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Relations Between Net Nitrogen Mineralization and Soil Characteristics Within an Arable Field

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Within-field variations in plant-available soil nitrogen (N) are likely to be affected by differences in soil characteristics. To study this, a 3-year field investigation was conducted during 1998–2000 on a 15 ha arable field in Sweden with considerable within-field soil texture variability. In 34 plots soil N uptake by crops, net nitrogen mineralization (Nm) during the growing season and soil mineral N in spring and shortly after harvest were determined. Beside these parameters, topography, soil organic matter content (SOM), clay content, pH(H_2O) and grain yield were recorded. The variations in Nm were considerably large both within the field and between years. The within-field variation in Nm could partly be explained by the variation in SOM and clay content (adjusted coefficient of determination $= 0.23$, $P < 0.001$). The pattern in Nm differed between years, partly because of seasonal variations in soil moisture. For these reasons, the pattern of Nm is difficult to predict without seasonal adjustments.

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Key words: available soil nitrogen, clay, grain yield, nitrogen mineralization, soil organic matter, topography, within-field variability.

Introduction

Nitrogen (N) fertilizer demand is dependent on the potential yield and the amount of plant-available N supplied by the soil. Large variations in grain yields within fields with cereal crops have been recorded in Sweden (Mattsson & Thylén, 1994) as well as in other countries (Kristensen et al., 1995). This provides good reason to believe that fertilizer demand also varies within the field. To estimate the within-field variability in N fertilizer demand, it is relevant to know how much plant-available soil N or net nitrogen mineralization (Nm) may vary within a field. In other investigations within-field variations between 0.3 and 1.8 kg N ha^{-1} day^{-1} (Debosz & Kristensen, 1995) and standard deviations of 30 kg N ha^{-1} during the growing season (Stenberg et al., 2002) have been recorded. Measuring this directly all over the individual fields in each season is not feasible. If the variation in these parameters could be described by the within-field variability in easily determined soil characteristics in a particular field, the significance of the variability, and maybe even the pattern of Nm, could be estimated. For this, the extent to which the variation may be explained by soil organic matter (SOM) content, clay, topography and pH is important. SOM indicates the amount of substrate that can be degraded to available N, except for crop residues. SOM, clay and topography influence soil moisture; this and pH strongly characterize the environment for microorganisms. A positive relationship with total soil N content and a negative relationship between N mineralization and clay plus silt content were found in a Danish investigation (Debosz & Kristensen, 1995).

The main objectives of this study were to describe the size of the within-field variability of Nm and its relations with soil parameters, such as SOM, clay content, topography and pH, in an arable field in south-western Sweden. The study was conducted for three growing seasons to determine whether there is any consistency in the spatial pattern of net nitrogen mineralization (Nm) and its relation to soil parameters between years. The relevance of the within-field variation of Nm for variations in fertilizer demand, compared with that caused by grain yield level, is also discussed. Finally, the study evaluated whether soil mineral N in spring could be used as an estimator of plant-available N during the growing season.

Materials and methods

Site description

Field experiments were conducted during 1998–2000 on a 15 ha field with large soil texture variability at the Ribbingsberg farm (58°06′ N, 12°51′ E) in south-western Sweden. The experiments started in 1998 with winter wheat, with oats as the preceding crop. In 1999 spring barley was grown and in 2000 the crop was winter wheat again. To estimate the amounts of soil N available to plants in each season, N taken up by plants that did not receive N fertilization was determined at 34 different sites within the field (Fig. 1). These were systematically distributed at 50 m intervals with some exceptions, where sites were removed or moved because of various obstructions. For the determination of plant-available soil N, an area of 6 × 10 m was left without fertilizer N application at each site. These plots were moved slightly from year to year to an undisturbed position, but were still considered to represent the same sites. Fertilized areas of 10 m^2 adjacent to the 34 unfertilized plots were harvested with a combine to determine grain yield level at each site. The fertilization rates were 160, 100 and 170 kg N ha^{-1} in 1998, 1999 and 2000, respectively. The fertilizer N was applied mainly as NO_3–N. Before the experiments started, the field received pig slurry in some years. During the investigation period fertilization was carried out only with mineral fertilizers. The yearly rates of phosphorus (P) and potassium (K) application were approximately 20 kg P and 50 kg K ha^{-1}, respectively.

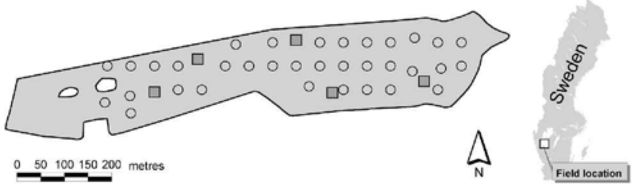

Fig. 1. Location of the 34 field plots for net nitrogen mineralization measurements (circles) and the five sites for soil water measurements (squares).

Sampling strategy

The topography of the field was measured using the Global Positioning System (GPS). An accuracy of a few centimetres could be obtained by using a local base station standing on a fixed point. The GPS equipment for kinematic measurements was placed on a four-wheeled motorcycle driving at 20-m intervals over the field, recording the elevation every second (about every 6 m). Some hilly areas were sampled more intensively. In connection with other trials within the field, the groundwater level was measured repeatedly at five sites using perforated tubes bored vertically to a depth of 1.0 m.

All other measurements were performed at the 34 sites. At each of these sites, composite soil samples consisting of 15 cores from the topsoil (0–20 cm) were taken to determine clay content, SOM and pH(H_2O). For another investigation, samples consisting of 10 cores from the 30–40 cm soil level were taken to determine SOM. This parameter was also used for this investigation, since it reflects topsoil depth, which was observed to vary between 20 and 40 cm.

In each year soil samples were taken at the beginning of the growing season (April) and just after harvest (August to early October) within the unfertilized areas for determination of mineral N (NH_4–N and NO_3–N). For this, 18 cores from the 0–30 cm soil layer and nine from the 30–60 cm and 60–90 cm depths were mixed to composite samples for each area and depth. The samples were stored frozen until analysed.

The amounts of soil N taken up by plants in the plots that did not receive N fertilization were determined. For this, the above-ground plant parts in six 0.25 m^2 areas were cut within each plot at ripeness (GS 91 according to Zadoks et al., 1974) and threshed. These samples were used for determining dry matter and total N content in straw and kernel and for measuring the straw:kernel ratio. In addition, a 10 m^2 area in each plot was harvested with a combine for a more reliable measure of kernel yield. Straw yields were calculated by multiplying straw:kernel ratios by kernel yields.

Laboratory analyses

Soil texture was determined with the pipette method (Gee & Bauder, 1986). Total N and carbon contents were measured through dry combustion at 1250°C on a LECO analyser (CN-2000). SOM content in the topsoil (0–20 cm) was calculated by multiplying the carbon content by the factor 1.724. SOM content in the subsoil (30–40 cm) was estimated from the loss on ignition (550°C for 2 h) corrected for the loss of structural water from clay minerals (Ekström, 1927). For clay contents of 20% or lower, the correction factor is $k = 0.1 \times$ (% clay) and for clay contents higher than 20% $k = 1.06 + 0.047 \times$ (% clay). The $pH(H_2O)$ was measured in deionized water at a soil:solution ratio (w/v) of 1:2.5.

The plant samples from the unfertilized areas were dried at 60°C before N analysis. Straw and grains were separated. N concentration in straw in 1998 and 2000, as well as in grain in all years, was determined using Dumas elemental analysis on a LECO analyser (FB-428). For straw in 1999, the Kjeldahl method (Bremner, 1965) was used on a Kjeltec analyser.

The soil samples taken for determination of mineral N were ground and homogenized in a frozen state. Subsamples of 30 g were extracted with 100 ml 2 *M* KCl. The analyses were done using colorimetric methods on a Technicon autoanalyser. The values obtained were calculated as kg N ha^{-1}, assuming that the weight by volume was 1.25 g cm^{-3} within the 0–20 cm layer and 1.50 g cm^{-3} below 20 cm.

Calculations and statistical analyses

The amounts of soil N available to plants at the 34 sites were calculated from straw and grain yield and their N contents. It was assumed that the roots contained 25% of the total amount of N in the crop (Hansson et al., 1987). Nm was calculated using Equation (1). Accordingly, Nm here is defined as in Equation (2).

$$\begin{aligned}\text{Net N mineralization} &= (\text{Total N in crop at ripeness}) \\ &+ (\text{Residual mineral N in } 0\text{–}90 \text{ cm soil at harvest}) \\ &- (\text{Mineral N in } 0\text{–}90 \text{ cm soil in early spring})\end{aligned} \quad (1)$$

$$\begin{aligned}\text{Net N mineralization} &= (\text{N mineralization}) \\ &- (\text{N immobilization}) - (\text{N losses}) \\ &+ (\text{Atmospheric } NH_4\text{–N and } NO_3\text{–N deposition})\end{aligned} \quad (2)$$

All variables measured were checked for normal distribution, and summary statistics including mean, standard deviation and maximum and minimum values were calculated. Multiple linear regression analyses were carried out to investigate the possibilities of explaining differences in Nm by within-field variations in SOM, total soil N, clay, elevation and $pH(H_2O)$. A normalized value of Nm was used to make it possible to include all years in the same analysis. Normalization was performed by dividing each value of Nm by the average Nm for the year in question. For multiple linear regression analysis the adjusted coefficients of determination are presented:

$$r_{\text{adj}}^2 = 1 - (1 - r)^2 \left(\frac{n - 1}{n - p - 1} \right) \quad (3)$$

where r_{adj}^2 is the adjusted coefficient of determination, r^2 is the coefficient of determination, n is the sample size and p is the P-value (Hintze, 1995).

Mapping

Interpolation was performed with ordinary block kriging (Burrough & McDonnell, 1998). The elevation data were interpolated to obtain coincident data for the 34 plots. The other variables were interpolated only to produce maps for visualization of the data. These interpolated values were not used for any statistical analysis. The maps were produced in the GIS software ArcView (ESRI).

Results

Within-field variations

The variations in Nm were very large both within the field and between years (Table 1). On average for the three growing seasons, Nm amounted to 77 kg N ha^{-1}, with a range of 39–113 kg N ha^{-1}. Clay content varied considerably within the field (Table 1) and had a bimodal distribution. One half of the field constituted a loam with about 23% clay in the topsoil, while the other half consisted of sandy loam with about 10% clay (Fig. 2). The difference in elevation from the lowest to the highest of the 34 sampling sites was 8.5 m (Table 1). The variation in $pH(H_2O)$ was low (Table 1). The groundwater level was shallower on the loam than on the more elevated sandy loam in all years, especially in 1999, when it was higher than drainage depth (1.0 m) until early July.

Correlations with net nitrogen mineralization

With multiple linear regression, the within-field variability in Nm could partly be explained by differences in SOM and clay content in the topsoil. The average Nm for the three years correlated better with SOM and clay ($r_{\text{adj}}^2 = 0.34$, $P < 0.001$) than did normalized annual Nm ($r_{\text{adj}}^2 = 0.23$, $P < 0.001$). Almost the same degree of explanation was achieved by exchanging clay content with elevation ($r_{\text{adj}}^2 = 0.25$, $P < 0.001$) or SOM with soil N ($r_{\text{adj}}^2 = 0.26$, $P < 0.001$). Nm correlated rather well with SOM content in the 30–40 cm layer ($r_{\text{adj}}^2 = 0.35$, $P < 0.001$).

Table 1. Means, standard deviations, coefficients of variance, minimum and maximum values of different variables at the 34 sites

Variable	Mean	SD	CV (%)	Min.	Max.
Clay in topsoil[1]	15.6%	6.9	44	6.6	26.5
Soil organic matter in topsoil[1]	3.5%	0.48	14	2.7	4.6
Soil N in topsoil[1]	0.16%	0.025	16	0.11	0.21
$pH(H_2O)$ in topsoil[1]	6.1	0.14	2.2	5.8	6.3
Elevation	107.1 m	2.3	2.1	103.0	111.5
Normalized net N mineralization	1.0	0.32	32	0.3	1.9
Average net N mineralization	77 kg N ha^{-1}	20	24	39	113
Soil mineral N in spring 1998[2]	18 kg N ha^{-1}	6.7	36	7	37
Soil mineral N at harvest 1998[2]	33 kg N ha^{-1}	15	47	9	64
Soil N uptake by plants 1998	83 kg N ha^{-1}	26	31	30	137
Net N mineralization 1998	97 kg N ha^{-1}	33	34	40	163
Daily net N mineralization 1998	0.50 kg N ha^{-1}	0.17	34	0.21	0.84
Grain yield 1998 (winter wheat)	7030 kg ha^{-1}	801	11	5170	8660
Soil mineral N in spring 1999[2]	24 kg N ha^{-1}	7.7	32	9	42
Soil mineral N at harvest 1999[2]	23 kg N ha^{-1}	6.5	28	10	34
Soil N uptake by plants 1999	45 kg N ha^{-1}	16	37	12	74
Net N mineralization 1999	44 kg N ha^{-1}	16	36	13	81
Daily net N mineralization 1999	0.34 kg N ha^{-1}	0.12	36	0.099	0.62
Grain yield 1999 (spring barley)	4080 kg ha^{-1}	738	18	2480	5370
Soil mineral N in spring 1999[2]	25 kg N ha^{-1}	3.0	12	20	31
Soil mineral N at harvest 2000[2]	25 kg N ha^{-1}	3.6	14	19	33
Soil N uptake by plants 2000	92 kg N ha^{-1}	21	23	55	139
Net N mineralization 2000	92 kg N ha^{-1}	23	26	44	139
Daily net N mineralization 2000	0.69 kg N ha^{-1}	0.16	26	0.29	0.93
Grain yield 2000 (winter wheat)	6360 kg ha^{-1}	810	13	4530	7630

[1] 0–20 cm.
[2] 0–90 cm.

$pH(H_2O)$ showed no significant correlation with Nm (Table 2). The larger Nm in the eastern part of the field (Fig. 2) in all three years should be due to the higher SOM in combination with low clay content here. The correlations between years for the different soil mineral N parameters were rather poor. The correlation between Nm in 1998 and Nm in 2000 was better than between Nm in 1999 and Nm in either 1998 or 2000 (Table 2). Similarities in spatial pattern between years in soil mineral N in spring, soil N uptake by plants and soil mineral N after harvest were generally even smaller than for Nm (Table 2).

Discussion

Impact of clay content on net nitrogen mineralization

Net N mineralization, as defined here, is the result of several processes in the field: mineralization, immobilization, denitrification, leaching, atmospheric deposition and ammonium fixation and release. Clay content may have a restraining influence on leaching (Gustafson, 1982). As a medium for ammonium fixation, clay can limit N availability. However, if large amounts of ammonium N are applied, clay releases ammonium more continuously in favour of the crop (Scherer, 1993). Moreover, clay has a high water holding capacity. The influence of clay on soil water content, and thereby also on oxygen content, may affect the microbial processes of mineralization, immobilization and denitrification. Clay content also influences soil structure, which in turn affects the accessibility of organic matter for the microbes (Adu & Oades, 1978). All of these functions of clay make the relations complex and would have influenced the results. In all three years the effect of clay on Nm was negative (Fig. 3). This may be partly due to unavailable organic matter trapped in soil aggregates and/or poor oxygen supply to microorganisms owing to rainy weather in all three growing seasons. Denitrification may also have contributed to this result.

Impact of topography and soil moisture on net nitrogen mineralization

Topography was thought possibly to affect Nm by influencing soil water content. In this field, clay content is closely correlated to topography, and it is not clear which of these two variables was more important for the variations in Nm. However, in 1999 the Nm values were smaller in the lower part of the field (Fig. 3). The soil here was very wet as a result of abundant precipitation from the winter until the beginning of July, when the groundwater reached the drainage depth (1.0 m) for the first time in that season. However, the influence of water content on Nm is complicated, since different microbial processes respond differently to varying water contents. N mineralization has a peak in a water-tension range of 0.50–0.15 bars, and decreases to a minimum under air-dry conditions as well as at tensions close to zero, after which ammonium production may increase again (Miller & Johnson, 1964). Denitrification, turning nitrate into elementary N or dinitrogen oxide under anaerobic conditions, increases at very high water contents (Firestone, 1982). In addition, the impact of soil moisture on Nm varies during the season, since Nm is also affected by temperature. Because of these complexities, it is not surprising that the correlation found between Nm and factors affecting soil moisture, such as elevation and clay content, was limited.

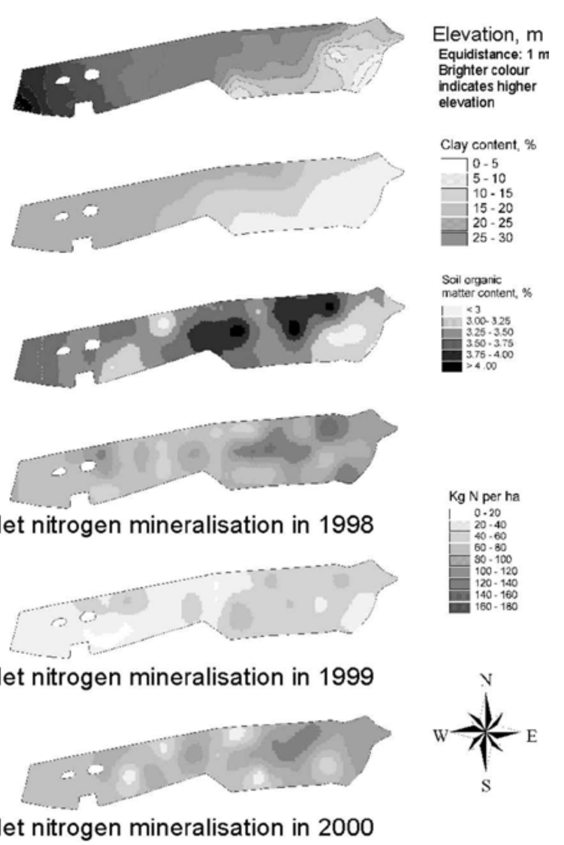

Fig. 2. Maps of elevation, clay content (0–20 cm), soil organic matter content (0–20 cm) and net nitrogen mineralization in different years.

Impact of soil organic matter content on net nitrogen mineralization

A better relation between SOM and Nm was expected. The moderate variation in SOM (Table 1) may be one reason for the weaker relation obtained. In two studies on nearby fields with larger variation in SOM (2.0–22.6% and 2.8–17.2%) the correlation with SOM was better ($r = 0.69$ and $r^2 = 0.83$, respectively) (Börjesson et al., 1999; Stenberg et al., 2002). The within-field variations in N uptake by plants were also larger in these investigations (SD = 30 kg N ha^{-1} on average for both investigations). Another possible explanation for the poor correlation between SOM and Nm in this investigation could be that the properties of the SOM vary within the field, but then more similar patterns of Nm should have been found between the three years. However, N immobilization (Jansson & Persson, 1982) may have varied owing to within-field variations in the amounts of crop residues altering the pattern of Nm between years. Areas with unfavourable conditions for mineralization in one year may also have more organic N available for mineralization in the next year. This statement is supported by the fact that the average Nm for the three years correlated better with SOM and clay ($r^2_{\text{adj}} = 0.34$***) than did annual Nm.

An increase of 1% in SOM within the topsoil increased the Nm value in this investigation by about 20 kg N ha^{-1} (Fig. 3). Other investigations, conducted on farms without animal production, resulted in only 5 kg N ha^{-1} per percentage unit of SOM (Lindén et al., 1992b). In addition, the average amounts of Nm were larger than generally registered under Nordic conditions with cereals as preceding

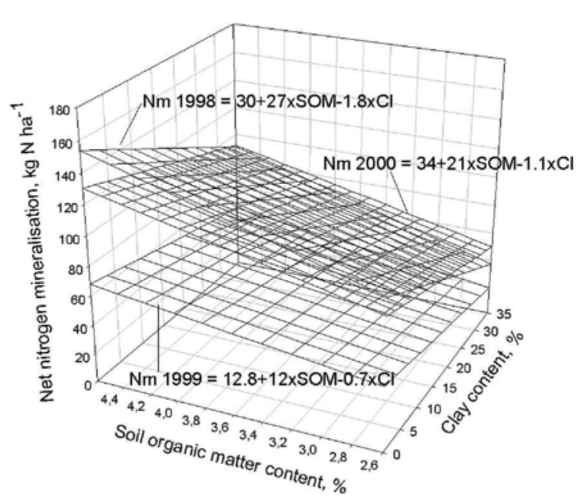

Fig. 3. Plots of multiple linear regression equations for net nitrogen mineralization (Nm), soil organic matter content (SOM) and clay (Cl) in different years (1998, 1999 and 2000).

Table 2. Correlation matrix of different variables at the 34 sites: correlations with other variables in the same year are listed in the columns Ns, Nh, Np and Nm; correlations of the same variables for different years are given in the columns 1998 and 1999

	Cl	SOM	Ntot	pH	El	Ns	Nh	Np	Nm	1998	1999
Cl											
SOM	0.05										
Ntot	0.03	0.93***									
pH	−0.39*	−0.17	−0.06								
El	−0.85***	−0.31	−0.29	0.52**							
Ns98	−0.10	0.16	0.13	−0.11	−0.13						
Nh98	−0.62***	0.25	0.29	0.28	0.52**	0.27					
Np98	−0.11	0.37*	0.33	−0.15	−0.05	0.57***	0.49**				
Nm98	−0.35*	0.38*	0.37*	0.04	0.23	0.37*	0.80***	0.90***			
Y98	0.37*	−0.28	−0.32	−0.06	−0.22	−0.05	−0.39*	−0.08	−0.23		
Ns99	−0.64***	0.40*	0.38*	0.09	0.37*					0.45**	
Nh99	−0.10	0.41*	0.42*	−0.10	−0.10	0.39*				0.38*	
Np99	−0.53**	0.36*	0.39*	0.28	0.42*	0.69***	0.45**			0.43*	
Nm99	−0.28	0.34*	0.39*	0.21	0.22	0.39*	0.68***	0.88***		0.49**	
Y99	−0.39*	0.29	0.35*	0.57***	0.45**	0.45**	0.34	0.69***	0.63***	−0.06	
Ns00	0.26	0.47**	0.31	−0.50**	−0.54***					0.41*	0.17
Nh00	−0.02	0.37*	0.34	−0.17	−0.23	0.29				0.36*	0.65**
Np00	−0.25	0.49**	0.58***	0.04	0.18	−0.07	0.24			0.39*	0.47**
Nm00	−0.25	0.49*	0.58**	0.02	0.18	−0.13	0.35	0.98***		0.59***	0.44
Y00	0.20	0.39*	0.36*	0.07	−0.23	−0.09	0.30	0.26	0.29	0.02	0.28

Cl: clay content; SOM: soil organic matter content; Ntot: total soil nitrogen content; El: elevation; Ns: soil mineral nitrogen in spring. Nh: soil mineral nitrogen at harvest, Np: plant available soil nitrogen, Nm: Net nitrogen mineralization.
$^{***}P<0.001$, $^{**}P<0.01$, $^{*}P<0.05$.

crops (20–70 kg N ha^{-1}) (Østergaard et al., 1983; Kyllingsbæk, 1986; Lindén, 1987; Lindén et al., 1992a). The greater mineralization in this investigation may be due to frequent application of slurry in earlier years, influencing SOM composition and properties, and/or moister weather conditions.

Impact of topsoil depth on net nitrogen mineralization

The variation in SOM in the 30–40 cm layer agreed with observed differences in topsoil depth. Sites with deeper topsoil will more or less have a larger SOM content within this depth. With a deeper and thereby larger volume of topsoil per hectare, Nm per hectare may in consequence also be higher (Lindén et al., 1992a). This is a probable explanation for the correlation found between SOM in the 30–40 cm layer and Nm. In future investigations, it would be interesting to include topsoil depth as one of the independent variables.

Impact on the within-field variation in fertilizer nitrogen demand

The annual variations in grain yields were not as large as in Nm, as expressed by the corresponding coefficients of variance (Table 1), but their impacts on the within-field variation in N fertilization demand may be of similar size. If 20 kg N ha^{-1} were to be added for each 1000 kg of yield, according to current recommendations (Albertsson, 2002), the standard deviation for N fertilization demand based on yield levels would be about 15 kg N ha^{-1} each year. This is equal to, or slightly less than, the standard deviation for Nm (Table 1), which should be in proportion to its impact on N fertilization demand. In 1999, the correlation between yield and Nm was rather large (Table 2), indicating that N supply was limiting yield. However, the potential yield may be different from the actual yield. Therefore, its importance for the variation in N fertilizer demand in this field remains uncertain.

Soil mineral nitrogen in spring

In many other investigations, the amounts of soil mineral N in spring were larger than here (Scharpf, 1977), thus constituting a more important part of plant-available soil N. Then, soil mineral N in spring was considered to give good estimates of the demand for N fertilization during the growing season (Scharpf, 1977). In the present investigation, however, annual measurements of within-field variations in soil mineral N in spring gave poor estimates of plant-available soil N during the growing season, possibly owing to the small overwintering amounts of mineral N. The within-field variation in soil mineral N in spring (0–90 cm) was also small (Table 1). There was some correlation with soil N uptake by plants in 1998 and 1999, but not in 2000 (Table 2). If the topsoil alone is considered, there were no correlations in any of the years. In addition, the amounts of soil mineral N in spring were small compared with soil N taken up by plants (Table 1). Net N mineralization, however, was more similar in size to plant-available soil N (Table 1) and thus correlated better with this parameter (Table 2). This indicates that almost the entire amounts of soil N taken up by the crops originated from Nm during the growing season. Low levels of soil mineral N in spring in Nordic countries are not unusual (Lindén et al., 1992b). In such cold-temperate, frequently humid regions much of the N mineralized during autumn and winter may be lost through leaching in this period. Therefore, Nm should be more important to predict.

Estimation of nitrogen supply to crops

The variations between years and within the field in Nm indicate that average values cannot be used for more precise calculations of the need for fertilizer N for a field such as this one. The pattern of Nm is difficult to predict with satisfactory precision from easily measured, stable parameters such as SOM and clay content. Simulation models calculating net N mineralization from soil and weather data, such as the SOILN model (Eckersten & Jansson, 1991), may give better results. Existing mechanistic models, however, need large amounts of input data, and are very laborious and time-consuming. For estimating the within-field variations in the supply of plant-available soil N at different times on all fields of a farm and on a large number of farms, this is not a realistic measure when judging the additional N to crops during the growing season. Using methods of plant analyses (Simán, 1974), the within-field variability in the N status of the crop can be determined or estimated, considering all influences earlier in the growing season on the present soil N status, but these methods are also laborious. Remote sensing (Filella et al., 1995) may replace plant analyses and simulation models in this respect. For instance, on the basis of measurements of reflectance from the crop in different wavelength bands, N deficiency in the crop can be estimated and fertilization can then be performed in real time (Reusch, 1997). If remote sensing takes into account the most important previous influences on crop N status, clay and SOM contents and perhaps topsoil depth could be complementary in the estimation of the continued Nm during the remaining part of the growing season.

Conclusion

The within-field variation in Nm in this field was large and would have a considerable impact on the within-field variation in fertilizer N demand. The spatial pattern in Nm varied between years, probably owing to differences in soil moisture, and this variation can only partly be explained by stable soil parameters such as clay and SOM. The pattern of Nm is therefore difficult to predict with satisfactory precision from these parameters alone without seasonal adjustment.

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