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ALUMINUM-BASED WINTER WHEAT BIOMASS AND GRAIN YIELD SPATIAL VARIABILITY IN ARABLE SOILS: CONCEPT AND FIELD TEST

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Abstract

The paper outlines a concept related to selecting a site for experimental purposes. Selection of an experimental plot most frequently relies on performing visual evaluation of a given site, followed by the establishment of a field trial. In general, the question of geochemical variability is 'intentionally' postponed! Verification of this approach has been undertaken, testing such parameters as soil pH and exchangeable aluminum (Al_{ex}) versus spatial (investigated area, 12 672 m^2) and downward (sampling depths, i.e., 0-20, 20-40 and 40-60 cm) distribution. Winter wheat biomass at tillering (BBCH29) and grain yield at harvest (BBCH99) were additionally considered. The results have revealed that pH values fluctuated between 3.6 and 4.4 with respective coefficients of variation (CV) ranging from 3.10 to 5.92%. The concentrations of Al_{ex} ranged from 38.0 to 144.9 mg kg^{-1}, corresponding to CV within 28.34 and 44.03%. The variograms and geostatistical maps have demonstrated the spatial as well as downward variability of these parameters. The spatial distribution of plant biomass followed quite closely the exchangeable aluminum (Al_{ex}) levels, which implies that natural soil parameters such as Al_{ex} are not easily compensated for by agricultural practices, for instance nitrogen application. The spatial *grain yield* – Al_{ex} dependence which emerged at harvest confirmed the variability observed at tillering (BBCH29). Thus, the spatial variability of pH, Al_{ex} and wheat biomass as well as grain yields (BBCH99) verified the approach to selecting an experimental site. It was demonstrated that selection of a research site on the basis of its appearance and shape alone may lead to misinterpretation of experimental results.

Key words: exchangeable aluminum, pH, wheat biomass, grain yield, spatial variability, geostatistics.

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WPŁYW GLINU NA PRZESTRZENNĄ ZMIENNOŚĆ BIOMASY I PLONU ZIARNA PSZENICY OZIMEJ NA GLEBACH UPRAWNYCH: KONCEPCJA I BADANIA TERENOWE

Abstrakt

Praca przedstawia koncepcję związaną z wyborem stanowiska na cele doświadczalne. To podejście opiera się na częstej ocenie wzrokowej danego stanowiska, a dalej – założeniu doświadczenia polowego. Zmienność geochemiczna bywa generalnie „celowo” odłożona! Przedstawioną koncepcję zweryfikowano za pomocą parametrów, takich jak pH oraz zawartość glinu wymiennego (Al_{ex}), pod względem przestrzennym (pole badawcze 12 672 m^2) i w głąb profilu glebowego (warstwy gleby: 0-20, 20-40 i 40-60 cm). Następnymi parametrami do opracowania przestrzennej zmienności były biomasa pszenicy ozimej w fazie krzewienia (BBCH29) oraz plon ziarna w fazie dojrzałości pełnej (BBCH99). W badaniach wykazano, że wartości pH wahały się między 3,6 a 4,4, a odpowiednie współczynniki zmienności (CV) wynosiły 3,10-5,92%. W przypadku Al_{ex}, jego zawartość zmieniła się w szerokich granicach (38,0-144,9 mg kg^{-1}), co odpowiadało wartościom CV od 28,34 do 44,03%. Opracowane wariogramy oraz mapy geostatystyczne wyraźnie podkreślały zmienność zarówno przestrzenną, jak i w głąb profilu glebowego badanych parametrów. Przestrzenne rozmieszczenie biomasy roślinnej postępowało zgodnie z zawartością Al_{ex}. Oznacza to, że naturalne czynniki glebowe, jak Al_{ex}, nie są łatwo zrównoważone zabiegami agrotechnicznymi, np. nawożeniem azotowym. Przestrzenna zależność: plon ziarna – Al_{ex}, która ujawniła się w fazie żniw, potwierdziła zmienność zaobserwowaną w fazie krzewienia (BBCH29). Zatem przestrzenna zmienność pH, Al_{ex} oraz zarówno biomasy pszenicy, jak i plonów ziarna (BBCH99) zweryfikowały koncepcję związaną z wyborem stanowisk na cele badawcze. Wykazano, że wybór stanowiska badawczego oparty tylko na wyglądzie terenu i jego kształcie może doprowadzić do błędnej interpretacji danych eksperymentalnych.

Słowa kluczowe: glin wymienny, pH, biomasa pszenicy, plon ziarna, zmienność przestrzenna, geostatystyka.

INTRODUCTION

The evaluation of agricultural practices requires good knowledge of mechanisms which control the geochemistry of minerals and interact with soil spatial variability (BUCHTER et al. 1991, DIIWU et al. 1998, HUANG et al. 2001, KIRCHMANN, THORVALDSSON 2000). The growth of crops is conditioned mainly by natural factors, of which climate and soil cover are dominant. For instance, poor soil fertility prevents crops from reaching the maximum growth and therefore impairs yields (KATYAL 2003). There have been reports that poor soil fertility leads to sparse plant cover, which promotes erosion, especially that 90% of plant available N and S, 50-60% of K, 25-30% of P and almost 70% of micronutrients are found in organic matter (STEVENSON, COLE 1999, PUGET, LAL 2005, DOLAN ET al. 2006, MAIA et al. 2010). It is commonly held that samples taken close to one another have more similar properties than distant ones. However, classical statistics, where measured data are independent, is not in line to analyze the spatial dependency of a variable (BREJDA et al. 2000). At present, tools are needed to evaluate soil resources in terms of spatial and temporal changes in soil quality in order to ascertain sustainability of farm practices (CORVIN, LESCH 2005, FLORIN et al. 2009).

The advent of precision agriculture and the environmental impact of excess nutrients encourage the application of geostatistical procedures for describing physical and chemical parameters and, on the other hand, nutrient spatial distribution in arable areas (YANG et al. 1995, NEWMAN et al. 1997, BORUVKA et al. 2005, VERMA et al. 2005, YANG, ZHANG 2008, DONG et al. 2009).

Traditionally, a field is regarded as a homogeneous unit. Thus, the agricultural practice and levels of inputs are basically uniform across a whole field, although it has long been known that yields can vary greatly within a field and that the intra-field yield variation is caused by variation in soils, years and soil x year interactions (MERCER, HALL 1911, JOERNSGAARD, HALMOE 2003, PANAYIOTOPOULOS et al. 2004). Selection of an arable area for experimental trials continues to be a challenge due to several constraints, i.e. (i) preceding crops, (ii) size of plots, (iii) date when a field trial begins, (iv) tillage characteristics, (v) soil physical and chemical 'homogeneity'. Whereas points (i) to (iv) are mostly modifiable and controllable, it appears that a more complex point (v) needs some operational approach, which will minimize (intentionally) soil heterogeneity. Therefore, the subjective assumption implying that an experimental area is morphologically homogeneous (except a slope), and therefore is expected to comply with experimental principles, has been broadly accepted. The same concerns mineral elements, including plant nutrients, generally considered geochemically homogeneous, both spatially and downward. Chemical soil tests performed before a field trial deal most specifically with liming evaluation and/or supplementation with macro- and micronutrients, but are less concerned with their in-field variability. The latter, however, is practically decisive for assessing plant biomass and yield stability structure on a small or large scale.

Acid soils are frequently low in calcium and magnesium but contain appreciable concentrations of aluminum in exchangeable and/or active forms. The problem of nutrient supply to growing crops surpasses the question of balanced amounts of applied fertilizers, as it also involves crop accessibility to soil natural nutrient pools (JANIK 2008, WŁODARCZYK et al. 2008). The latter is strictly connected with the growth of the root system in soil. There are some factors limiting roots' accessibility to nutrients even in soils of high natural fertility, the most important ones being soil acidity and related aluminum phytotoxicity (KIDD, PROCTOR 2001, ATKINSON et al. 2005). Spatial distribution of soil reaction (i.e. pH) and aluminum may probably reflect yield and plant biomass characteristics.

The purpose of the current paper has been to outline the problem of field variability that experimenters frequently face when selecting a site for trials. Most specifically, soil pH and exchangeable aluminum concentrations were the parameters considered in this study. The verification of this concept was additionally undertaken by applying geostistical tools for evaluating winter wheat biomass at tillering (BBCH29) and grain yield at harvest (BBCH99).

MATERIAL AND METHODS

Field description

The experimental site was selected in the late summer 2006 and field trials were established at the same time in Gluszyna Lesna (52°14, N and 16°56, E), on a 300 hectare agricultural farm near Poznan (Poland). Soils under these trials belong to the agronomical categories comprising soils from IV to V classes, i.e. mostly sandy ones, vulnerable to chemical degradation, with low pH and relatively high concentrations of exchangeable and active forms of aluminum. The site for establishing the field trial was selected 'visually' by surveying the whole area (i.e. 300 ha) – Photo 1.

A site of 144 m x 88 m (i.e. 12 672 m^2) was delimitated and divided into 16 plots of 30 m x 22 m (i.e. 600 m^2). Technical paths occupied 3072 m^2.

Photo 1. Area selected 'visually' for a field trial

Soil samples (initial samples) were collected at the depths 0-20, 20-40 and 40-60 cm within the respective 16 plots under the preceding crop (late summer, Photo 1) before agricultural practices (i.e. tillage, and winter wheat sowing, Photo 2). Next, in the early spring 2007, the whole experimental site was divided into 200 subplots (4 m x 12 m), where nitrogen (ammonium nitrate) was applied in a dose of 120 kg ha^{-1} split as follows: 60 kg at regrowth and 60 kg at ear formation. Soil and plant samples were additionally collected at tillering (BBCH29) and at harvest (grain yields, BBCH99).

Photo 2. Experimental site preparation. 'Visually' homogeneous

Soils chemical analysis

Prior to chemical analyses, soil samples were air-dried, crumbled to pass through a 1.0 mm screen and stored in plastic bags. The pH was determined potentiometrically according to Polish Standard (1994) in 1.0 mol KCl dm^{-3}. Exchangeable aluminium (Al_{ex}) was determined according to LOGAN et al. (1985) and FILIPEK (1999), by applying 1 mol KCl for displacing Al ions. Recovered extracts were divided into two aliquots, of which one was directly titrated to determine the concentrations of H and Al, whereas the other one was titrated after Al precipitation with NaF. Exchangeable Al was obtained from the difference between these chemical tests. All analyses were performed in duplicates.

Geostatistical analysis

Data analyses were conducted in three steps: 1) normality tests (Kolmogorov-Smirnov test); 2) distribution by classical statistics (mean, minimum, maximum, standard deviation, coefficient of variation, skewness, kurtosis); 3) contour maps showing the spatial distribution of each tested variable. The best results were obtained by applying semivariogram analysis. In our study, the number of observations at the onset of the field trial was 16, for both pH and exchangeable aluminum (Al_{ex}) in each layer of soil. In such a case, the minimum curvature methods generally give good results. The principle of minimum curvature is two-dimensional interpolation, which allows drawing reasonable maps of geophysical data. As Briggs puts it, 'results are' not always as a draftsman would have them, but are an adequate substitute in most cases' (Briggs 1974). Spatial variability with interdependence is commonly described with a semivariogram (Warrick et al. 1986, Goovaerts 1997, Webster, Oliver 2001). In geostatistics, the concept of variance from classical statistics is extended to semivariance. Considering a field experimental site with equally spaced samples and measurements of soil properties Z, a set of values $Z(x_1)$, $Z(x_2)...Z(x_n)$ at location x_1, x_2, x_n were obtained. The semivariance $\gamma(h)$ is estimated as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=l}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where:

$N(h)$ is the number of pairs separated by lag distance h; $Z(x_i)$ is a measured sample value at point i; and $Z(x_i + h)$ is a measured sample value at point $i + h$.

Semivariograms, which graph the semivariance between spatially separate data points as a function of the distance, are well documented, particularly for the spatial relationship of soil properties (Warrick et al. 1986, Buchter et al. 1991, Bocci et al. 2000, Fu et al. 2010). The creation of a semivariogram requires a large number of observations. The number of samples of plant biomass at tillering (BBCH29) and grain yield at harvest (BBCH99) was 200. The same applied to the exchangeable aluminum (Al_{ex}) content at both growth stages. A set of geostatistical maps is reported in the current paper.

RESULTS AND DISCUSSION

Soil pH – spatial and downward variability

The most striking finding about the soil of the experimental site was that it was very acid even far in the depth (Table 1) and the pH values

Table 1

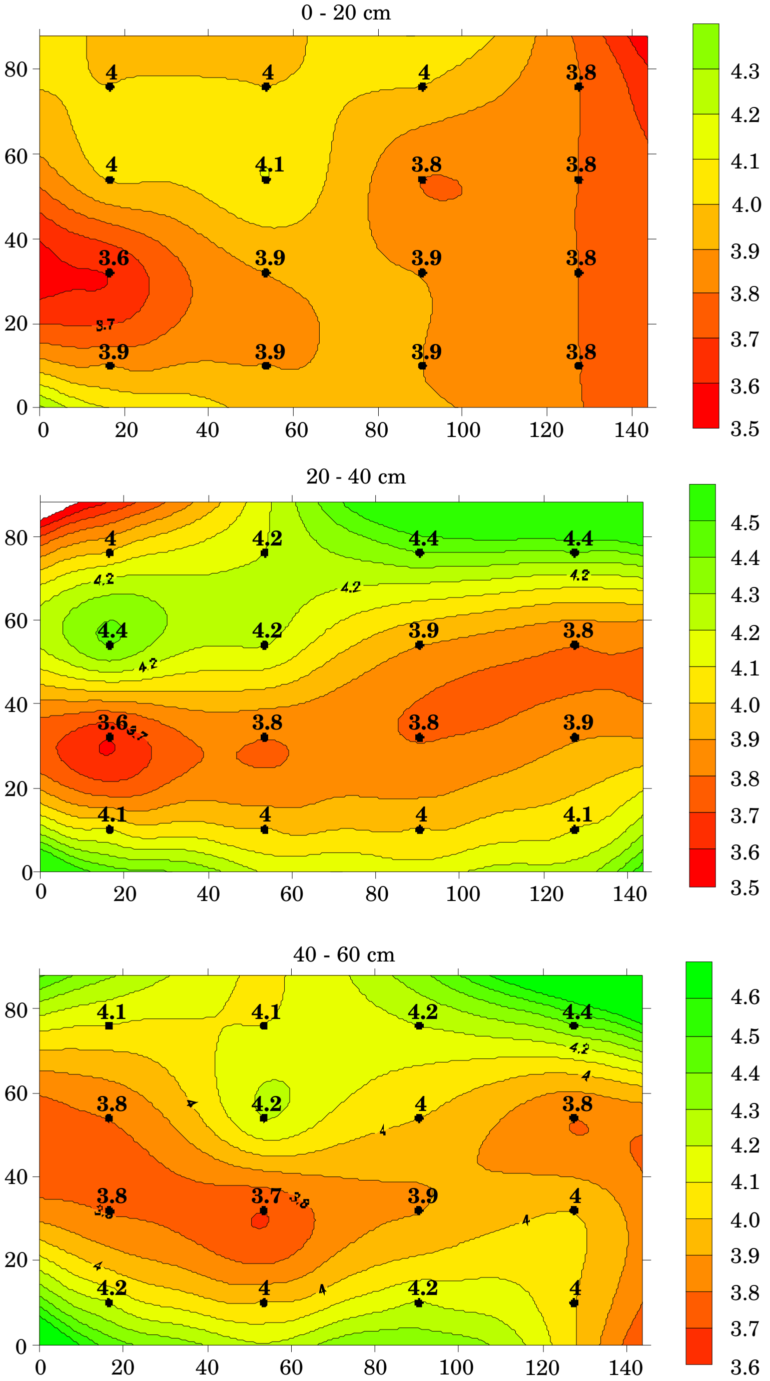
Statistical parameters for pH values within the experimental site (n=16)

Depth (cm)	Mean	Median	Min.	Max.	SD[a]	CV[b] (%)	Skewness	Kurtosis
0 – 20	3.9	3.9	3.6	4.1	0.12	3.10	-0.52	0.94
20 – 40	4.0	4.0	3.6	4.4	0.24	5.92	0.13	-0.66
40 – 60	4.0	4.0	3.7	4.4	0.19	4.76	0.05	-0.55

a – standard deviation; *b* – coefficient of variation

showed limited spatial variability. These observations were supported by the coefficients of variation (CV) ranging from 3.10 to 5.92% for the whole investigated area. This was practically unexpected for such a relatively large area (*ca* 12 672 m^2) subjected to intensive agricultural practices for a year. As it could be observed, the skewness is close to zero, which – along with the median quite similar to the mean – implies that the distribution of pH values within the soil layers is symmetric to the mean value. The same applies to kurtosis, which in fact assumed values different from zero. Therefore, it can be claimed that the distribution of pH values for a given depth does not differ from the normal distribution.

Such spatial distribution of pH values implies that pH homogeneity (*inter alia*) should not be strictly taken into consideration when establishing a field trial. According to YANG et al. (1995), conventional pH measurements treat soil pH as a random, independent variable for providing the mean pH of soil samples. This is assumed to represent the unsampled neighborhood. However, the measurement will be inadequate if spatially dependent heterogeneity of the soil property exists among the samples. Surface horizons are considered to exhibit more sensitivity to external influence (acid deposition, liming, N-fertilization) and their spatial variation is stronger (BORUVKA et al. 2005). But in the deepest mineral horizons, the effect of pedogenetic processes is more important, so it is difficult to clearly distinguish between effects of the particular factors. This has been illustrated by the spatial distribution of pH values as shown in Figure 1 for the layers 0-20, 20-40 and 40-60 cm. Moreover, correlation coefficients established for pH values between investigated soil layers exhibited the following values: 0-20 cm *versus* 20-40 cm: r=0.59; 20-40 cm *versus* 40-60 cm: r=0.62. It means, that pH values in the soil layer 0-20 cm are significantly positively correlated with those recorded for the 20-40 cm layer. The same applies to 20-40 cm and 40-60 cm.



0 - 20 cm

20 - 40 cm

40 - 60 cm

Fig. 1. Spatial distribution of pH in the investigated area (88 m x 144 m)

Variability of exchangeable aluminum (Al_{ex})

The verification of the concept was closely dependent on the concentrations of exchangeable aluminum (Al_{ex}) in soils within the investigated area. It was assumed that any chemical changes related to soil reaction (pH) may be directly reflected by correspondingly high or low Al concentrations. Moreover, the geochemistry of this metal in arable soils is strictly connected to its harmful impact on plants and this could be potentially expected under such extremely acid growth conditions as the ones in our study.

Table 2 contains detailed data on Al_{ex} spatial variability. Noteworthy is a wide range of the Al_{ex} content, especially in the deepest layer, i.e. 40-60 cm (27.20-144.90 mg kg^{-1}), unlike in the upper horizon 0-20 cm (38.00-96.00 mg kg^{-1}). Aluminum spatial variability (Figure 2) is well expressed by high coefficients of variation, whose values for the layers 20-40 cm and 40-60 cm are double the ones in the 0-20 cm layer. The positive skewness and the fact that the medians were lower than the mean values are a proof of non-symmetrical Al_{ex} distribution within particular soil layers. The acidification as reported above is quite similar throughout the whole investigated soil profile. This implies that chemical reactions in upper soil layers directly influence geochemical processes located downward (RÖVER, KAISER 1999). The same may be expected for aluminum, since its leaching or mobility in soil is strictly controlled by pH. Correlation coefficients obtained for the pairs 0-20 cm *versus* 20-40 cm and 20-40 cm *versus* 40-60 cm were respectively: r=0.72 and r=0.40. In practice, these results deserve attention when establishing a young plant stand within the layer 0-40 cm. While planning the horizontal (spatial) and vertical (downward) management of these soils, we must take into consideration the actual 'non-homogeneity' of the soil.

Table 2

Statistical parameters for aluminum content within the experimental site (n=16)

Depth (cm)	Mean	Median	Min.	Max.	SD[a]	CV[b] (%)	Skewness	Kurtosis
	(mg kg^{-1})							
0 – 20	61.79	56.15	38.00	96.00	17.51	28.34	0.62	-0.64
20 – 40	58.86	55.20	29.00	117.70	24.59	41.79	1.00	0.80
40 – 60	71.56	67.00	27.20	144.90	31.50	44.03	0.92	0.56

a – standard deviation; *b* – coefficient of variation

The spatial studies that are most often cited deal with large or very large areas considered to represent a given soil or plant parameter (HUANG et al. 2001, TURGUT et al. 2008, KOBIERSKI et al. 2011). This approach has been exploited for several reasons, e.g. (i) the magnitude of an area to be investigated, (ii) reliability on previously elaborated soil agronomical classes, and (iii) *intentional* assumption that the area is homogenous! Such consider-

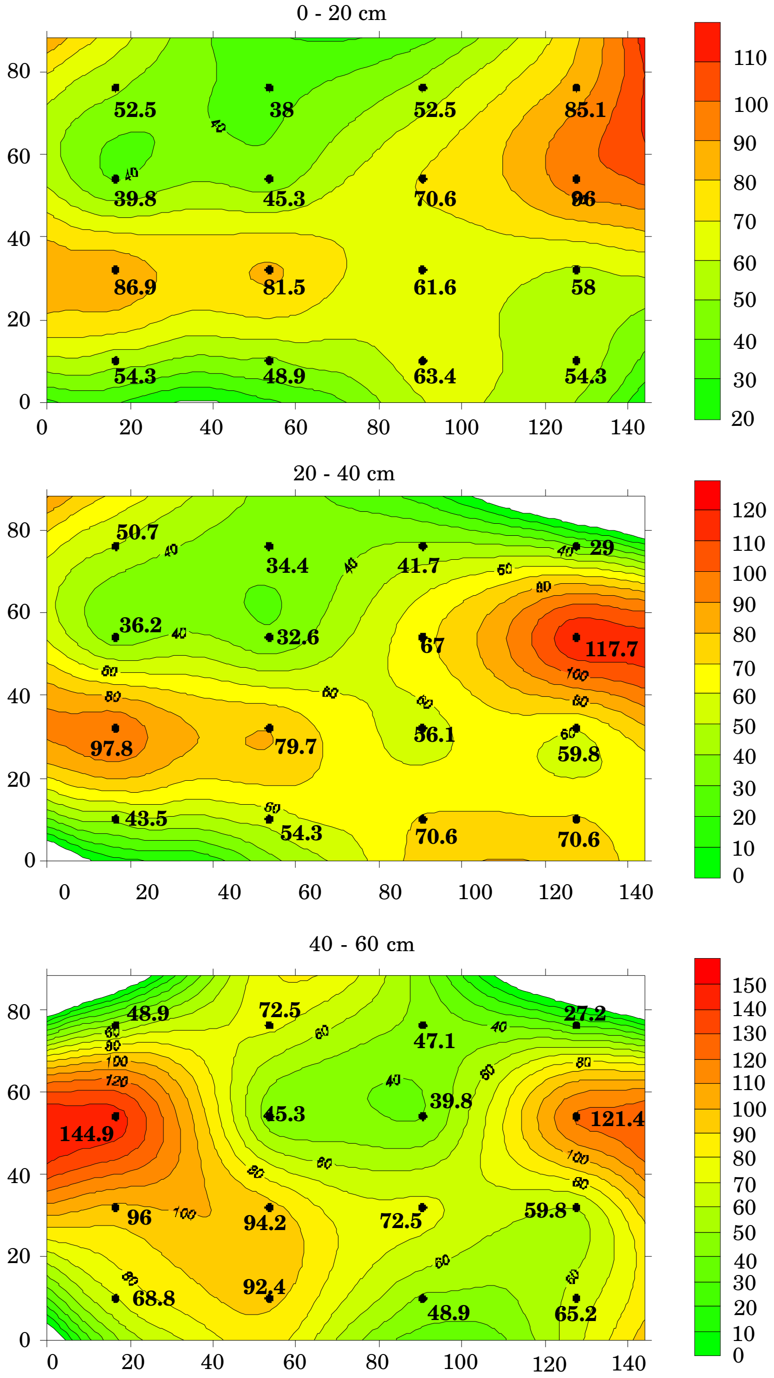


Fig. 2. Spatial distribution of exchangeable aluminum – Al_{ex} (mg kg^{-1}) in the investigated area (88 m x 144 m)

ations may be disastrous in terms of plant response to Al phytotoxicity and further disorders in the plant growth. On average, the coefficient of variation (CV) is *ca* 40%, which seems relatively high for an area of 12 672 m^2. The spatial variability of exchangeable aluminum (Al_{ex}) within such a relatively small area confirmed that the concept of selecting an experimental site most frequently based on visual appreciation/selection followed by agricultural practices may explain the up-to-date irregularities in harvested crops (Bouma 1997, Sawyer et al. 2004).

Aluminum-induced biomass and grain yield spatial variability

Two phenological stages have been selected for this purpose, i.e., tillering (BBCH29) – Figure 3, when winter wheat growth is intensive, and har-

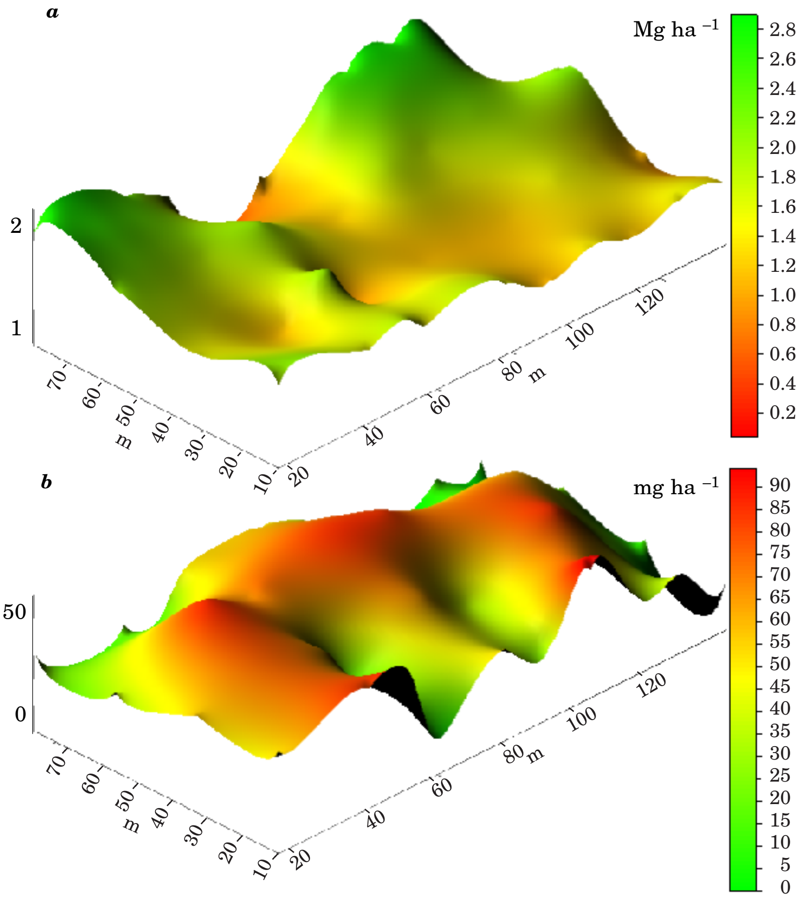


Fig. 3. Spatial variability of winter wheat biomass at tillering (*a*) and exchangeable aluminum (Al_{ex}) at the same growth stage (*b*)

vest (BBCH99) – Figure 4, so as to obtain a more detailed view on grain yield spatial distribution. As shown in Figure 3, the plant biomass spatial distribution resembled the distribution of exchangeable aluminum (Al_{ex}) concentrations, implying that natural soil parameters such as aluminum are not easily compensated for by agricultural practices, for instance nitrogen application. The distribution of both variables, i.e. winter wheat biomass and Al_{ex}, is spatially dependent. It seems that the visual homogeneity, previously considered as a site selection criterion, may not give a true picture of intra-field variability, which affects wheat biomass. For example, most of

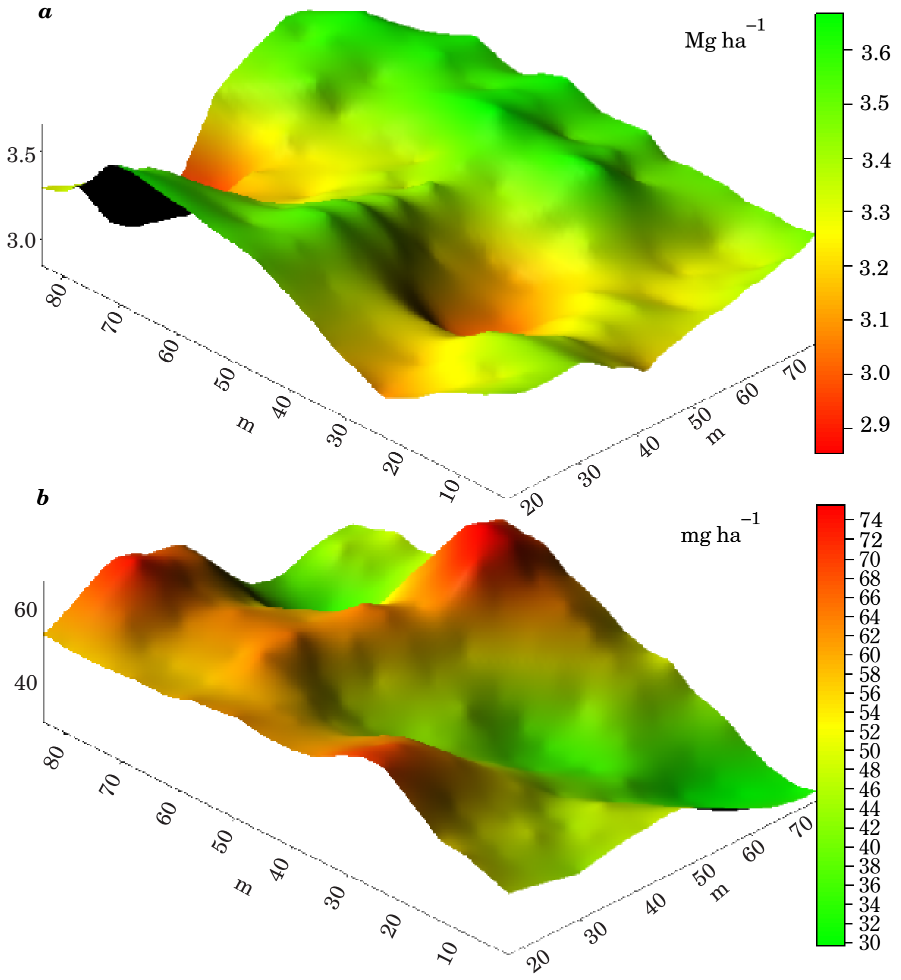


Fig. 4. Spatial variability of winter wheat grain yields at harvest (*a*) and exchangeable aluminum (Al_{ex}) at the same growth stage (*b*)

the high positions expressing the highest biomass corresponded with the lowest zones of Al_{ex} concentrations. This implies that biomass spatial variability was closely dependent on exchangeable aluminum concentrations, i.e., naturally controlled.

Studies dealing with spatial variability of wheat yields are scarce (Mohammadi 2002, Washmon et al. 2002, Casa, Castrignanň 2008) as compared to those concerning soil chemical properties, for instance plant nutritional status. The *grain yield* – Al_{ex} spatial dependence (Figure 4) which emerged at harvest is a topic rarely investigated by soil scientists or agronomists. The maps shown in Figure 4 were drawn by using the kriging method and parameters of semivariograms are summed up in Table 3. Until now, extension services have dealt with field heterogeneity by elaborating composite soil samples consisting of a number of cores collected from 'visually homogeneous' agricultural lands. This practice 'intentionally' excludes spatial variability, first from soil chemical properties and next from plant biomass as well as yields (roots, grains). Yield increase and/or decrease is a direct consequence of inherent aluminum spatial variability, which most frequently is not included in a crop production forecast.

Table 3

Parameters of theoretical semivariograms (n=200)

Parameter	Semivariogram	Nugget C_0	Scale C	Sill $C+C_0$	Range	Anisotropy	
						ratio	angle
		(mg kg^{-1})^2			(m)	(°)	
Exchangeable aluminum	spherical	912	240	1152	29.7	1	0
Wheat grain yields	exponential	(Mg ha^{-1})^2			34.9	2	106.2
		0.06	0.07473	0.13473			

CONCLUSIONS

1. The experimental site for verifying the concept was selected *via* visual observation. This approach imitated *in situ* conditions frequently faced by field experimenters and agronomists.

2. The data have shown that pH values fluctuated between 3.6 and 4.4 with coefficients of variation (CV) ranging from 3.10 to 5.92%. In the case of Al_{ex}, its concentrations ranged from 38.0 to 144.9 mg kg^{-1}, corresponding to CV within 28.34 and 44.03%.

3. Variograms and geostatistical maps generated on the basis of pH and Al_{ex} have emphasized the spatial as well as downward variability of these parameters. These characteristics outline the complex nature of biogeochemical reactions in arable soils.

4. Plant biomass spatial distribution resembled the distribution of exchangeable aluminum (Al_{ex}) levels. The spatial variability of Al_{ex} and wheat biomass (BBCH29) as well as grain yields (BBCH99) rather than pH variability confirmed our concept related to the selection of sites for experimental purposes.

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