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## Quantifying soil water effects on nitrogen mineralization from soil organic matter and from fresh crop residues

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**Abstract** A loamy sand was incubated with and without addition of carrot leaves at six different water contents ranging from 6% to 20% ( $\text{g } 100 \text{ g}^{-1}$  dry soil) and N mineralization was monitored during 98 days. We calculated zero- and first-order rates for mineralization in the unamended soil and first-order rates for N mineralization in the residue-amended soil. Although N mineralization was strongly affected by soil moisture, rates were still important at 6% water content (corresponding to permanent wilting point), particularly in the residue-amended soil. Soil water content was recalculated as soil water tension and as percent water-filled pore space (%WFPS) and a parabolic, a logistic and a Gaussian-type function were fitted to the relation between N mineralization rates and water content, %WFPS or pF. Water potential was a less suitable parameter than either %WFPS or water content to describe the soil water influence on N mineralization, because N mineralization rates were extremely sensitive to changes in the water potential in the range of pF values between 1.5 and 2.5. In the residue-amended soil the Gaussian model yielded an optimum %WFPS of 56% for N mineralization, which is slightly lower than optimum values cited in literature. N mineralization in the unamended soil was more influenced by soil water than N mineralization from fresh crop residues. This could be explained by less water limitation of the microbial population decomposing the residues, due to the water content of the residues. The effect of the water contained in the residues was most pronounced in the lowest water content treatments. The water retention curves of both undisturbed and repacked soil were determined and suggested that extrapolation of results obtained during laboratory incubations, using disturbed soil, to field con-

ditions will be difficult unless soil bulk density effects are accounted for, as is the case with the use of %WFPS.

**Keywords** Crop residues · Nitrogen mineralization · Soil water content · Water-filled pore space

### Introduction

Soil moisture is amongst the most frequently studied environmental factors that control mineralization. The influence of soil water content on microbial processes in soil is more important in arid and semi-arid soils than in humid climates, not only because of low moisture availability in (semi-)arid soils, but also because of the extreme variability in rainfall events in comparison to humid climates (Fisher and Whitford 1995). Mazzarino et al. (1991) found that 90% of the mineral N accumulated in 1 year was mineralized during the 5-month wet season in the Dry Chaco ecosystem in Argentina. However, in humid climates like the Western European maritime climate, prolonged dry spells occasionally occur, and the soil water content will limit process rates such as N mineralization at some periods of the year (Franzluebbers et al. 1994). Moreover high soil moisture contents that reduce soil aeration below the optimum will also reduce aerobic biological processes.

The majority of studies on the influence of soil water on N mineralization focus on mineralization from native soil organic N. Less attention has been paid to the influence of soil water content on the N mineralization from added residues (Birch 1964; Breland and Hansen 1996; Das et al. 1993; Doel et al. 1990; Schomberg et al. 1994). Although in agriculture fresh residues are usually incorporated in soil (except for cereals), all the above studies used dried and ground residues. Quantitative relations have been established between soil water content and N mineralization after a fixed period of time, but these relations are for N mineralization from native soil organic matter (Gonçalves and Carlyle 1994; Myers et al. 1982; Stanford and Epstein 1974). To our knowledge

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no mathematical descriptions have been made of the relation between soil water content and N mineralization parameters determined over a period of several months.

When determining relations between soil water content and N mineralization, soil water content has been expressed in different forms, such as gravimetric water content (Cassman and Munns 1980), volumetric water content (MacDuff and White 1985), soil water tension (Miller and Johnson 1964; Sierra 1997), soil water content rescaled between a minimum and maximum value (Myers et al. 1982; Stanford and Epstein 1974) and water-filled pore space (WFPS) (Aulakh et al. 1996).

In this paper, we measured the N mineralization during laboratory incubations from native soil organic matter and added fresh crop residues under a wide range of soil water contents. We developed quantitative relations between N mineralization rates and soil water, both for native soil organic matter and for the added fresh residues.

## Materials and methods

Soil, sampled from the upper 15 cm on a field in Pittem (West Flanders), had a loamy sand texture (77% sand, 17% silt, 6% clay), an organic C content of 1.14% and a total N content of 0.097%, and had been used in previous incubation experiments (De Neve et al. 1996; De Neve and Hofman 2000). The bulk of the soil was dried to a water content of 0.075 g g<sup>-1</sup>, and a small portion was dried further to 0.035 g g<sup>-1</sup> for the lowest water content treatment. The soil was not sieved but large aggregates were crumbled and visible organic debris and stones were removed by hand.

Carrot leaves (12.9% dry matter and 2.74% total N of dry matter) were used as crop residues. Fresh leaves were cut into small pieces and 6 g of these residues (equivalent to 0.77 g dry weight) were mixed thoroughly with an amount of soil equivalent to 283 g of oven-dry soil. The soil-crop residue mixture was put in PVC tubes of 0.18 m length and a diameter of 0.046 m, and then compacted manually (De Neve and Hofman 2000) to obtain a target bulk density of 1.4 Mg m<sup>-3</sup>.

Percent of WFPS (%WFPS) was calculated as (gravimetric water content × soil bulk density) × 100 / total porosity, where total soil porosity = 1 - (soil bulk density / 2.65) (Linn and Doran 1984). After the soil was brought to the desired bulk density, distilled water was added to bring the soils to the desired water contents, which were 0.06, 0.09, 0.12, 0.15, 0.17 and 0.20 g g<sup>-1</sup>. The average water contents obtained differed slightly from these target values, and are given in Table 1, together with the corresponding

moisture tension and %WFPS. Less water was added to the treatments with crop residues than that added to the unamended soil, to account for the water content of the crop residues. The tubes were covered with a single layer of gas-permeable parafilm and were incubated at 17°C. Water content was monitored regularly by weighing the tubes and distilled water was added, when needed, to keep the moisture content at the desired level.

For the crop residue-amended soil, sampling was done by removing intact tubes in triplicate 9, 16, 28, 42, 63, 79 and 98 days after the start of the incubation. The soil was removed from the tubes, mixed thoroughly, and shaken with 1 M KCl (1:2 extraction ratio) for 1 h on a rotary shaker. Then the soil slurries were filtered and NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N were measured colorimetrically using a continuous flow autoanalyser (ChemLab System 4). NO<sub>3</sub><sup>-</sup> was reduced to NO<sub>2</sub><sup>-</sup> using nitrate reductase from *Escherichia coli* as the catalyst (Beernaert et al. 1987), which after formation of a diazo-compound was measured at 520 nm. NH<sub>4</sub><sup>+</sup> was reacted with sodium salicylate and sodium dichloroisocyanurate to give a blue colour which was measured at 650 nm. Water content of the soil in each tube was determined by oven drying at 105°C. One tube of the unamended soil was sampled after 9, 16, 42, 63 and 98 days and analysed for NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N as described above.

Net N mineralization of the crop residue-amended soil was calculated by subtracting mineral N of the unamended soil from that of the amended soil. At day 28 and 79 net amounts of mineral N were calculated using linearly interpolated values for mineral N of the unamended soil (values for day 16 and 42 and for day 63 and 98, respectively).

The moisture retention curve of the soil was determined for undisturbed soil cores taken in the field and for repacked soil cores. For water tensions between 0 and -0.01 MPa the sand box method was used, whereas for the lower water tensions (down to -1.5 MPa) the pressure membrane method was used. For the determination of the water retention curve of repacked soil, rings (98 cm<sup>3</sup> volume) were packed with the disturbed soil and compacted to a bulk density of 1.4 Mg m<sup>-3</sup>, i.e. the bulk density used in the incubations. The water retention function of Van Genuchten (1980) was fitted to the desorption data (Fig. 1a, b):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (ah)^n]^m} \quad (1)$$

where  $\theta_r$  and  $\theta_s$  are the residual and the saturated soil water content, respectively (m<sup>3</sup> m<sup>-3</sup>),  $h$  is the soil water tension, and  $a$ ,  $n$  and  $m=1-1/n$  are parameters obtained by fitting Eq. 1 to measured water retention data.

### Mathematical analysis

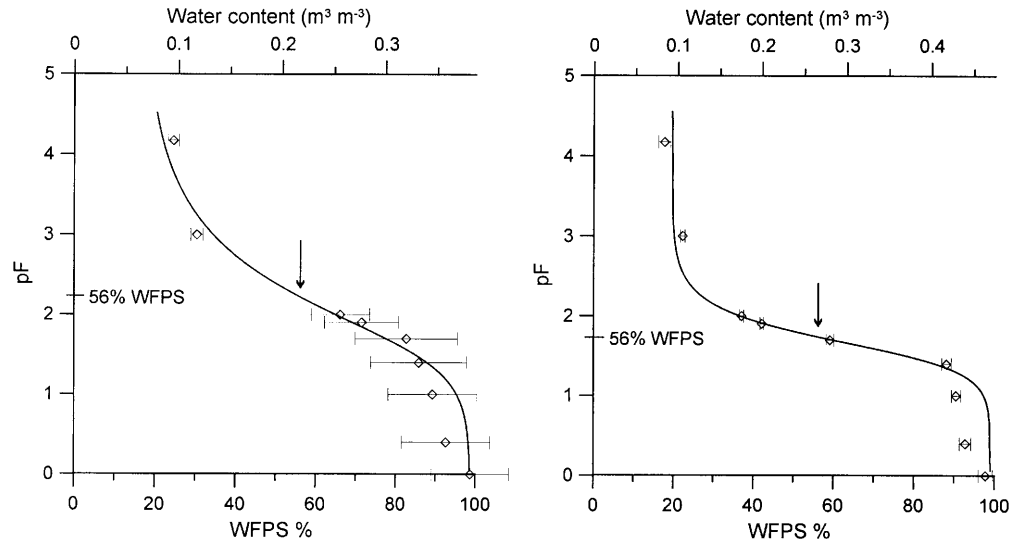
The N mineralization rates for the unamended soil were calculated using both zero-order and first-order kinetics:

$$N(t) = kt \quad (2)$$

**Table 1** Average soil water content, and corresponding % water-filled pore space (%WFPS) and water potential, during the incubation for unamended and residue-amended soil. SDs are given in parentheses

	Target gravimetric soil water content (g 100 g <sup>-1</sup> dry soil)					
	6	9	12	15	17	20
<b>Unamended soil</b>						
Average water content (g 100 g <sup>-1</sup> )	5.60 (0.10)	9.06 (0.52)	11.50 (0.26)	14.55 (0.36)	16.77 (0.43)	19.54 (0.47)
%WFPS	16.6	26.9	34.1	43.2	49.8	58.0
Water potential (kPa)	-1485	-17.9	-11.1	-7.8	-6.4	-5.2
<b>Crop residue-amended soil</b>						
Average water content (g 100 g <sup>-1</sup> )	6.02 (0.46)	9.33 (0.92)	12.20 (0.47)	15.15 (0.62)	17.02 (0.66)	20.28 (0.21)
%WFPS	17.9	27.7	36.2	45.0	50.5	60.2
Water potential (kPa)	-1485	-16.7	-10.1	-7.4	-6.3	-4.9

**Fig. 1** Water retention function of van Genuchten (1980) fitted to the measured water retention data for the undisturbed soil (*left*) and the repacked soil (*right*); the *arrow* indicates the water tension at 56% water-filled pore space (%WFPS). Horizontal bars represent  $\pm 1$  SD



$$N(t) = N_A(1 - e^{-kt}) \quad (3)$$

where  $N(t)$  (in mg N kg<sup>-1</sup> soil) is the amount of N mineralized at time  $t$ ,  $N_A$  is the amount of mineralizable N (in mg N kg<sup>-1</sup> soil) and  $k$  is the rate constant in mg N kg<sup>-1</sup> soil week<sup>-1</sup> (zero-order) or in week<sup>-1</sup> (first-order kinetics).

The relationship between N mineralization rates and soil water status was described using three functions. The first was a parabolic function (Myers et al. 1982):

$$k(W) = aW^2 + bW \quad (4)$$

where  $k(W)$  is the mineralization rate as a function of the water status of the soil [ $W$ ; expressed as either gravimetric water content ( $W_g$ ), %WFPS or pF units].

The second was a logistic function:

$$k(W) = \frac{1}{\delta + \beta(W - \omega)} + k_{\min} \quad (5)$$

where  $\beta$  is a slope parameter (mg<sup>-1</sup> N kg soil week for the unamended soil or week for the amended soil),  $\omega$  is a dimensionless constant defining the point of inflection of the logistic curve,  $k_{\min}$  is the minimum value of N mineralization (mg N kg<sup>-1</sup> soil week<sup>-1</sup> for the unamended soil or week<sup>-1</sup> for the amended soil), and  $\delta$  (mg<sup>-1</sup> N kg soil week for the unamended soil or week for the amended soil) is defined by (Gonçalves and Carlyle 1994):

$$\delta = \frac{1}{k_{\text{opt}} - k_{\min}} \quad (6)$$

where  $k_{\text{opt}}$  is the asymptotic maximum mineralization rate (same units as  $k_{\min}$ ).

The third was a Gaussian (bell-shaped) function:

$$k(W) = k_{\text{opt}} e^{-\xi(1 - \frac{W}{W_{\text{opt}}})^2} \quad (7)$$

where  $k_{\text{opt}}$  is the mineralization rate at  $W_{\text{opt}}$  [i.e. at optimum gravimetric water content ( $W_{g,\text{opt}}$ ), optimum %WFPS ( $WFPS_{\text{opt}}$ ), or optimum water potential ( $pF_{\text{opt}}$ )] and  $\xi$  is a parameter reflecting the moisture dependence of the mineralization process. The Gaussian-type function was used in analogy to the function used by De Neve et al. (1996) to describe the temperature dependence of N mineralization and nitrification. The curve fitting was done with the SPSS statistical package (SPSS version 7.5), using the Levenberg-Marquardt algorithm.

## Results

### Soil water contents

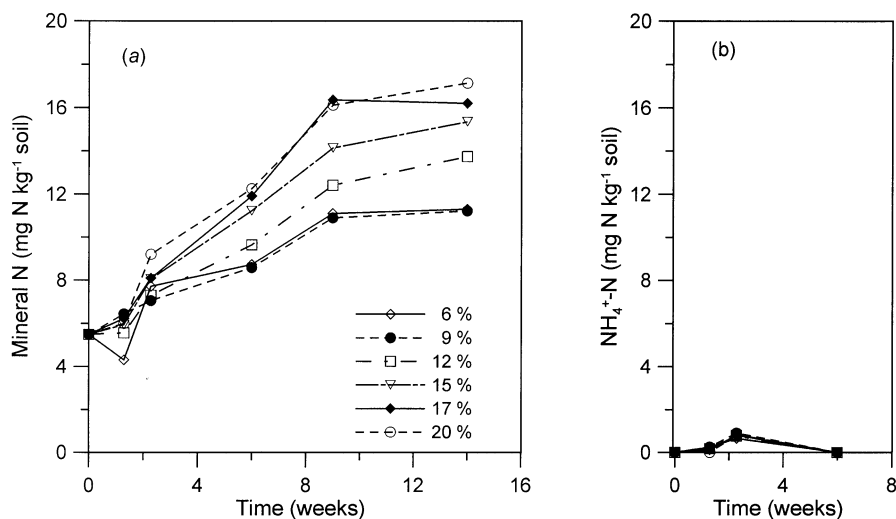
The measured values of soil water content were averaged over the whole experiment for each treatment, both for the unamended soil and the soil amended with crop residues (Table 1). For calculating quantitative relationships between the different descriptors of water content and N mineralization parameters, the average values were used (Table 1). In the text, however, we refer to the treatments using the target gravimetric water contents.

### N mineralization

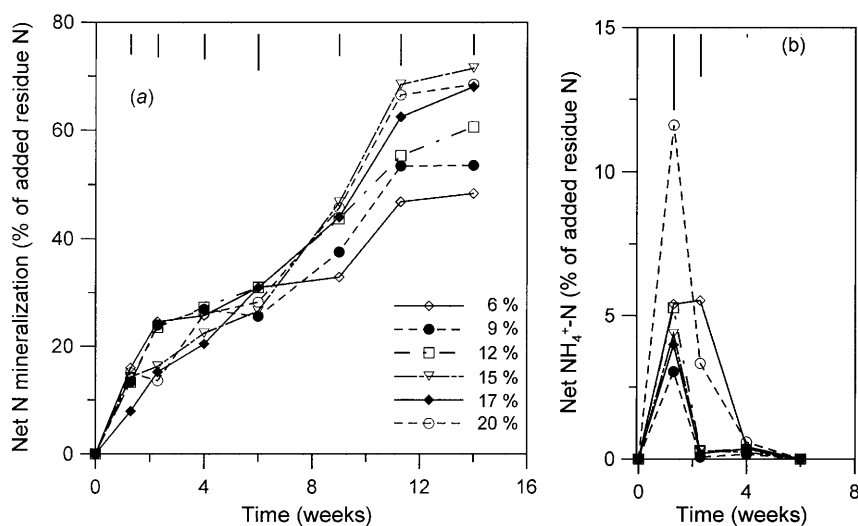
Mineralization of the unamended soil was influenced strongly by the soil water content and increased about twofold between the lowest and highest water content (Fig. 2). We tried to fit both zero- and first-order kinetics models to the data of N mineralization in the unamended soil (Eqs. 2, 3). The zero-order N mineralization rate constants ( $k$ ) varied between 0.48 (6% and 9% water content) and 0.96 mg N kg<sup>-1</sup> soil week<sup>-1</sup> (20% water content) (Table 2). The first-order kinetics model resulted in a poor fit at the low moisture contents, and was unusable for the 9% treatment (for the 9% treatment the adjusted  $R^2$  value was negative, which means that taking the average value was better than the model predictions). We therefore used the zero-order mineralization rates for all calculations for the unamended treatments.

Soil water content seemed to have had only a very limited effect on nitrification of the mineralized N. Even at the smallest and largest moisture content NH<sub>4</sub><sup>+</sup>-N was converted to NO<sub>3</sub><sup>-</sup>-N very rapidly. In the unamended soil, NH<sub>4</sub><sup>+</sup>-N contents were always close to or under the detection limit. The fast rates of nitrification found here were in agreement with nitrification rates determined earlier for this soil (De Neve and Hofman 2000).

**Fig. 2** N mineralization (a) and production of  $\text{NH}_4^+\text{-N}$  (b) in the unamended soil as a function of soil moisture content and time



**Fig. 3** Net N mineralization (% of the added N) (a) and production of  $\text{NH}_4^+\text{-N}$  (% of the added N) (b) in the crop residue-amended soil as a function of soil moisture content and time. Vertical bars represent average SDs across treatments

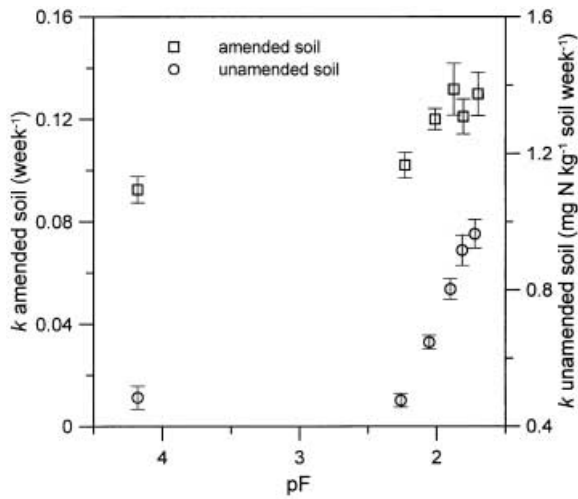


**Table 2** N mineralization rate constants in the unamended soil (zero-order kinetics) and in the residue-amended soil (first-order kinetics) as a function of soil water content. SEs of parameter estimates in parentheses.  $R_a^2$  Adjusted  $R^2$  values

	Target gravimetric soil water content ( $\text{g } 100 \text{ g}^{-1}$ dry soil)					
	6	9	12	15	17	20
N mineralization unamended soil						
$k$ ( $\text{mg N kg}^{-1} \text{ soil week}^{-1}$ )	0.48 (0.07)	0.48 (0.04)	0.65 (0.04)	0.80 (0.06)	0.92 (0.09)	0.96 (0.08)
$R_a^2$	0.626	0.710	0.757	0.733	0.692	0.711
Mineralization of added residue N						
$k$ ( $\text{week}^{-1}$ )	0.093 (0.010)	0.102 (0.010)	0.120 (0.008)	0.132 (0.020)	0.121 (0.014)	0.130 (0.017)
$R_a^2$	0.848	0.911	0.964	0.891	0.935	0.915

The accumulation of mineral N in the crop residue-treated soil showed that maximum mineralization of the added N was reached only towards the end of the incubation and only in the highest water content treatments (Fig. 3).  $\text{NH}_4^+\text{-N}$  evolution in the residue-amended soil (Fig. 3) followed the same pattern as in the unamended

soil, with a peak of  $\text{NH}_4^+\text{-N}$  at the first sampling (9 days after the start of the incubations), followed by a rapid decrease to values near the detection limit. Only in the highest and lowest water content treatments was there a significant surplus of  $\text{NH}_4^+\text{-N}$  until the third week. After the third sampling,  $\text{NH}_4^+\text{-N}$  contents were negligible in



**Fig. 4** N mineralization rates in the unamended and residue-amended soil as a function of water potential (pF). Vertical bars represent 1 SE

**Table 3** Parameter estimates resulting from fitting a parabolic function (Eq. 4) to the relation between N mineralization and gravimetric water content ( $W_g$ ), %WFPS or pF in unamended and residue-amended soil

		$a$	$b$	$R_a^2$
N mineralization unamended soil	$W_g$	$-1.15 \times 10^{-3}$	0.072	0.901
	%WFPS	$-1.31 \times 10^{-4}$	0.0243	0.901
	pF	-0.128	0.642	0.066
Mineralization of added residue N	$W_g$	$-4.93 \times 10^{-4}$	0.0161	0.708
	%WFPS	$-5.58 \times 10^{-5}$	0.00541	0.711
	pF	-0.0185	0.0987	0.113

**Table 4** Parameter estimates resulting from fitting a logistic function (Eq. 5) or a Gaussian-type function (Eq. 7) to the relation between N mineralization and  $W_g$  or %WFPS in unamended and residue-amended soil. SEs of parameter estimates in parentheses.  $\beta$

#### Logistic function

		$\beta$ (mg <sup>-1</sup> N kg soil week or week)	$\omega$	$k_{opt}$ (mg N kg <sup>-1</sup> soil week <sup>-1</sup> or week <sup>-1</sup> )	$k_{min}$ (mg N kg <sup>-1</sup> soil week <sup>-1</sup> or week <sup>-1</sup> )	$R_a^2$
N mineralization unamended soil	$W_g$	0.593 (0.107)	18.7 (1.9)	0.978 (0.052)	0.455 (0.046)	0.987
	%WFPS	0.839 (0.051)	42.3 (2.3)			
Mineralization of added residue N	$W_g$	0.435 (0.251)	14.5 (2.7)	0.128 (0.004)	0.092 (0.007)	0.943
	%WFPS	0.755 (0.147)	42.9 (7.9)			

#### Gaussian function

		$W_{g,opt}$ or %WFPS <sub>opt</sub>	$k_{opt}$ (mg N kg <sup>-1</sup> soil week <sup>-1</sup> or week <sup>-1</sup> )	$\xi$	$R_a^2$
N mineralization unamended soil	$W_g$	34 (31)	1.34 (1.15)	1.62 (0.58)	0.946
	%WFPS	102 (92)			
Mineralization of added residue N	$W_g$	18.7 (2.9)	1.29 (0.04)	0.761 (0.199)	0.902
	%WFPS	56 (9)			

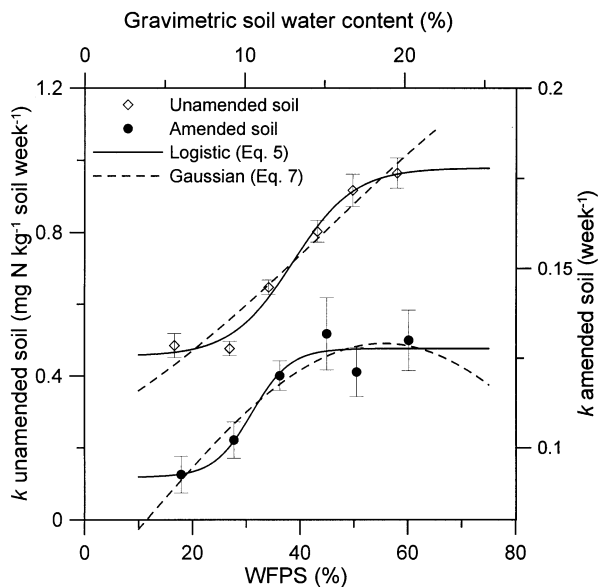
the residue-amended soil (<0.5 mg N kg<sup>-1</sup> dry soil). This indicates that nitrification was suboptimal at these moisture contents during the early stages of the incubation. However, the complete disappearance of the NH<sub>4</sub><sup>+</sup>-N after 4 weeks shows that even at 20% moisture the suboptimal conditions lasted only for a limited period of time. SDs for both mineralization rates and NH<sub>4</sub><sup>+</sup>-N contents were fairly similar across water contents, except at 20% moisture, where SDs were higher. Only the SD averaged over all water contents is given in Fig. 3.

The N mineralization of the crop residues was assumed to follow first-order kinetics [Eq. 3, where  $N(t)$  is now the amount of N mineralized as % of total residue N added and  $N_A$  is the amount of mineralizable N as % of total residue N added]. It was assumed that soil water content would affect only the rate constant  $k$  and not  $N_A$  (Campbell et al. 1988). Therefore,  $N_A$  was assumed to be a fixed value at all water contents and was set equal to the maximum amount of N mineralized (71.5% of total residue N). This value was used to calculate mineralization rates ( $k$ ) for all treatments (Table 2).

#### Relation between mineralization rates and soil moisture

The rate constants for N mineralization from soil organic matter and from the crop residues were plotted against the actual water contents and corresponding values of water tension and %WFPS from Table 2 (Figs. 4, 5). We tried to fit parabolic, logistic and Gaussian functions to the relations between N mineralization rates and water content, %WFPS, or water potential. The results of the curve fitting are given in Tables 3 and 4. The logistic and Gaussian functions could not be fitted to the water potential-N mineralization rate relationship, and the para-

Slope parameter,  $\omega$  dimensionless constant defining the point of inflection of the logistic curve,  $k_{opt}$  asymptotic maximum mineralization rate,  $k_{min}$  minimum value of N mineralization,  $opt$  optimum,  $\xi$  parameter reflecting the moisture dependence of mineralization



**Fig. 5** N mineralization rates in the unamended and in the residue-amended soil as a function of %WFPS and gravimetric water content. Vertical bars represent 1 SE

bolic functions yielded very low  $R^2$  values (between 0 and 0.23). For the unamended soil the Gaussian model resulted in an estimated optimum %WFPS above saturation (%WFPS<sub>opt</sub>=102).

## Discussion

Although N mineralization rates increased strongly with water content in the unamended soil, it was remarkable that even at the lowest soil water content (which corresponded to permanent wilting point; PWP) N mineralization was still important. When calculated to the field scale, N mineralization would amount to 2.0 kg N ha<sup>-1</sup> 30 cm<sup>-1</sup> week<sup>-1</sup> for the 6% moisture treatment. The occurrence of N mineralization at considerable rates at low water potentials has been already observed. Miller and Johnson (1964) found important N mineralization at moisture tensions between 7 bar and 22 bar for different soils. Myers et al. (1982) showed that the N mineralization rate at 10 bar was about half of the value at optimum moisture content. Gonçalves and Carlyle (1994) also found N mineralization rates at 10% of field capacity (FC) which were half of the rates at FC. Perhaps the observed N mineralization rates at low water potentials were partly due to sample pre-treatment (air-drying, sieving and rewetting). Orchard and Cook (1983) found a very strong (40-fold) increase in microbial activity upon rewetting a dry soil when the change in water potential following rewetting was >5 MPa. This wetting effect becomes less important with increasing water content (Pilbeam et al. 1993) and decreases with a longer incubation time. A decrease in N mineralization rates at the lowest water contents at the end of the incubation was

observed here, and also by Gonçalves and Carlyle (1994).

The ratio of the N mineralization rates between 20% and 6% water content was 2.00 and 1.40 in the unamended and residue-amended soil, respectively. The low water potential restricted N mineralization of the unamended soil more severely than that of the amended soil, probably because additional water was provided by the decomposing residues to the decomposing microflora. Indeed, the water content of the fresh residues was 6.8 g g<sup>-1</sup> (expressed on a dry residue basis), as compared to 0.06 g g<sup>-1</sup> for the soil in the lowest water content treatment. During the initial stage of residue decomposition there were no significant differences between the amounts of N mineralized at the different moisture contents, and mineralization was even slightly higher at the lowest moisture contents. The explanation for this is probably that in the initial decomposition stage rewetting of the soil immediately surrounding the added residues was much stronger at the lower than at the higher water contents. The residues provided the water where it was needed, i.e. in the soil immediately surrounding the residues, where nearly all microbial activity is concentrated during the decomposition process. Gaillard et al. (1999) found that microbial activity strongly increased in the immediate vicinity of incorporated straw residues, and that the activity steeply decreased to reach the reference value in the bulk soil between 3 mm and 4 mm from the straw. After 8 weeks, however, the rate of mineralization in the drier soil clearly was much lower, probably as a result of the complete equilibration of the soil water content.

Water potential seems to be the logical parameter to be used for expressing relationships between N mineralization and soil water status. Indeed, the water potential concept allows one to compare the water availability in soils of widely varying textures. However, gravimetric soil water content has been used much more widely than water potential to express the moisture dependence of N mineralization. This preference for using soil water content can at least partially be explained by comparing Fig. 4 with Fig. 5. Nearly all of the reduction in the N mineralization rate with decreasing soil water content is situated in a range of 0.54 pF units only (between pF 1.72 and pF 2.26 for the unamended soil). The reduction of N mineralization as a function of water content is much more equally spread over the entire range of water contents. Figure 4 shows that N mineralization was extremely sensitive to very small changes in water potential in the range of pF 1.7–2.3. This sensitivity of N mineralization to changes in soil water potential was very pronounced here because, as in nearly all other studies, disturbed soil was used. In the disturbed soil the water retention function was much flatter in the medium water potential range (pF 1.5–2.5) than in undisturbed soil because one size class of pores dominates as a result of re-packing the soil. Another reason why water potential is perhaps not the best parameter to predict microbial activity is given by Skopp et al. (1990). They indicated that

using soil water potential to describe soil water effects on microbial activity tends to emphasize the driest conditions (lowest water potentials). The high water activity of most soils suggests that other processes also regulate microbial activity by limiting the diffusion of substrate (at water contents below the optimum) and  $O_2$  (at water contents above the optimum). The diffusion coefficients (of substrate and  $O_2$ ) are typically characterized using soil water content relationships, rather than water potential.

Gravimetric soil water content cannot be used, however, to compare microbial activities between soils differing significantly in structure and bulk density. Linn and Doran (1984) showed that %WFPS was a very useful indicator of microbial activity, and that maximum aerobic activity occurred at 60% WFPS across a wide range of soils. We therefore think that %WFPS can be a good alternative to water content or water tension for expressing the influence of water content on N mineralization.

In the literature several relationships have been proposed for relating N mineralization to soil water content or soil water tension. Myers et al. (1982) proposed a parabolic relation which used a normalized water content by rescaling the water content between minimum and maximum available water ( $-0.03$  and  $-4$  MPa respectively), for all soils studied. Stanford and Epstein (1974) derived a linear relation between N mineralized and soil water content, expressed as percentage of optimum soil water content, which was assumed to be FC. A linear relation between N mineralization and soil water in the range between PWP and FC was also used by MacDuff and White (1985). Gonçalves and Carlyle (1994) proposed a logistic relation between N mineralization and soil water content. Singh and Singh (1994) fitted an exponential function to the relation between N mineralization measured in the field and soil moisture content. Our results indicate that simple linear or quadratic functions cannot be used to describe the soil water effect on N mineralization over a large range of water contents. As the data of several other researchers suggest (Cassman and Munns 1980; Gonçalves and Carlyle 1994; Reichmann et al. 1966), a logistic or Gaussian function seems more suitable. This is shown by the improved  $R_a^2$  values of those functions as compared to the parabolic functions (Tables 3, 4). Additionally the logistic and Gaussian functions yield parameters that have a biological significance. Fitting the logistic function (Eq. 5) yields the minimum and maximum N mineralization rates. All three parameters of the Gaussian function have an easily interpretable biological meaning, namely the mineralization rate  $k_{opt}$  at optimum soil water content or %WFPS<sub>opt</sub>, the optimum soil water content or %WFPS<sub>opt</sub>, and the moisture-dependence parameter  $\xi$ . However, these models also have some limitations for the description of the influence of soil water on N mineralization and nitrification. The logistic model has an asymptotic maximum which is not a realistic description of the nitrification process, as aerobic microbial activity was found to be maximum at 60% WFPS (Linn and

Doran 1984) and declines rapidly at higher moisture contents. Ammonification is also reported to be maximum at 60% WFPS (Pal and Broadbent 1975), and Pilbeam and Warren (1995) found gross mineralization rates in a sandy soil to decline at soil moisture contents above  $0.21 \text{ g g}^{-1}$ . The Gaussian model has advantages over the logistic model, because it allows one to calculate an optimum soil moisture content (or %WFPS) corresponding with maximum activity, it requires only three parameters to be estimated, and its parameters are more easily interpreted. However, for description of the ammonification process (or mineralization *sensu stricto*), the Gaussian model will not be applicable over the whole moisture range because it approaches zero at high water contents.

In the residue-amended soil, the optimum value of the %WFPS for the N mineralization rates resulting from fitting the Gaussian model was 56. This is lower than the value of 60% WFPS reported by Linn and Doran (1984). However, the mineralization rates had rather high SEs, and there seems to be a rather broad range of %WFPS values which can be considered optimum for N mineralization (Fig. 5).

When studying the effect of soil water on soil biological processes, soil structure obviously is of importance. Soil structure influences the soil water content-soil water tension relation mainly in the range of high water potentials. In most incubation studies on N mineralization, including those that dealt with the effect of soil water content, small amounts of soil were put loosely in the incubation containers (usually flasks or jars), thus disregarding completely the influence of soil bulk density and soil structure. There are only a few exceptions where soil density during incubation was measured or adjusted to a target value (Jensen 1994; Sierra 1997). Because soil bulk density is not considered in much of the research on the soil moisture-N mineralization relation, it is very difficult to extrapolate the results to undisturbed soils, such as under field conditions. As mentioned before, the water retention functions of disturbed and undisturbed soil can differ considerably (Fig. 1a, b), and this difference can be expected to be more pronounced in heavier textured soils. This difference in water retention functions between disturbed and undisturbed soil will complicate field use of mathematical relations based on soil water content or water tension, derived during laboratory incubations, particularly at the high water tension range. This is illustrated in Fig. 1, where the critical value of 56% WFPS is indicated both for disturbed and undisturbed soil. In the disturbed soil, the optimum of 56% WFPS for N mineralization corresponds to a water tension of  $-5.5$  kPa. In the undisturbed soil, however, the same water tension of  $-5.5$  kPa corresponds to 77% WFPS, and hence N mineralization and nitrification will be restricted in the undisturbed soil at moisture tensions which are still optimal in the disturbed soil (assuming that %WFPS<sub>opt</sub> in the undisturbed soil would be similar to that in the disturbed soil).

The results obtained here showed that N mineralization from native soil organic matter was more dependent

on soil water content than N mineralization from added fresh residues. N mineralization rates in both residue-amended and unamended soil were still important at moisture contents around PWP. Finding a single mathematical expression for describing the N mineralization-water relation over the whole moisture range between 0 and 100% WFPS will be extremely difficult. The quantitative relations developed here between N mineralization and soil water content can be particularly useful for better prediction of N release from crop residues because through the use of %WFPS the effect of soil bulk density is taken into account, and because fresh rather than dried and ground residues were used.

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