 = 0.84$ and 0.81 for 1989 and 1990, respectively), and with the N concentration ($r^2 = 0.79$ and 0.81, respectively).

Organic N was low and relatively constant during the incubation in soil samples taken in October (Fig. 5), while mineral N increased linearly. In spite of differences in the rate of mineralization between samples taken from 0–30 and 30–60 cm, there was little difference in the course of organic N during the incubation.

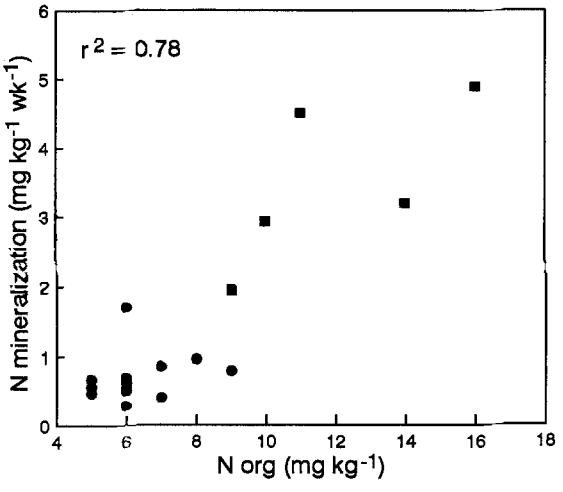


Fig. 4 Rate of N mineralization (g kg^{-1} $week^{-1}$) as a function of the content of soluble organic N in soil samples from 0–30 cm taken in March 1989 (● loamy soil, ■ sandy soils)

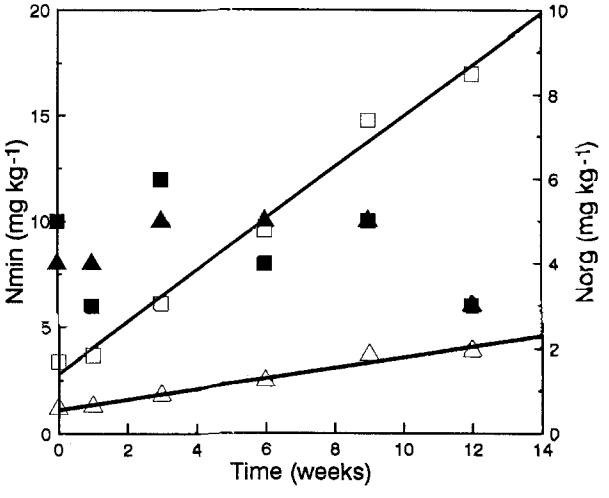


Fig. 5 Cumulative mineral N (*Nmin*) during a 12-week incubation in soil samples taken from depths of 0–30 cm (□) and 30–60 (△) cm, and time-course of organic N (*Norg*) in soil samples from depths of 0–30 (■) and 30–60 (▲) cm in a polder soil (Lovinkhoeve, Table 1) sampled in October 1989

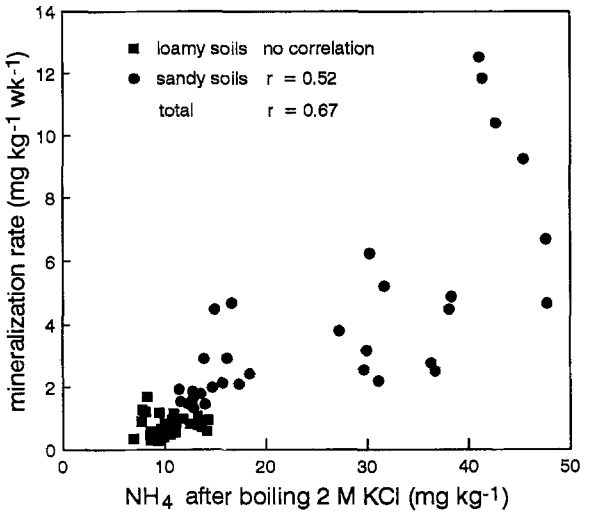


Fig. 6 Rate of mineralization (mg kg^{-1} $week^{-1}$) as a function of the increase in NH_4^+ (mg kg^{-1}) after boiling with 2 *M* KCl for 2 h, for all soil samples taken from a depth of 0–30 cm in 1989 and 1990

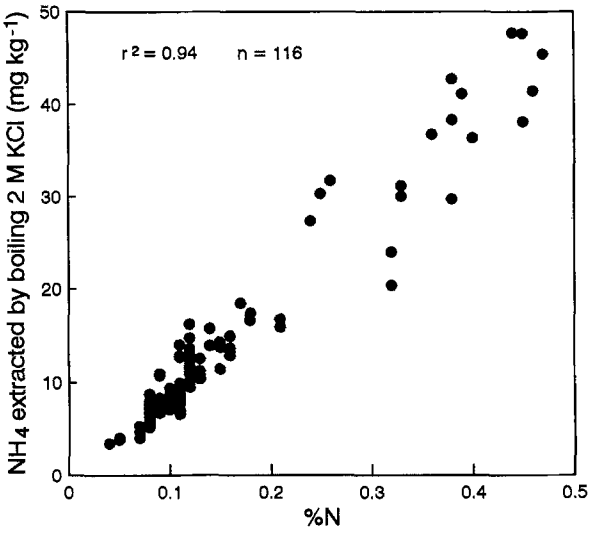


Fig. 7 Increase in NH_4^+ after boiling with 2 *M* KCl for 2 h (mg kg^{-1}) as a function of the soil N content (%) for all soil samples (top- and subsoils) taken in 1989 and 1990

Extraction of NH_4^+ after boiling with 2 *M* KCl

There was no correlation between the increase in NH_4^+ content after boiling for 2 h with 2 *M* KCl and the mineralization rate during incubation in loamy samples taken from 0–30 cm (both 1989 and 1990), but there was a significant correlation for the corresponding sandy soils (Fig. 6, $r^2 = 0.52$). In all soil samples analyzed by this chemical method, the increase in NH_4^+ was highly correlated with the N concentration (Fig. 7, $r^2 = 0.94$).

Soil microbial biomass

Microbial biomass activity, expressed as the difference in C production or in N production between fumigated and unfumigated samples over 10 days after fumigation, and C:N ratios, expressed as the ratio of C production to N production, are given in Table 4 for all topsoil samples (0–30 cm) taken in 1989. The CV shows considerable variability between March, June, and October, both for C production and N production. For each of the three sampling dates, the variability in C production between locations was higher than in N production. Plots of N and C production in the June samples against those in March or October samples show that N production was relatively constant throughout the season (Fig. 8a), but C production fluctuated strongly (Fig. 8b); hence the calculated C:N ratios varied also (Table 4). Different cropping systems at the same location barely affected C production, but had a distinct effect on N production. In the Noordoostpolder soils (Lovinkhoeve, OBS) N production was

Table 4 Microbial biomass C flush, N flush, and C:N ratio (defined as ratio C flush to N flush) for topsoils (0–30 cm) sampled in March, June, and October 1989 (averages of three replicates), and for topsoils (0–10 and 10–30 cm) sampled in March 1990 (averages of two replicates). Coefficients of variation given in parentheses. *Org. fert.* organic fertilizer

Location, management	March			June			October		
	C flush (mg kg^{-1})	N flush (mg kg^{-1})	C:N	C flush (mg kg^{-1})	N flush (mg kg^{-1})	C:N	C flush (mg kg^{-1})	N flush (mg kg^{-1})	C:N
Lovinkhoeve, no green manure	423 (3.0)	32.8 (4.2)	16.3	473 (1.0)	33.8 (4.0)	17.8	500 (5.8)	41.5 (3.5)	15.3
Lovinkhoeve, +green manure	453 (1.0)	41.6 (3.3)	13.8	403 (17.0)	38.7 (3.5)	13.2	560 (2.5)	42.4 (9.1)	16.7
Lovinkhoeve, no org. fert.	416 (13.1)	39.4 (3.4)	13.4	587 (5.6)	39.8 (3.5)	18.7	527 (3.9)	38.3 (3.8)	17.4
Lovinkhoeve, +org. fert.	430 (1.9)	49.3 (2.8)	11.1	563 (7.2)	53.0 (4.5)	13.5	573 (3.0)	47.8 (3.1)	15.2
Lovinkhoeve, conventional	420 (18.8)	46.8 (0.0)	11.4	537 (3.2)	65.8 (2.2)	10.3	527 (1.8)	54.3 (2.7)	12.3
Lovinkhoeve, integrated	477 (9.4)	51.0 (29.9)	11.8	463 (7.3)	73.7 (7.0)	8.0	610 (4.8)	67.3 (2.2)	11.5
OBS, conventional	403 (2.3)	38.8 (9.4)	13.2	420 (3.4)	39.3 (3.5)	13.6	503 (9.5)	36.9 (3.8)	17.3
OBS, integrated	397 (13.7)	48.0 (2.9)	10.5	383 (6.9)	41.4 (3.3)	11.7	573 (2.2)	47.9 (10.2)	15.2
OBS, organic farming	477 (2.0)	75.8 (4.9)	8.0	430 (3.8)	73.9 (1.9)	7.4	493 (5.8)	69.8 (7.1)	9.0
Flevopolder-Lelystad	507 (0.9)	38.3 (14.9)	16.7	300 (9.8)	36.1 (3.7)	10.5	453 (6.8)	40.1 (3.5)	14.3
Flevopolder-Almere	523 (5.6)	49.0 (25.2)	13.5	567 (3.6)	65.1 (4.6)	11.0	510 (4.2)	63.0 (4.8)	10.3
Bouwing, no green manure	553 (2.3)	37.3 (9.9)	18.8	483 (3.5)	45.2 (3.1)	13.5	677 (3.0)	54.2 (4.5)	15.8
Bouwing, +green manure	–	–	–	487 (5.1)	24.3 (5.7)	25.4	673 (1.9)	34.5 (4.2)	24.7

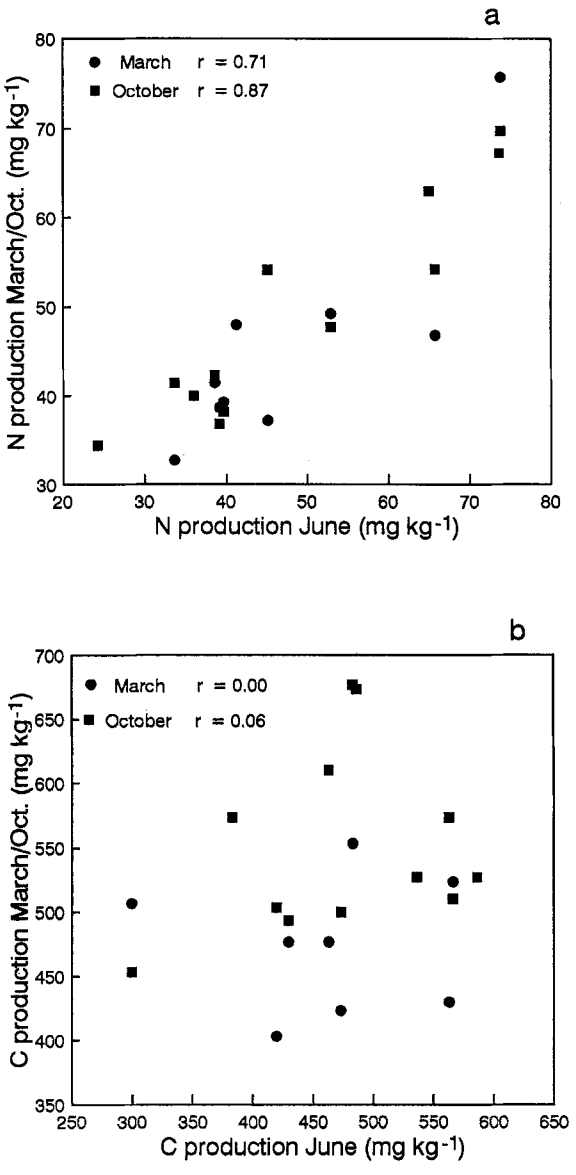


Fig. 8 a, b Relationship between C production in soil samples taken in June and in March or October from a depth of 0–30 cm (**a**) and between N production in samples taken in June or October from 0–30 cm (**b**). Averages with a CV of >10% are omitted

higher when larger amounts of organic material had been incorporated. In the Bouwing soil the result was the opposite, with N production being highest in the soils that had not been supplied with green manure. In the subsoils (30–60 cm), C production was of the same order of magnitude as in the topsoils, but N production was substantially lower, generally giving calculated C:N ratios exceeding 30 (data not shown).

Neither biomass N nor biomass C was significantly correlated with any of the characteristics reported in the preceding sections, including N mineralization.

Discussion

Rates of mineralization measured during aerobic incubation of sieved soil samples under controlled conditions were compared with different indices which have been correlated with the rate of mineralization under field conditions. Cumulative mineral N increased linearly during the incubation in 148 out of 160 samples, in accord with results reported by Tabatabai and Al-Khafaji (1980) and Addiscott (1983). Sieving destroys soil aggregates and may therefore lead to increased mineralization for periods of several days to several weeks, but after this initial mineralization flush, rates become equal in sieved and undisturbed soil samples (Nordmeyer and Richter 1985; Hassink 1992); thus mineralization rates measured in sieved soils can be considered representative of the field situation. In the present experiments, there was no mineralization flush and cumulative mineral N increased linearly with time from the start of the incubations (Fig. 1). Mineralization rates were considerably higher in the sandy soils than in the loamy soils; in most of these sandy soils the soil organic matter content was considerably higher than in the loamy soils.

Figure 2 shows that mineralization rates measured in the June samples were generally lower than in those taken in March, while rates measured in the October samples were generally higher. The higher rates in March may have been a result of decomposing crop residues from a preceding crop, which no longer contributed to mineralization in June; in October, residues from the current crop, presumably roots, were decomposing. Bonde and Rosswall (1987), in Sweden, also found a decrease in mineralization between April and August, followed by an increase in the fall.

In interpreting field data and in simulation models for soil N dynamics, it has been assumed that a fixed proportion of soil organic matter or soil organic N components decomposes each year (Kortleven 1963; Johnsson et al. 1987), but Fig. 3 shows that this was not true of the loamy soils studied, and only to a limited extent for the sandy soils.

A significant correlation was found between rates of mineralization for soil samples taken in spring (March 1989 and 1990) and organic N, the soluble organic N fraction extracted with 0.01 M $CaCl_2$ (Fig. 4), in accord with Appel and Mengel (1990). This was mainly due to results from the sandy soils; in the loamy soils, both the mineralization rate and organic N were low, and close to the limit of accuracy for the analytical methods applied. In the course of 12-week incubations organic N values were relatively constant (Fig. 5), as reported by Appel and Mengel (1990). Recently, N uptake was analyzed at the stage of maximum leaf development in 53 field experiments with sugar beet, using a curvilinear multiple regression analysis that included organic N measured in spring, mineral N measured in spring, N fertilizer, and year effects (N uptake = a·organic N+b·mineral N+C·fertilizer N +year). The analysis showed that organic N contributed

significantly to the variation in N uptake (Houba et al. 1994). Appel and Mengel (1992) also found a significant correlation by multiple regression analysis between the N uptake by cereals, soil mineral N and organic N measured in spring. The results of the present analysis also strongly suggest that organic N can be used as an indicator of mineralization capacity at a given site.

It has been suggested that organic N reflects the size of the microbial biomass, but in the soils studied, organic N and the microbial biomass were not correlated. Our measurements of microbial biomass N and C generally showed poor reproducibility. The biomass C:N ratio, calculated as the ratio of additional C production to additional N production after fumigation, ranged from 8.0 to 24, with an average of 13.8. In a review of microbial biomass measurements in a large number of soils from different countries, Jenkinson (1988) reported a much lower C:N ratio of 5.3. However, the C:N ratios reported by Hassink et al. (1991) reported for Dutch polder soils were of the same magnitude as those reported here, suggesting that in very young polder soils, more native organic C is liberated for microbial transformation by fumigation than in older soils. This, in fact, makes the fumigation-incubation method unsuitable to compare the microbial biomass in soils of different origins.

In the Noordoostpolder soils (Lovinkhoeve, OBS) N production was higher when a larger amount of organic material was incorporated, a phenomenon also observed by Hassink et al. (1991). There is no obvious explanation, nor for the fact that in the Bouwing soil the opposite effect was observed.

Neither microbial N nor C was significantly correlated with mineralization, which is not surprising, as Jenkinson (1988) stated "it is well to be clear about what biomass measurements do not provide. They are essentially 'standing crop' measurements, not measurements of microbial activity such as ... mineralization of N".

Gianello and Bremner (1986) found a highly significant ($P = 0.001$) correlation between rates of mineralization, measured according to Stanford and Smith (1972), and the increase in NH_4^+ after boiling with 2 M KCl, for widely different Brazilian soils. In the present experiments, a significant correlation was found only for sandy soils. However, a highly significant correlation was obtained between the increase in NH_4^+ and the N content of the soil. Hence, this method seems to dissolve a fixed proportion of soil organic matter. In the present experiments mineralization rates were poorly correlated with soil organic matter and soil N contents, whereas in the soils used by Gianello and Bremner (1986), a fixed proportion of the soil organic matter is apparently mineralized annually. One explanation for this striking difference might lie in the soil history. Although no information on the soil history was given, it may be assumed that in the Brazilian soils the organic matter was in equilibrium, so that N immobilization equalled N mineralization on an annual basis. This was certainly not the case for most soils in the present study, particularly as the newly reclaimed polder soils have been under cultivation only for a relatively short time.

On the basis of the correlations between the mineralization rate and various chemical indices of mineralization, we conclude that soluble organic N extracted with 0.01 M $CaCl_2$ is the only one of the methods tested that appears useful for routine measurements of the mineralization capacity of individual sites.

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