The spatial variability of mineral nitrogen content in topsoil and subsoil

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ABSTRACT

Spatial variability of soil mineral nitrogen N_{min} (N-NH_4^+, N-NO_3^-) in a soil profile down to 60 cm was determined in a 19-ha experimental field in Prague-Ruzyně for four years. Winter wheat was grown in the years 2000 and 2001, oats in 2002 and mustard in 2003. Root length distribution and depth of the crops were determined at four locations representing different soil conditions within the experimental field. The coefficient of variation as the measure of the variability of nitrate N in topsoil and subsoil (0–30 and 30–60 cm, respectively) in the experimental years ranged between 18–39 and 20–37%, respectively. It was mostly the same or slightly greater in subsoil than in topsoil in respective years. The variability of ammonium N in topsoil and subsoil ranged between 4–58 and 11–27%, respectively. It was similar in topsoil and subsoil, except for autumn 2000. There was a positive relation between nitrate content in top and subsoil on all sampling terms. We did not find a relationship between N_{min} contents in experimental years. Spatial dependencies were evaluated on the basis of model variogram parameters. The nugget value expressed as a percentage value of the total variogram's sill was used for the class of spatial dependence determination. When a spatial dependence of the observed factor was found it was within a range of medium-strong dependence. Only in two cases a strong spatial dependence was found. A considerable variability was also found out in the variogram's range, which was between 61 and 396 m. All these facts pose a problem for further actions, such as appropriate design of a sampling grid, measured data spatial interpolation and application maps design.

Keywords: mineral nitrogen; N_{min}; spatial variability; kriging; roots; winter wheat; oats; mustard

Soil sampling for N_{min} (N-NH_4^+, N-NO_3^-) is an accepted technique to determine available nitrogen supply after different pre-crops and fertilizer management and to improve N fertilizer recommendations (Geypens and Vandendriessche 1996, Vaněk et al. 1997, 2003). N_{min} content is mostly determined at spring before the start of intensive N uptake. A field-average N_{min} content has been commonly used to determine a uniform rate of N fertilization across the whole field. Only little information is still available about spatial variability of N_{min} in agricultural fields (Ilsemann et al. 2001). Often only N-NO_3^- content in an arable layer was monitored. Geostatistics aimed at detecting, estimating and mapping the spatial pattern of soil and plant variables provides tools for utilizing the information on spatial variability. To interpolate data at unsampled points semivariogram models are used to provide the necessary information for kriging. In Czech conditions Brodský et al. (2001a, b) used the method for agrochemical traits. The only data on mineral nitrogen variability in Czech Republic were published by Šilha and Vaněk (2003).

The use of precision agriculture techniques, as spatially variable N rates, promises improvement of yield, quality and efficiency of N use. Accounting for a variable distribution of N in a soil profile offers additional benefits. Good quality of products is often decisive for a high profit, considering the supply of nitrate leached to deep subsoil and utilized to the end of growth may diminish possible negative effects on the quality of sugar beet or malt barley, and positively affect the quality of wheat grain. Maximizing utilization of nitrate in deep subsoil layers reduces risk of nitrate leaching.

For effective N variable fertilization farmers need to estimate reliably local N supply from soil, nitrogen demand and yield potential (Delin and Lindén 2002, Baxter et al. 2003a, Kersebaum et al. 2003). It is not an easy task as there are both years a local variation of N response curve (Lark and Wheeler, 2003, Kersebaum et al. 2003) caused by interaction with other factors.

The objective of the work was to describe the spatial variability of N_{min} in top and subsoil in

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one field during four years and to estimate the importance of variable subsoil N supply in precision agriculture system.

MATERIAL AND METHODS

Soil mineral nitrogen content N_{min} (N-NH_4^+, N-NO_3^-) was determined in a 16-ha experimental field (Figure 1) in Prague-Ruzyně, Czech Republic (50°05′N, 14°18′E). It is Orthic Luvisol soil with a different share of marl skelet in the subsoil, altitude 340 m a.s.l. Normal precipitation and temperature are 526 mm per year and 7.9°C (1961–1990; data from near airport Ruzyně). The average yearly temperature was extraordinarily above normal and above normal (Kožnarová and Klabzuba 2002) in 2000, 2002 and 2003, respectively. The sum of precipitation was above normal in 2001 and 2002 (only due to flooding in August), below normal and extraordinarily below normal in 2000 and 2003, respectively. The spatial variability of various plant and soil traits has been studied in the field from the year 2000 (Lipavský et al. 2002, Haberle et al. 2003). Winter wheat was grown in the field in the years 2000 and 2001, oats in 2002 and mustard in 2003; winter rape was a preceding crop in 1999. Standard agrotechnics and recommended doses of nitrogen were used throughout the experiment. No organic fertilizer was used from year 1999.

The experimental field was sampled at the same 60 locations (45 in autumn 2000) with the help of global positioning systems (GPS) in a grid with 50 m spacing and in several additional points (Figure 1). Samples were taken from a soil layer 0–30 cm and subsoil layer 30–60 cm in spring 2001, 2002 and 2003, at autumn 2000 and 2002. A deep subsoil layer 60–90 cm was sampled in a limited number of points (12–24) in the experiment. At each location 6–8 (4 from layer 60–90) soil cores were taken within 3–4 m from the centre with gouge auger and soil was mixed to obtain one bulk sample for laboratory analysis. Sampling was done within two days, samples were kept in a cooler during sampling, processed the same or next day, homogenized and grinded where needed; a fraction under 2 mm was analysed. Soil was shaken in 1% K_2SO_4 and 1:5 soil:solution ratio for 1 hour. N-NH_4^+, N-NO_3^- were determined by colorimetry (SKALAR). The concentrations were recalculated to dry weight. Changes of N-NO_3^- in all three layers during wheat growth in 2001 were monitored at twelve selected locations to estimate the distribution of apparent depletion of N from the soil profile. Root length distribution and maximal rooting depth of the crops were determined in four locations after flowering as an indicator of potential depth of nitrogen depletion. The locations were selected to represent different soil conditions of the field (Table 1).

Statistical and geostatistical analysis

The data analysis was carried out for every sampling term. Obtained data on soil N-NH_4^+ and N-NO_3^- and N_{min} contents in top and subsoil were evaluated by standard statistical and geostatistical methods. Coefficients of the variation, skewness and semivariograms were calculated from nitrate, ammonium and N_{min} data in the individual layers. The Kolmogorov-Smirnovovův test was used to test normality of measured values. The experimental and model variograms were created for each sample and the nugget/range ratio was used for a spatial variability expression. Selection of an appropriate variogram model was carried out on the basis of visual assessment, parameters r^2 and RSS. When the ratio was lower than 25% it meant a strong spatial dependence, the ratio between 25 and 75% indicated the dependence of medium strength and all values over 75% showed a very weak dependence (Cambardella and Karlen 1999).

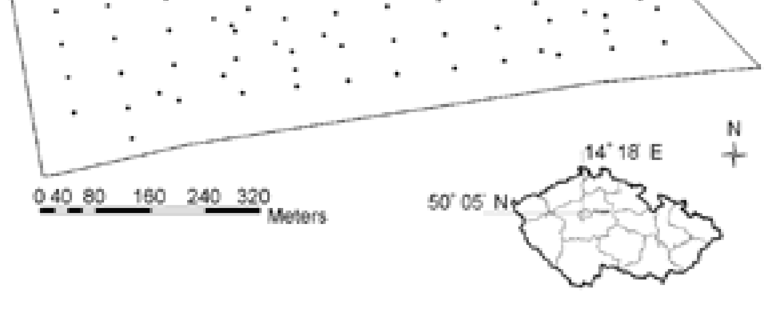

Figure 1. Map of the experimental field in RICP Prague-Ruzyně

Table 1. The soil texture in topsoil and subsoil at selected points where root distribution was observed

Location point	> 2 cm % from total sample	Sand	Fine sand	Silt	< 0.01 mm
		% from soil share under 2 cm			
Layer 0–30 cm					
7	8.2	10.8	15.7	32.4	41.1
9	12.4	11.1	11.1	28.7	49.1
38	5.0	7.5	21.6	31.3	39.6
41	16.2	12.0	15.7	25.7	45.7
Layer 30–90 cm					
7	11.5	26.9	26.6	18.4	28.1
9	20.0	14.6	16.2	17.9	51.3
38	1.3	3.9	13.1	36.7	46.3
41	30.7	16.9	15.8	18.8	48.5

ARC GIS v. 3.2 and 8.3 software with geostatistical modul, GS+ (Gamma Design Software) and statistical programme Unistat were used.

RESULTS AND DISCUSSION

The observed data was analysed statistically; basic statistical parameters are shown in Table 2. The skewness of data was between 1.32 and –0.71 suggesting (near) normal distribution, mostly between 0.00 and 0.60, i.e. the distribution was more right tailed. About two thirds of the data sets had kurtosis under 0 (mostly between –1.00 and 1.00) indicating that the distribution was narrower than a normal one. The test of normality showed that N_{min} and both N forms data had a normal or near normal distribution (not shown). Ilsemann et al. (2001) found asymmetric lognormal frequency distribution of $N\text{-}NO_3^-$ in top and subsoil at two sites and both normal and lognormal ones valid in the third site. Also other authors observed lognormal $N\text{-}NO_3^-$ distributions (e.g. Meirvenne and Hofman 1989) but normal distribution was reported, too (Dahiya et al. 1985, López-Granados et al. 2002).

Variability of N_{min}

The coefficient of variation (*CV*) of nitrate N in topsoil (0–30 cm) and subsoil (30–60 cm) in experimental years ranged between 18–39 and 20–37%, respectively (Table 2). It was mostly the same or slightly greater in subsoil than in topsoil. The variability of ammonium N in topsoil and subsoil ranged between 4–58% (the second highest values being 31%) and 11–27%, respectively. It was similar for top- and subsoil, except for autumn 2000. The minimum and maximum values observed in a layer differed in nitrate up to fivefold. Total N_{min} (0–60 cm) had an always-lower variability than N_{min} content in individual layers. The variability of nitrate content in 60–90 cm was about the same level as in 30–60 cm and higher than in 0–30 cm, that of ammonium was always much lower than in 0–30 cm (not shown). The content of N_{min} in 60–90 cm was mostly greater or about the same level as in 30–60 cm in the experimental years.

Observed variability is in accordance with data reported elsewhere. Ilsemann et al. (2001) observed *CV* of late-fall $N\text{-}NO_3^-$ in 0–90 cm within 1-ha area of fields after cereals in three sites to range from 31 to 36%, Meirvenne and Hofman (1989) 21–31% in a 1 ha field after potatoes in autumn and spring, Dahiya et al. (1985) between 19–23% in spring, Delin and Lindén (2002) 12, 32 and 36% in spring and 14, 28 and 47% after harvest of winter wheat in three years, respectively. Higher values were found by López-Granados et al. (2002) under Mediterranean climate.

There was a positive relationship between nitrate content in topsoil (0–30 cm) and subsoil (30–60 cm) on all sampling terms (r = 0.65, 0.27, 0.62, 0.40 and 0.35, respectively) and consequently a positive relation between N_{min} content in top and subsoil. The relation was not strong and stable enough to predict subsoil N_{min} from topsoil analysis reliably as proposed by Ehrhardt and Bundy (1995). We found a weak or none such a relationship in ammonium nitrogen content (r = 0.23, 0.14, 0.07, 0.03 and –0.13, respectively) and in relation of ammonium N and nitrate N in the same layer (r = –0.26 to +0.27; mostly between –0.11 to +0.10).

Table 2. Basic statistical data on variability of N_{min} (mg/1000 g dry soil) and geostatistics

Date		Layer	No. of samples	Mean	Median	Min	Max	SD	*CV* %	Skew	Ao	Co	Co + C	Model	Co/ Co + C
15.8. 2000	N-NO_3^-	0–30	60	7.05	6.80	3.58	14.78	2.72	39	1.0	128	4.2	8.3	Sph.	50.6
		30–60	–	–	–	–	–	–	–	–	–	–	–	–	–
	N-NH_4^+	0–30	60	0.81	0.78	0.06	1.80	0.32	4	0.32	396	0.04	0.13	Sph.	30.8
		30–60	–	–	–	–	–	–	–	–	–	–	–	–	–
	N_{min}	0–30	60	7.86	7.55	3.91	15.48	2.74	35	0.83	153	5.16	8.6	Sph.	60
		30–60	–	–	–	–	–	–	–	–	–	–	–	–	–
13.11. 2000	N-NO_3^-	0–30	45	12.47	12.65	8.87	18.26	2.30	18	0.55	–	6.02	6.02	P.n.	100
		30–60	45	7.68	6.95	3.43	12.86	2.64	34	0.16	310	5.2	8.2	Sph.	63.4
	N-NH_4^+	0–30	45	0.33	0.30	0.04	0.74	0.19	58	0.58	–	0.02	–	Lin.**	–
		30–60	45	0.47	0.46	0.29	0.72	0.11	23	0.23	–	0.11	0.11	P.n.	100
	N_{min}	0–30	45	12.79	12.94	9.0	18.7	2.32	18	0.54	–	6.17	6.17	P.n.	100
		30–60	45	8.15	7.30	3.84	13.29	2.65	32	0.15	238	4.78	8.2	Sph.	58.3
13.3. 2001	N-NO_3^-	0–30	60	6.42	6.39	3.34	9.81	1.50	23	0.15	–	2.3	2.3	P.n.	100
		30–60	60	12.41	12.86	5.88	20.62	3.28	26	0.13	73	3.5	9.4	Sph.	37.2
	N-NH_4^+	0–30	60	12.17	12.36	6.23	19.68	3.04	25	0.29	–	5.27	11.5	Sph.	45.8
		30–60	60	12.96	12.62	6.7	20.31	2.75	21	0.34	382	7.4	7.4	P.n.	100
	N_{min}	0–30	60	18.6	18.58	10.2	25.74	3.51	19	–0.39	300	11.2	16.4	Gaus.	68.3
		30–60	60	25.37	25.46	12.5	38.37	4.38	17	0	75	11	16.9	Sph.	65.1
3.4. 2002	N-NO_3^-	0–30	60*	7.17	7.03	3.49	13.07	2.15	19	0.32	90.1	2.02	5.24	Exp.	38.5
		30–60	60*	6.01	5.70	2.52	14.29	2.0	33	1.32	339	2.13	5.17	Sph.	41.2
	N-NH_4^+	0–30	60*	17.31	15.72	6	29.91	5.37	31	0.26	61	11.27	32.86	Exp.	34
		30–60	60*	17.92	17.82	8.92	29.48	4.88	27	0.23	–	24.8	24.8	P.n.	100
	N_{min}	0–30	60*	24.48	24.17	10.0	38.25	5.30	22	0.12	100	6.84	31.6	Exp.	21.6
		30–60	60*	23.93	24.47	12.6	35.03	4.76	19	–0.08	–	24.3	24.3	P.n.	100
12.11. 2002	N-NO_3^-	0–30	60	5.63	5.13	2.58	11.36	1.83	33	0.97	276	1.25	4.15	Sph.	30.1
		30–60	60	4.25	3.91	0.85	8.17	1.57	37	0.64	–	2.4	2.4	P.n.	100
	N-NH_4^+	0–30	60	6.56	6.58	4.02	9.8	1.13	17	0.26	–	1.4	1.4	P.n.	100
		30–60	60	7.83	7.68	4.57	14.81	1.76	23	1.04	–	3.2	3.2	P.n.	100
	N_{min}	0–30	60	12.19	12.21	7.99	17.97	2.1	17	0.57	72.3	1.21	5.25	Exp.	23
		30–60	60	12.08	11.94	7.28	17.96	2.29	19	0.32	–	5.3	5.3	P.n.	100
13.4. 2003	N-NO_3^-	0–30	60*	14.67	13.99	8.88	23.37	3.12	21	0.59	180	5.5	9.4	Sph.	58.5
		30–60	60*	7.65	7.70	4.08	12.02	1.63	21	0.15	–	2.7	2.7	P.n.	100
	N-NH_4^+	0–30	60*	6.64	6.77	4.6	8.52	0.72	11	–0.71	69	0.14	0.58	Exp.	24.1
		30–60	60*	7.65	7.70	4.08	12.02	1.63	21	0.15	–	2.3	–	Lin.**	–
	N_{min}	0–30	60*	21.31	20.96	15.8	30.18	3.13	15	0.61	–	9.5	9.5	P.n.	100
		30–60	60*	15.30	15.39	8.16	24.04	3.26	21	0.15	–	9.2	–	Lin.**	–

Ao = range, Co = nugget, Co + C = sill, Sph. = spherical model, Exp. = exponential model, P.n. = pure nugget, Lin.** = linear non-closed, Gaus. = Gaussian model, 60* = points in data file was complemented by 8 additional points

Geostatistical results

The spherical, exponential and Gauss models with nugget were used for the experimental variograms regression. For the experimental variograms, for which it was not possible unambiguously to create a model variogram, the Pure Nugget model and linear not-closed models were used. In the Figure 2, there is an overview of model variograms for the year 2002. The spatial distribution of the data is illustrated in maps. Maps for kriging with the modelled variogram for N_{min} in top 0–30 cm on 3.4.2002 and 12.11.2002 are in Figure 3.

In our experiment, semivariograms did not show differences in spatial dependence based on direction, therefore isotropic semivariograms were chosen. The factors may be important in some cases (Meirvenne and Hofman 1989, Ilsemann et al. 2001). The comparison of a spatial variability, according to nugget, revealed greater differences in behaviour of N_{min} or N-NH_4^+ and N-NO_3^- in the soil. As the Table 2 shows, a strong dependence was observed just in two cases. Most often however, a medium or weak spatial variability were found. While every statistic evaluation was calculated for 60 points in data file (45 in summer 2000), the spa-

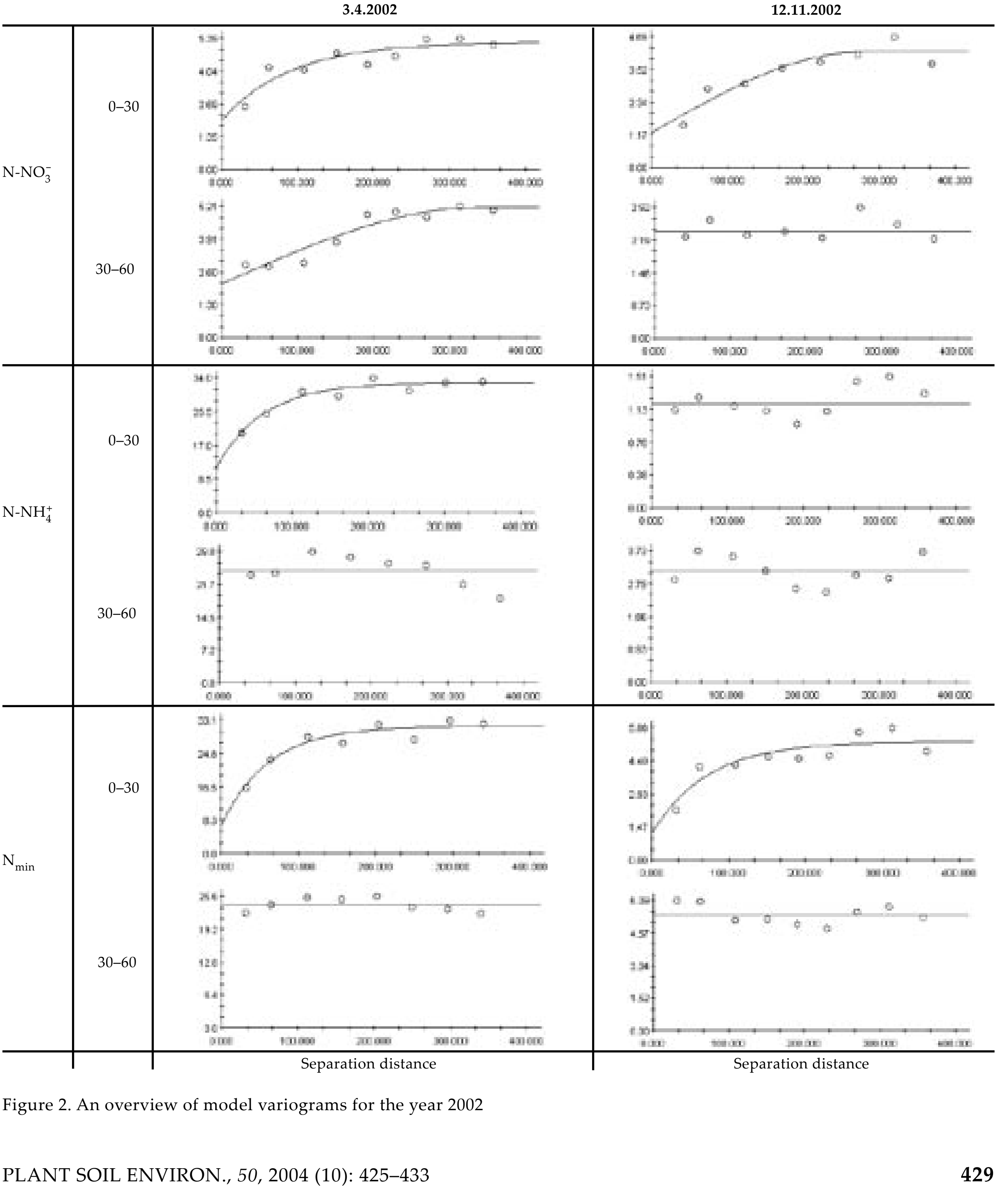

Figure 2. An overview of model variograms for the year 2002

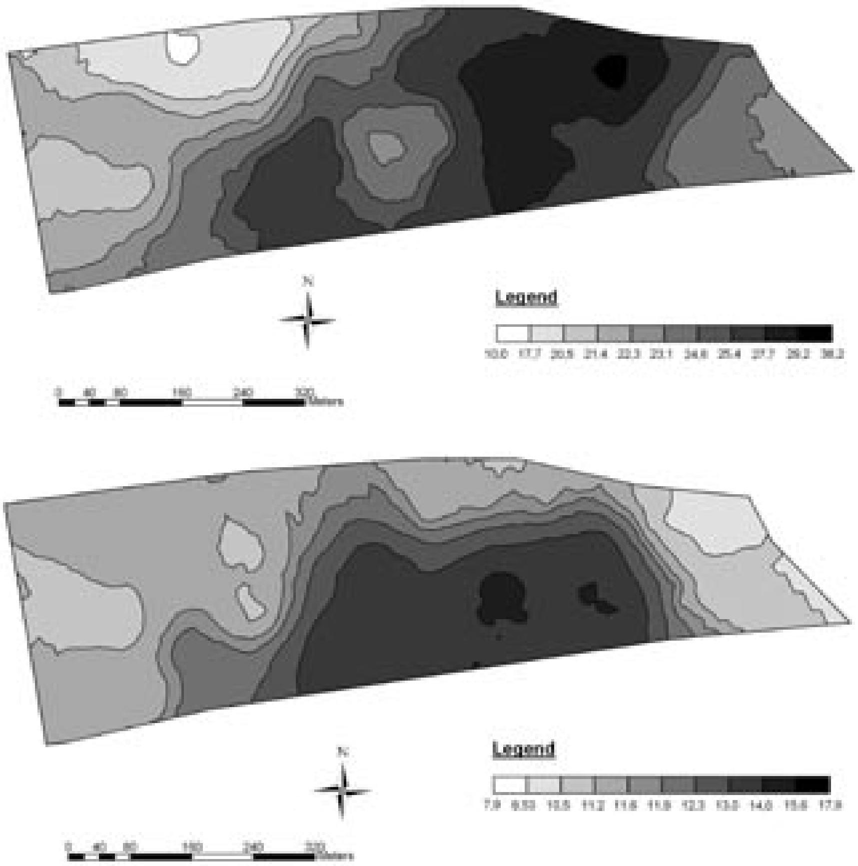

Figure 3. The maps for kriging with the modelled variogram – the spatial distribution of N_{min} in top 0–30 cm on 3.4.2002 (upper) and 12.11.2002 (below)

tial dependencies measurement from 3.4.2002 and 13.4.2003 was complemented by 8 additional points. Better results in spatial dependence description were achieved only in the year 2002. This fact has proved conclusions about considerable variability of observed soil properties.

The evaluation of the variograms range showed values from 61 to 396 m for particular data files. Lower values were caused mainly due to exponential model use, when the sill value was derived from a mathematical calculation. High differences in the separation distance and differences in spatial variability of observed soil properties are quite a big problem for an optimal sampling grid design. There are big differences among the ranges of spatial dependence for mineral nitrogen given

Table 3. Statistical residue characteristics of estimation by kriging interpolation method (0–30 cm)

	3.4.2002			12.11.2002		
	N-NO$_3^-$	N-NH$_4^+$	N_{min}	N-NO$_3^-$	N-NH$_4^+$	N_{min}
Mean value	0.02	–0.11	–0.07	–0.03	–0.01	–0.08
Median	0.01	–0.46	–0.45	0.01	–0.05	–0.45
MSE	2.17	5.01	4.87	1.47	1.16	1.83
RMSE	4.73	25.14	23.71	2.16	1.35	3.35
Skew	0.14	0.30	0.19	0.62	0.56	0.70
Correlation coefficient	0.47	0.84	0.84	0.98	0.18	0.94
Coefficient of determination	0.04	0.14	0.17	0.36	0.00	0.25

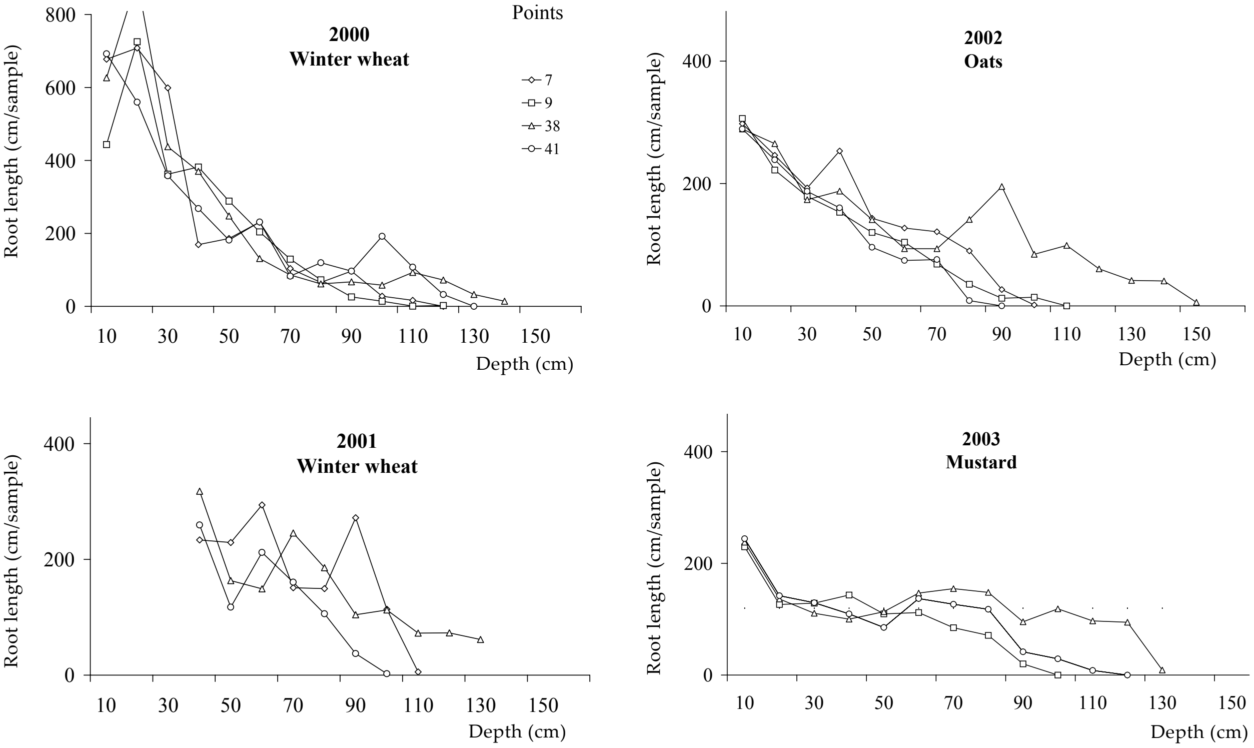

Figure 4. The root distribution of winter wheat, oats and mustard in selected points

in literature. López-Granados et al. (2002) observed a lack of spatial dependency for N-NH$_4^+$ at two depths and sites but strong or moderate spatial dependence with range 16.5–66 m of N-NO$_3^-$ in layer 0.25–0.35 m. Baxter et al. (2003b) found ranges 53 and 69 m for nitrate content in two sites and no spatial dependence until the trend in data was removed in the third site. Ilsemann et al. (2001) did not detect a range at three sites and they conclude that minimum distance between sampling positions was obviously too large to observe effects of small scale variability. Also Dahiya et al. (1985) reported no spatial correlation of soil N-NO$_3^-$. Meirvenne and Hofman (1989) observed ranges 9.5, 23 and 34 m for their data. Simard et al. (2001) using a grid 30 × 30 m found that unlike indicators of N mineralization (clay, organic matter) soil nitrate in spring was not spatially structured.

The variability structure is also very important for the quality of further interpolation. In our case the interpolation method of kriging was used. The estimated relevance was confirmed by a comparison between measured values and values which were estimated by means of the Cross-validation method. Statistical characteristic of possible interpolation method's errors for estimated values were obtained. Table 3 shows an overview of the statistical residue characteristics for selected data files with a different variogram structure. According to Brodský (2004), the residues distribution or their mean values are very important to be equal to zero and the value of mean square error (MSE) and root mean square error (RMSE) should be very small. In evaluated files, the average value of residues was very close to zero. A little increase in mean values was observed in N-NH$_4^+$ and N$_{min}$ data files from 3.4.2002 and N$_{min}$ from 12.11.2002. We can also see an increased asymmetry of mentioned files.

The quality of interpolation method is also possible to evaluate according to the correlation coefficient *R*, which tests and compares measured and predicted values. Table 3 also shows that the correlation ratio very closely coheres with the variogram structure or with spatial dependence value (Co/Co + C). The higher value of this relation is the lower correlation coefficient *r*. The coefficient of determination, which characterises tightness of residues regression with the regression line, had quite low values. It was also proven by extreme values of residues in selected files.

Root growth

Roots of both cereals penetrated under 130 cm in point 38 while in the others reached from 80 to 110 cm; the root depth of mustard in 2003 was also greater in point 38 (Figure 4). The location had a higher content of silt and lower one of stones and sand (Table 1). The depletion of readily available nitrate N from topsoil down to 90 cm was indicated by its successive decrease during growth of wheat in 2001 (not shown). The root depth and the apparent depletion of nitrogen were in agreement with data obtained for winter wheat in near field (Haberle and Svoboda 2000, Svoboda et al. 2000). Our results suggest that the spatial variability of deep subsoil N might contribute to variability of growth of the crops. Stofel et al. (1995) found also a variation of root length density in winter wheat and spring barley measured in 50 × 50 m grid, however, they did not find a correlation between root growth of wheat and barley at the same grid points in two years, respectively, and between root growth and soil parameters (soil depth, sand content).

The plant itself is the best indicator of nitrogen availability supposing that the effect of other growth and uptake limiting factors can be reliably estimated. The nitrogen status of a crop reflects the nitrogen supply of top layers that were already occupied, and in young plants it may not be a good predictor of N supply in deep layers for the rest of growth period (Svoboda et al. 2000). Evidently, extensive sampling of the topsoil and especially of the subsoil for N_{min} is impracticable. An empirical relationship of soil N content and depth distribution with other factors and mathematical models may be a solution (Delin and Lindén 2002, Baxter et al. 2003b, Kersebaum et al. 2003).

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ABSTRAKT

Prostorová variabilita obsahu minerálního dusíku v ornici a podorničí

V letech 2000–2003 byla na 19 ha pozemku v Praze-Ruzyni určena prostorová variabilita minerálního dusíku N_{min} (N-NH_4^+, N-NO_3^-) v půdě do hloubky 60 cm. Na pozemku byla pěstována ozimá pšenice (2000, 2001), oves (2002) a hořčice (2003). Koeficient variability nitrátového N v ornici (0–30 cm) a podorničí (30–60 cm) se ve sledovaných letech pohyboval mezi 18–39 a 20–37 %. Variabilita amonného N v ornici a podorničí byla v rozmezí 4–58 a 11–27 %. Ve všech pokusných letech byl zaznamenán kladný vztah mezi obsahem nitrátového N v ornici a podorničí. Nebyl pozorován vztah mezi obsahem minerálního N mezi jednotlivými ročníky. Prostorová závislost byla hodnocena na základě modelových parametrů variogramů. Hodnota prostorové závislosti, vyjádřená jako podíl zbytkového rozptylu (nuggetu) z hodnoty prahu variogramu (sill), byla použita pro určení třídy prostorové závislosti. Silná závislost byla nalezena ve dvou případech. Rozsah variogramu (range) se pohyboval mezi 61 a 396 m.

Klíčová slova: minerální dusík; N_{min}; prostorová variabilita; kriging; kořeny; ozimá pšenice; oves; hořčice

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