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Within-field variability of mineral nitrogen in grassland

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Abstract The within-field variability of soil mineral nitrogen (N_{min}) in a grazed grassland of 8000 m^2 was examined. NO_3^--N concentrations were characterized by a high spatial variability. This can be explained by the uneven deposition of animal excreta. All NH_4^+-N as well as NO_3^--N values were lognormally distributed, before and after the grazing season. At the end of the grazing season the largest part of the variability of NO_3^--N was found for NO_3^--N concentrations measured within a distance of a few metres. A high variability for NO_3^--N over very short distances was also indicated by a large nugget variance. During the grazing season, observed mean N_{min} values increased from 22 to 132 kg N ha^{-1}. Regions with clearly higher NO_3^--N concentrations could be identified. These zones matched with the drinking place and the entrance of the pasture, places which were more frequently visited than others. High residual N levels in autumn led to relatively high losses of N, mostly by leaching, during the subsequent drainage period. Knowing the variability of N_{min}, the number of samples needed to estimate the average N_{min} in a field could be calculated for different probabilities and various degrees of precision. From the spatial distribution of the N_{min} concentrations and the restrictions imposed by the new European decree, adapted fertilizer strategies can be proposed at least for places where systematically higher N_{min} concentrations can be expected.

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Introduction

N-balance studies on grassland, especially grazed grassland, always encounter the same problem: part of the N which is applied cannot be retrieved. First, it is not evident how to quantify all N inputs and outputs. Fertilizer inputs, as well as herbage and/or animal products for output, are rather easy to measure, whereas it is much more difficult to quantify atmospheric N deposition, symbiotic N fixation, and leaching and gaseous N emissions (NH_3, N_2O, NO_x) which are the most important N-output processes. Secondly, grazed grasslands show a very high variability of nutrient concentrations within the field. This spatial variability is the result of the relatively random return of excreta over the pasture area and of the habit of cattle to frequent certain parts of the pasture such as paths, drinking places, areas of shade, etc. (Afzal and Adams 1992). Although N immobilization can occur, N losses are at least partly responsible for the differences between input and output of N.

During grazing, herbage N is removed from the total area, while most of the N returns as excreta to small areas in high concentrations. Addiscott et al. (1991) mention that one urination of a cow on a restricted area amounts to a fertilizer application of 400–1200 kg N ha^{-1}. Because N uptake by grass in late autumn and winter is limited, it is of paramount importance to minimize the mineral N content in the soil (N_{min}) at that time because of the risk of leaching during winter.

The objective of this paper is to investigate the distribution and variability of N_{min}, which are required in order to evaluate if a given bulk soil sample is representative of the whole field, to calculate the number of soil samples necessary to obtain an acceptable mean value of Nmin and to derive the possible N losses during winter at a certain level of probability.

Materials and methods

Experimental site

The field experiments were carried out on a grassland plot of 8000 m^2 (100×80 m), located in Melle, Belgium (3°47′30″E, 51°N). The plot is almost completely flat (1–2% slope). The soil is a Hapludalf (Soil Survey Staff 1996) with a silt loam texture and a moderate drainage capacity. The soil pH was 6.9. The field has been under permanent pasture since 1954. There were 3 livestock units (LSU) ha^{-1} (stocking density). The agricultural activities in 1995 and 1996 are given in Table 1. The annual mineral N input was 260 kg N ha^{-1} and 235 kg N ha^{-1} for 1995 and 1996, respectively.

The pasture consists of perennial rye-grass (*Lolium perenne* L.) and rough-stalked meadow grass (*Poa trivialis* L.).

Soil sampling

To investigate the spatial variability of the mineral N content in the experimental field, about 200 soil samples were taken using a regular grid (Fig. 1), taking into account the experience of Van Meirvenne (1991). The distance between two sampling points was 10 m. However, at some places samples were taken at smaller distances, i.e. at 5 m and at 2 m, as shown in Fig. 1.

The soil sampling was carried out 4 times: in 1995, before and after a grazing period (14 March and 19 October) and in 1996–1997, before and after winter, i.e. on 29 October and 27 February. The first two dates were chosen to obtain information about residual mineral N before and after the grazing period. The last two dates were selected to provide information before and after the winter period (no grazing). Soil samples were taken at two depths: 0–30 cm and 30–90 cm. In the upper layer, NO_3^--N as well as NH_4^+-N concentrations were determined, whereas in the lower layer only NO_3^--N was measured. At each sampling point, three soil bores were taken within a radius of 0.5 m, by means of an auger 3–5 cm in diameter (Eijkelkamp 04–04) and mixed. At each sampling time, all samples were immediately deep frozen until analysis. At the same time some undisturbed soil samples of the two layers were taken in order to determine the soil bulk density; this was 1.34±0.07 g cm^{-3} for the 0 to 30-cm layer and 1.62±0.08 g cm^{-3} for the 30 to 90-cm layer. This made it possible to express the residual mineral N in kg N ha^{-1}.

Determination of N_{min}

After homogenization of the fresh soil, 30 g moist soil was mixed with 60 ml of either a 1 N KCl solution (0 to 30-cm layer) or a 1% $KAl(SO_4)_2$ solution (30 to 90-cm layer). Then the mixture [1:2 soil:solution (w:v)] was shaken for 1 h, using a reciprocating shaker, and filtered through a Schleicher and Schuell (5971/2) 150-mm filter paper. The KCl extracts were measured colorimetrically by a continuous flow autoanalyzer, determining at the same time the NO_3^--N and NH_4^+-N concentrations (Beernaert et al. 1987). In the $KAl(SO_4)_2$ solution, NO_3^- was measured potentiometrically with an ORION 93-07 NO_3^--specific electrode (Cottenie and Velghe 1973; ORION Research 1991).

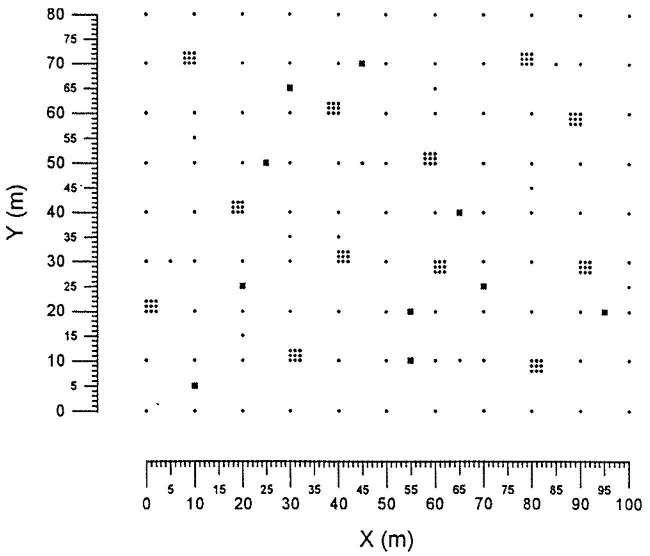

Fig. 1 Sampling grid. ● Sampling points on 14 March 1995 and 29 October 1996, ●+■ sampling points on 19 October 1995, ■ sampling points on 27 February 1997

Table 1 Overview of agricultural practices on the grassland in 1995 and 1996

1995	Activities	1996[a]	Activities
23 March	80 kg N ha^{-1}	12 March	40 kg N ha^{-1}
15 April	Start of grazing	10 May	40 kg N ha^{-1}
15 May	60 kg N ha^{-1}	23 May	60 kg N ha^{-1}
1 June	End of grazing	21 June	50 kg N ha^{-1}
21 June	Cutting	21 August	45 kg N ha^{-1}
29 June	Hay harvest		
30 June	60 kg N ha^{-1}		
15 July	Start of grazing		
7 August	60 kg N ha^{-1}		
1 November	End of grazing		

[a] In 1996 the grass was not mown, only trimmed

Spatial variability of N_{min}

Geostatistical methods (Van Meirvenne and Hofman 1989; Webster and Oliver 1990) were used to map the N_{min} variability of both the topsoil (0–30 cm) and the underlying layer (30–90 cm). Under conditions of quasistationarity, variograms were calculated to characterize the structure of the spatial variation of the NO_3^--N and NH_4^+-N contents in the upper layer and of the NO_3^--N content in the underlying layer for each survey. The degree of spatial variability between samples was measured by calculating the omnidirectional semivariance $\gamma(h)$ (Eq. 1).

$$\gamma = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{Z(xi) - Z(xi+h)\}^2 \qquad (1)$$

where $N(h)$ is the number of pairs of observations separated by lag distance h, and $Z(x_i)$ and $Z(x_i+h)$ give the value of the variable Z at two positions separated by h.

Results and discussion

Frequency distributions of soil N_{min}

Soil samples were taken at two depths (0–30 cm and 30–90 cm) at 4 different times. All data were statistically analysed and the most important descriptive statistics are summarized in Table 2.

Between the two sampling dates in 1995, the mean values for all measurements increased. The largest in-

Table 2 Summary of some statistical data of mineral N residues at 4 different times. *CV* Coefficient of variation

	14 March 1995			19 October 1995			29 October 1996			27 February 1997		
	NH_4^+-N	NO_3^--N		NH_4^+-N	NO_3^--N		NH_4^+-N (mg-kg^{-1}-soil)	NO_3^--N		NH_4^+-N	NO_3^--N	
Layer	0–30	0–30	30–90	0–30	0–30	30–90	0–30	0–30	30–90	0–30	0–30	30–90
Minimum	0.41	0.39	0.53	1.64	1.90	0.68	0.73	1.78	0.64	0.41	0.62	0.62
Maximum	3.88	4.21	15.03	8.18	70.52	32.07	25.05	28.94	29.01	20.18	10.97	17.49
Mean	1.51	1.35	1.51	3.72	13.81	7.34	3.61	7.68	5.25	3.54	4.10	3.63
Median	1.42	1.27	0.95	3.51	10.38	5.64	2.95	5.87	2.53	2.81	3.60	2.78
SD	0.58	0.56	1.90	1.22	11.18	6.12	3.12	5.54	5.75	2.72	1.92	2.69
Skewness	1.32	1.54	4.50	0.99	2.10	1.68	3.90	1.74	2.05	2.45	1.14	2.65
Kurtosis	5.71	7.64	26.34	4.10	8.63	5.63	22.41	5.99	7.09	11.86	4.68	11.65
CV (%)	38.32	41.73	125.69	32.66	80.97	83.37	86.52	72.08	109.42	76.98	46.90	74.12

crease (>a factor of 10) was noted for the NO_3^--N content in the top layer. This is attributed to the mineralization of organic N and especially to the added fertilizer N and urine N. In contrast, during the winter (1996–1997) all mean values decreased. The largest decrease (± a factor of 2) was noted for NO_3^--N in the top layer. This mineral N must have been lost by denitrification or moved to underlying soil layers by drainage and as such was unavailable to the grass.

High coefficients of variation (CV) for the soil NO_3^--N concentrations, ranging between 42% and 81% in the top layer and between 74% and 126% in the bottom layer, indicate a high variability and can be explained by the uneven deposition of animal excreta. It seems to be evident that the CV of NO_3^--N of the top layer increases during a grazing period while there is a decrease in the lower layers. High CV values have also been reported in other studies. Trudgill et al. (1991) found NO_3^- CV between 29% and 92% for soil, while Wade et al. (1996) reported a CV of 98.1% for NO_3^- concentrations under pasture.

Histograms of the raw data showed that all frequency distributions were definitely positively skewed. This was due to the low number of high N_{min} values, typical for grazed pastures. All NH_4^+-N as well as NO_3^--N values were lognormally distributed. This was also noticed by White et al. (1987) in soils under grassland, at sampling depths down to 1 m.

At the end of the grazing season of 1995, the skewness of the NO_3^--N concentrations in the top layer had increased, while those of the concentrations of NH_4^+-N in the top layer and the NO_3^--N in the bottom layer had decreased. This indicates the influence of grazing cattle on the N_{min} concentration.

During the grazing season, the proportion of the pasture which is affected by dung and urine increases. Most of the ingested N returns to the soil via excreta, especially via randomly distributed and localized urine patches. Most of the N in urine is present as urea which is rapidly hydrolysed to NH_4^+; this is subsequently nitrified to NO_3^-, which explains the lower skewness of the NH_4^+-N data and the higher one for the distribution of NO_3^--N concentrations in the top layer at the end of the grazing season. The doubling of the CV value of the NO_3^--N data for the top layer (from 42% to 81%) during the grazing season also indicates this transformation. White et al. (1987) examined the upper 5 cm of a grassland soil grazed by sheep. They noticed an increased skewness of the soil NO_3^--N distributions, just like the doubling of the CV observed in the present study, due to the return of N via excreta. The rather high decrease in the skewness of NO_3^--N data for the bottom layer can be explained by the fact that the high over-winter residual effect of urine patches diminished over the grazing season.

For the winter data, the opposite trend in skewness of the NO_3^--N distribution was noted: a decrease in the top layer (from 1.74 to 1.14) and an increase in the bottom layer (from 2.05 to 2.65). This indicates that during the winter period the high NO_3^--N concentrations in areas of the upper horizon diminished due to leaching and/or denitrification. Leaching resulted in an increase in the skewness of the distribution of the NO_3^--N values for the bottom layer. This over-winter residual effect of urine patches was also mentioned by Afzal and Adams (1992). They found in the top layer (10 cm) almost no effect of urine patches, while below a depth of 30 cm, high concentrations of NO_3^--N were measured, resulting in an increase in the skewness.

All distributions were leptokurtic and the kurtosis fluctuated, parallel to the skewness, during the grazing season of 1995 and the winter of 1996–1997.

Spatial variability

Before the variability of the soil N_{min} could be examined, the spatial dependency of the measured N_{min} concentrations needed to be determined. This was done by drawing experimental semivariograms (plots of $\gamma(h)$ against h) and fitting a model to them. Figure 2 shows some examples. To all experimental semivariograms, an isotropic spherical model was fitted.

Fig. 2 Experimental semivariograms and fitted spherical models of NO_3^--N in the upper layer before (*left*) and after (*right*) winter 1996–1997

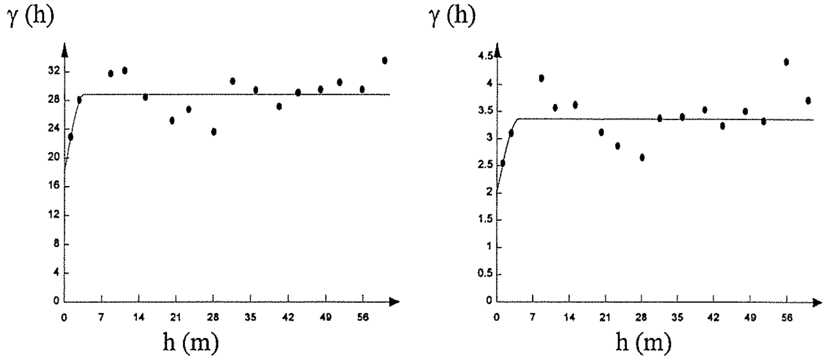

Table 3 Mean NO_3^-- and NH_4^+-N concentrations based on kriged estimates

Sampling time	Mineral N form	N concentrations (kg N ha^{-1})	
		0 to 30-cm layer	30 to 90-cm layer
14 March 1995	NO_3^--N	5.0	10.5
	NH_4^+-N	6.0	
19 October 1995	NO_3^--N	53.0	64.0
	NH_4^+-N	14.5	
29 October 1996	NO_3^--N	35.0	41.0
	NH_4^+-N	17.0	
27 February 1997	NO_3^--N	18.5	33.5
	NH_4^+-N	15.0	

Figure 2 shows no spatial dependency for the soil NO_3^--N concentrations in the upper layer before winter at lag distances of more than 3.7 m. White et al. (1987) also found that for soil NO_3^--N concentrations under grazed grassland all variance occurred within a distance of < 4 m. Hack-ten Broeke et al. (1996) noted a spatial dependency in NO_3^--N concentrations under grazed grasslands within a distance of 5 m, due to the uneven distribution of excreta.

A high variability in NO_3^--N concentrations over very short distances was indicated by a large nugget variance [$\gamma(h)$ for $h=0$]. In the upper layer, the nugget variance reached 60% of the total variance. In the bottom layer it ranged between 40% and 60%. Wade et al. (1996) also found high nugget variances for NO_3^- levels under pastures. For NH_4^+, it ranged around 56%. The nugget variance, however, was already reduced by bulking three soil samples, taken within a radius of 0.5 m, at each sampling point before analysis.

Influence of grazing on spatial and temporal N_{min} distribution

Once a model was fitted to the experimental semivariograms, ordinary point kriging was performed for a grid of 100–80 locations (1-m resolution). Hereby, estimates for the NO_3^--N and NH_4^+-N concentrations were made for the whole field, using the parameters of the isotropic variogram models. A "neighbourhood" of 15 m was used for the interpolation with a maximum number of retained "neighbours" of 15.

The N_{min} concentration in the grazed grassland calculated from the kriged estimates was clearly higher at the end (131.5 kg ha^{-1}) than at the beginning (21.5 kg ha^{-1}) of the 1995 grazing season (Table 3).

Some parts of the field showed a very high increase in the N_{min} concentration in comparison with other parts (Fig. 3). These zones matched with the drinking place (top right) and the entrance of the pasture (bottom left), places which were more frequently visited than normally grazed zones. These zones are called the "critical areas" of a pasture. The same holds for data in Fig. 4, showing the N_{min} distribution before and after winter. Milimonka et al. (1994) found that soil N concentrations under grassland around drinking places grazed by sheep were 7 times higher than areas grazed normally. West et al. (1989) also found higher total N concentrations around water sources in grazed pastures. Barrow (1967) distinguished between small- and large-scale heterogeneity in soils under grazed grasslands. Small-scale heterogeneity results from the relatively random return of excreta over the general area of the pasture, while large-scale heterogeneity results from the habit of cattle to frequent certain areas of the pasture such as water sources, paths and areas of shade.

The NH_4^+-N pattern showed much more homogeneity, compared to the NO_3^--N pattern. This was due to nitrification, occurring so fast that only recently produced urine patches were responsible for highly varying NH_4^+-N concentrations.

N_{min} loss during winter 1996–1997

Figure 4 shows the maps, resulting from kriging of the NO_3^--N data, before and after winter 1996–1997, using the same legend as in Fig. 3.

Before winter (29 October 1996), the N_{min} concentrations in both layers were quite high (Table 3), although somewhat smaller than in autumn 1995. After winter, the N_{min} amounts were still relatively high (±67 kg ha^{-1}), but clearly below the values measured

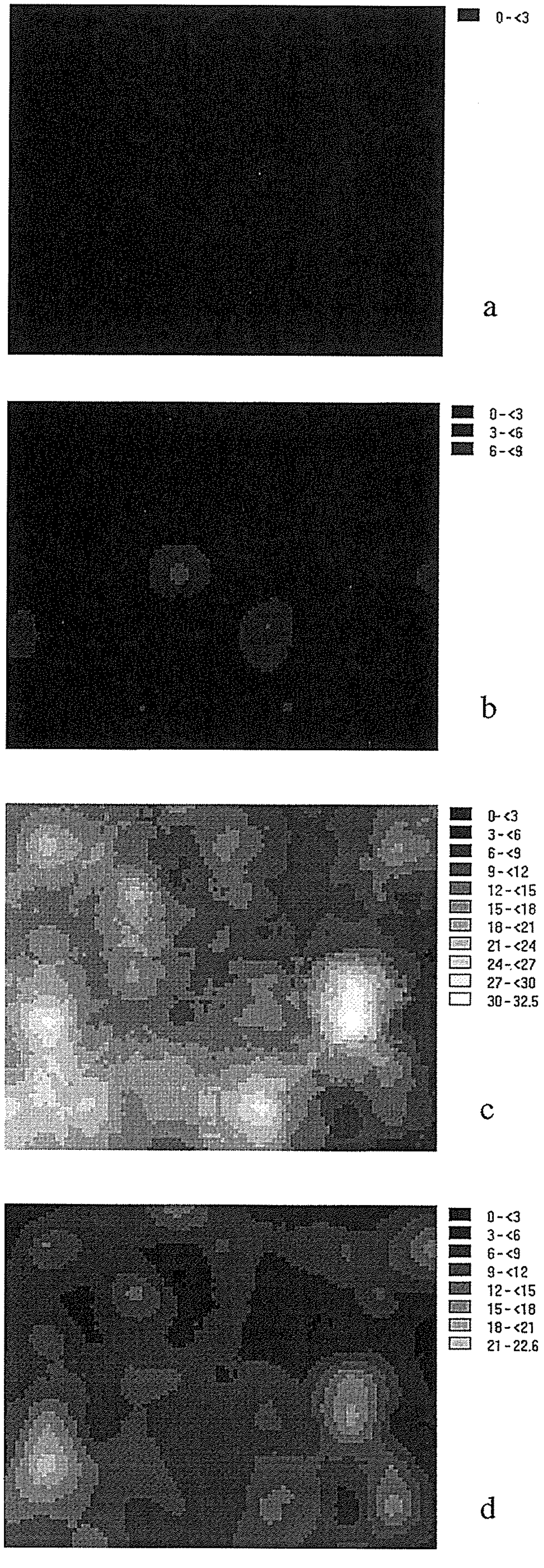

Fig. 3 Point-kriged NO_3^--N concentrations (mg N kg^{-1}) in March 1995 (**a, b**) and October 1995 (**c, d**) for 0 to 30-cm layer (**a, c**) and the 30 to 90-cm layer (**b, d**)

before winter, i.e. 93 kg N ha^{-1} (Table 3). At least 26 kg N ha^{-1} was lost during the 4 winter months, most of it by leaching. Denitrification could also have contributed to the total N_{min} loss, although denitrification losses in pasture under the prevailing weather circumstances were found to be low during the winter (data not shown). Taking into account an average N deposition of 10–15 kg N ha^{-1} and low N mineralization during winter time, the total N loss should have been higher. Nevertheless, the amount of N lost was relatively small, probably due to extremely dry and cold weather during December and January. According to the decree issued by the Ministry of the Flemish Community for the protection of the environment against the use of fertilizers in agriculture (Ministry of the Flemish Community 1999), acceptable N losses to ground and surface water are based on a maximum allowable NO_3^- concentration of 50 mg NO_3^- l^{-1}. Provisionally, the maximum concentration of NO_3^-N allowed has to be <90 kg N ha^{-1} in the soil profile to a depth of 90 cm in the period October–15 November. Figure 5 shows the differences in N_{min} before and after winter.

Sampling strategy

Due to the high variability of soil N_{min} under grazed grassland, it is difficult to obtain a good estimate of the average Nmin concentration and NO_3^--N losses on a field scale if it is based only on a limited number of soil samples. A clearer appreciation of the heterogeneity in soil N_{min} may improve the sampling strategy used (Afzal and Adams 1992). Based on the variance, the frequency distribution and its descriptive statistics, the minimum number of soil samples needed to get an acceptable error (McBratney and Webster 1983) with the lowest costs can be determined. This is calculated by Eq. 2:

$$N=\left\{\frac{t(a\mathrm{CV})^2}{\varepsilon}\right. \qquad (2)$$

where N is the number of samples needed to obtain an estimate of the mean value with a given degree of precision (ε) and significance level (P), $t(a)$ is Student's t-value for probability 1-a, and ε is the degree of precision (%).

Table 4 shows the results of this calculation for the sampling before (29 October 1996) and after winter (27 February 1997), for probabilities $P=0.2$, $P=0.1$ and $P=0.05$, and two different relative values of ε.

So, considering a relative ε of 20% and a probability of $P=0.2$, which is acceptable, 21 soil samples were required to calculate an estimate of the mean NO_3^--N

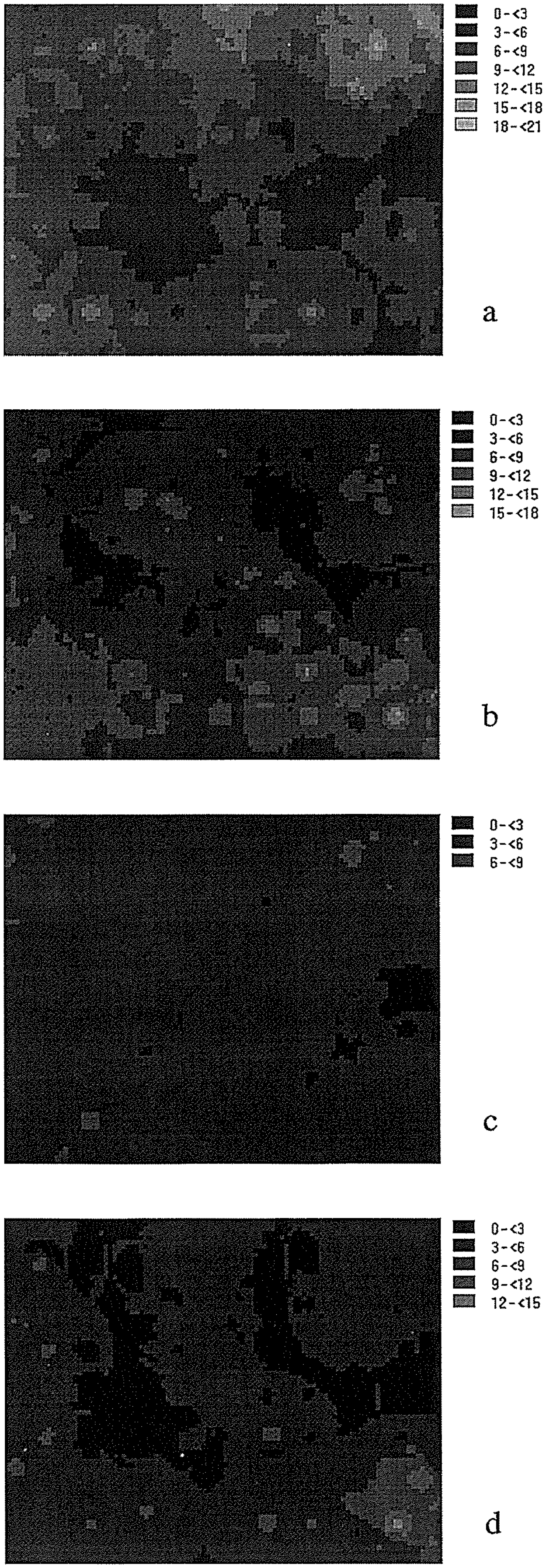

Fig. 4 Point-kriged NO_3^--N concentrations (mg N kg^{-1}) in October 1996 (**a, b**) and February 1997 (**c, d**) for the 0 to 30-cm layer (**a, c**) and the 30 to 90-cm layer (**b, d**)

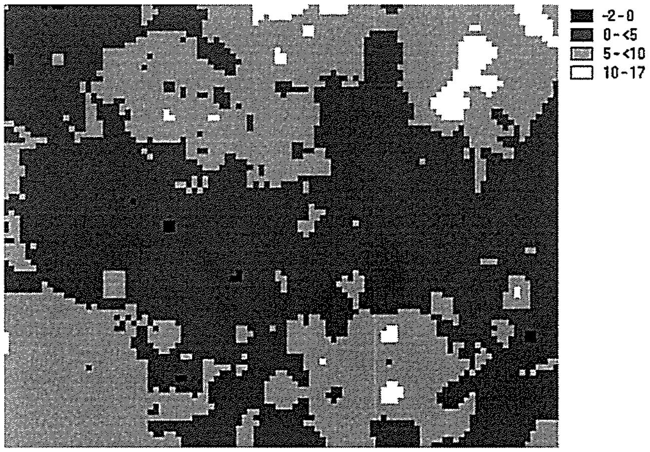

Fig. 5 Difference in NO_3^--N concentrations (mg N kg^{-1}) between October 1996 and February 1997 (0 to 90-cm layer)

concentration in the top layer for 29 October 1996. In February 1997, only nine soil samples were needed to achieve the same precision and probability. If, however, the proposed probability and/or ε are stricter, additional samples need to be taken. For $P=0.2$ and $\varepsilon=10\%$, 85 soil samples need to be taken in October, and 36 in February. The higher number of soil samples required before winter time to calculate a good estimate of the mean NO_3^--N concentration is due to the higher variability. After winter, the variability is much lower because of leaching losses to deeper soil layers. Furthermore, for $P=0.2$ and $\varepsilon=10\%$, 98 samples are required to calculate an acceptable estimate of the mean NO_3^--N concentration in the bottom layer in October, while 44 samples are sufficient for February.

According to the results presented in Table 4, it is clear that the number of soil samples necessary to cal-

Table 4 Number of samples required to estimate the NH_4^+-N or NO_3^--N concentrations in the field, for *P*-values and different relative degrees of precision (ε)

Parameter	*P*	29 October 1996		27 February 1997	
		$\varepsilon=10\%$	$\varepsilon=20\%$	$\varepsilon=10\%$	$\varepsilon=20\%$
NH_4^+-N (0–30 cm)	0.2	51	13	72	18
	0.1	85	21	119	30
	0.05	120	30	169	42
NO_3^--N (0–30 cm)	0.2	85	21	36	9
	0.1	141	35	60	15
	0.05	200	50	85	21
NO_3^--N (30–90 cm)	0.2	98	25	44	11
	0.1	162	40	72	18
	0.05	230	57	103	26

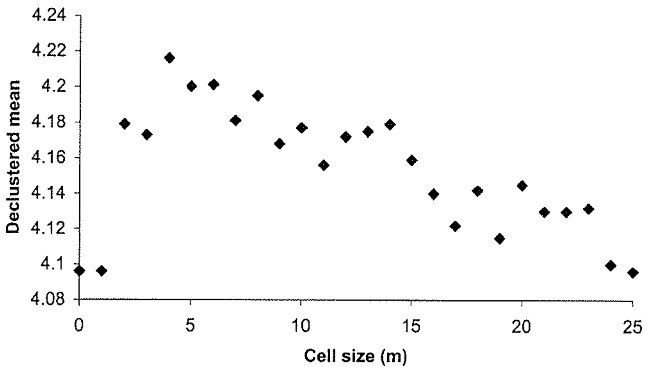

Fig. 6 Declustered mean NO_3^--N (mg kg^{-1}) versus cell size for the February 1997 sampling (0 to 30-cm layer)

culate a particular and acceptable estimate of the mean value of a parameter depends on the time of the year, the parameter to be estimated, the soil depth and the required accuracy for management practices.

The above calculations were made under the assumption that all measurement points were taken on the basis of different probabilities. This was not the case, so we investigated whether there was a preferential clustering using the cell-declustering procedure described in Deutsch and Journel (1998). In this procedure the field was subdivided into rectangular cells of a given size. The number of observations n_b falling into each cell b was counted. The observations inside that cell were weighted ($1/n_b$). Next, the weighted average of the entire field was calculated. This calculation was repeated for cell sizes ranging from 1–25 m and for the different data sets. It was found that the average NO_3^--N content increased from a unweighted calculation to a cell size of about 5–10 m, after which it decreased again (Fig. 6). This suggests that a preferential sampling at locations with lower than average NO_3^--N had taken place. Therefore, statistics were recalculated, using only observations separated by a distance larger than the range of their semivariogram (Table 5). The CV did not change much, so the error made by considering the data as being non-preferentially located was small.

In conclusion, NO_3^--N concentrations under grassland are characterized by a high spatial variability, even over very short distances, as indicated by high CV values and large nugget variances. Especially at the end of the grazing season, CV values increased in the top 30 cm, due to the influence of grazing. Concentrations were spatially dependent over a distance of only 3.7 m because of the random location of urine and dung patches. However, critical zones (regions with clearly higher NO_3^--N concentrations) could be identified. They were found around drinking places and paths.

Table 5 Recalculated statistics, based on spatially independent data

	October 1996			February 1997		
	NH_4^+-N	NO_3^--N		NH_4^+-N	NO_3^--N	
	0–30	0–30	30–90	0–30	0–30	30–90
Mean	4.05	8.08	5.52	3.31	4.23	3.52
SD	3.76	5.83	5.93	3.40	1.98	2.55
CV	92.96	72.21	107.52	72.59	46.76	72.25

N losses during winter 1996–1997 were limited to about 26 kg N ha^{-1}. These were due to the dry and cold weather conditions.

Because NO_3^--N losses are proportionally related to soil NO_3^--N concentrations, areas with (expected) high Nmin concentrations should be identified. These critical zones for NO_3^--N losses can be mapped by kriging the field data. Generally, information about systematically higher NO_3^--N concentrations in some parts of fields can be used to improve fertilization strategies, especially for larger fields.

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