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MAPPING OF SOIL CONDITIONS IN PRECISION AGRICULTURE*

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A b s t r a c t. The present paper verifies the efficiency of the method for electrical conductivity (EC) measurement for the assessment of spatial variability of soil properties in precision agriculture. The verification was carried out in a 53-ha experimental field situated in South Moravia, Czech Republic. EC was measured using the EM-38 (Geonics Ltd, Canada) in 2004 and 2005. At the same time, topsoil samples were taken for agrochemical analyses of P, K, Mg, Ca, humus content and pH value, and for soil texture analysis. A strong correlation between years of EC measurements ($r^2 = 0.936$) was found, which confirms the stability of EC measurement from a short-time point of view. Strong relationships between EC and clay content ($r^2 = 0.548$) as well as sand content ($r^2 = -0.406$) confirm the influence of soil texture on EC. Furthermore, almost all examined agrochemical characteristics (P, K, Mg content and pH value) and humus content show relatively balanced, moderately strong correlations with EC. It indicates that the soil EC measurement is a suitable tool for mapping field spatial variability of soil conditions. This information can be used mainly for directed sampling when locations of soil sampling points are determined by preliminary knowledge of field heterogeneity – EC maps. In contrast to traditional grid sampling, reduction in soil samples and at the same time keeping the level of soil maps details can be expected.

K e y w o r d s : soil electrical conductivity, spatial variability, precision agriculture

INTRODUCTION

Knowledge of soil properties is one of preconditions for good agronomic decision making. In traditional agriculture, the most common practice is to get this information by soil sampling, but the use of this method in precision agriculture is much more cost

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and technology consuming. This is the reason why new methods are still required. They enable mapping spatial variability of soil conditions with adequate spatial distribution, measurement accuracy, high interpretability of measured values, and they are less cost and labour consuming than traditional methods. One of these methods is the measurement of soil electrical conductivity (EC).

The measurement of the EC enables quick and relatively exact identification of differences in soil substrate using geophysical soil properties. This is a technique that has become an essential tool for identifying soil physicochemical properties influencing crop yield patterns and for establishing the spatial variation of these soil properties (Corwin and Lesch 2003). Using a device working on an electromagnetic induction (EMI) principle is a non-invasive measurement (e.g. Geonics EM-38, Canada, used in this study). Conversely, the measurement of EC based on electrical resistance (ER) principle is an invasive method (e.g. VERIS device, USA).

Geoelectrical methods began to be used in the early 1930s in geology (McNeil 1980 in Dobers 2002). The first application of EC in agriculture was for measurement of soil salinity in the late 1970s in the USA. Today, this method is one of the most frequently used tools in precision agriculture research. It is employed for spatio-temporal characterisation of edaphic and anthropogenic properties that influence crop yield (Corwin and Lesch 2005a).

In the present study, the EM-38 device was used that measures EC on EMI principle. It is equipped with two spools at exactly defined distance between them being 1 m. The first spool induces a primary electromagnetic field which goes into the soil. In the soil environment, a secondary electromagnetic field is created based on physicochemical soil properties. The second spool measures the response of both fields and the resultant EC of soil is estimated from their comparison (Lück *et al.* 2000), and therefore it is called apparent electrical conductivity, EC_a. The measured values are in mS m^{-1} unit. The EM-38 is designed for measurement in two dipoles, horizontal and vertical. In a homogeneous soil profile, the signal of the vertical dipole penetrates to the depth of 1.5-2 m, and that of the horizontal dipole to 0.75-1 m.

The soil EC is influenced by a lot of soil parameters. Corwin and Lesch (2005a) consider soil salinity, saturation percentage (SP), water content and bulk density (ρ_b) as the most important ones. Additional factors include soil texture, organic matter (these two factors directly influence SP and ρ_b) and cation exchange capacity (CEC). The effect of all these factors is possible to find in most mentioned studies. They differ only in their relevancy in relation to specific field conditions. The detailed overview of studies on the effect of soil environment components on EC is given by Corwin and Lesch (2005b).

The objective of this study was to compare traditional methods for the assessment of soil environment properties and techniques for soil EC measurement. The main goal was to verify the efficiency of this indirect method for the assessment of spatial variability of soil properties in precision agriculture.

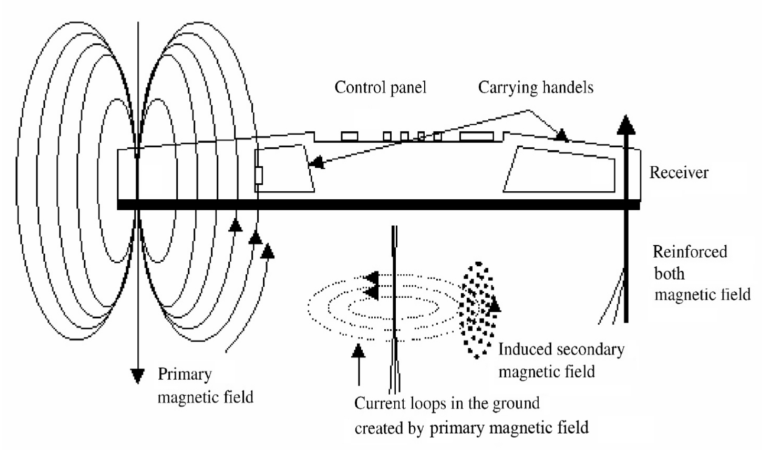


Fig. 1. Principle of EM-38 operation (Lesch *et al.* 2005, modified)

MATERIALS AND METHODS

The investigation was conducted in an experimental field (53 ha – see Fig. 2) situated in South Moravia at the altitude of 175 m, in a region with annual precipitation of 483 mm and annual mean temperature of 9.2°C. The soil is pedo-

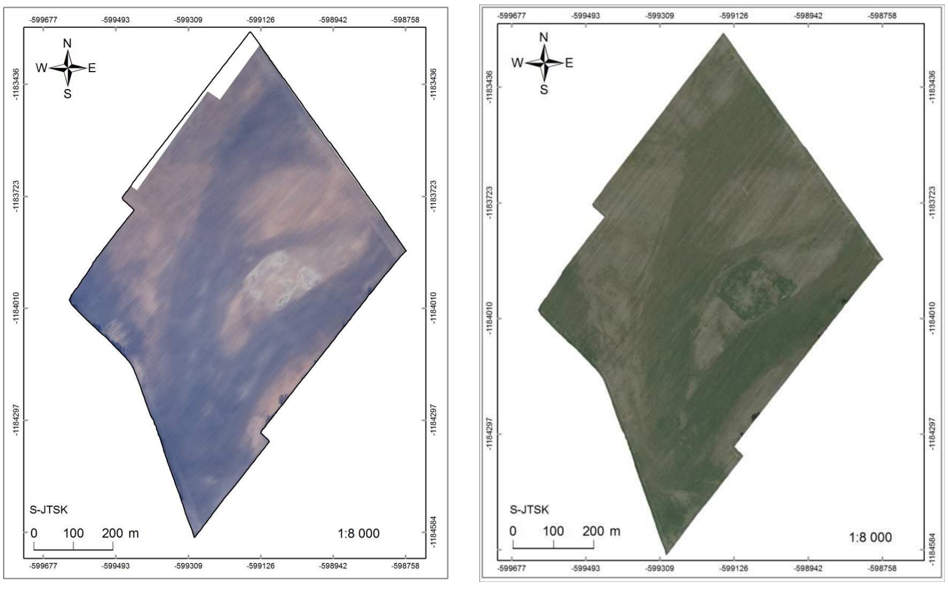


Fig. 2. Aerial images of the field – bare soil (2007) and winter wheat (2006 - source: http://geoportal.cenia.cz)

logically classified as chernozem on sandy loess with the dominant sandy loam texture. Crop rotation: winter wheat (2004), maize (2005), winter wheat (2006) and poppy (2007).

Measurement of soil electrical conductivity

EC was measured using the EM-38 in the spring of 2004 (dataset EC_04) and in the autumn of 2005 (dataset EC_05). In the field, the device was drawn by an off-road vehicle along wheel tracks over the distance of 18 m in the horizontal dipole of the measurement. The actual data were saved together with DPGS location and then corrected to a constant temperature of 20°C.

Fig. 3. EM-38 device and the off-road vehicle with EM-38 mounted on a wooden sledge

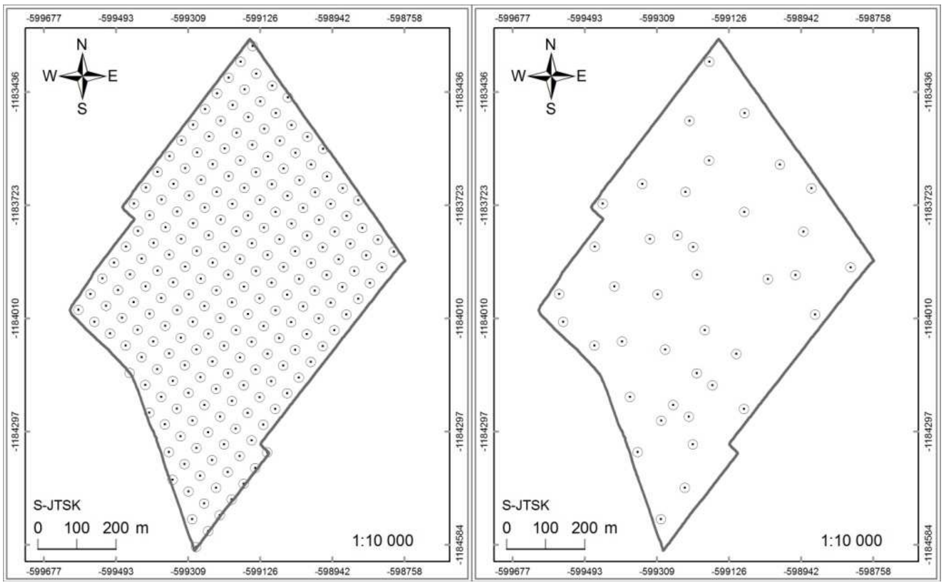
Soil sampling

The topsoil (0-30 cm) samples for agrochemical analysis of nutrient (P, K, Mg, Ca) and humus ($C_{ox} \times 1.724$) content and pH_{KCl} value were taken in the spring of 2004 in a regular grid of 50 x 50 m (214 samples, 4 samples per ha – Fig. 5). The laboratory analysis was performed according to the Mehlich III methodology (Zbiral 2002) valid in the Czech Republic.

In 2005, 40 topsoil samples were taken for soil texture analysis (clay, silt and sand content) in an irregular grid based on EC_04 map (so-called directed sampling).

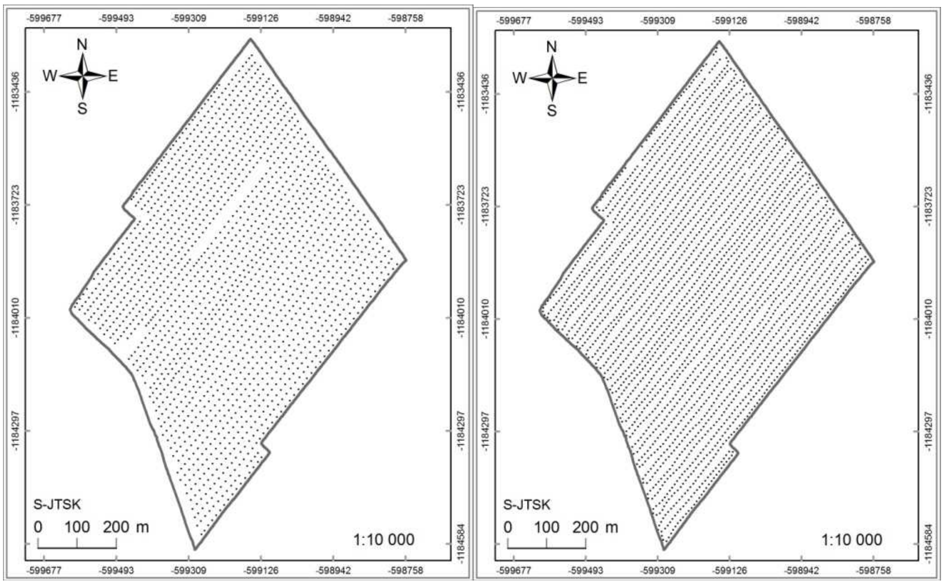
Point data processing

Continuous maps were generated from EC and soil sampling datasets. An ordinary kriging technique with nugget variance calculation was used. The maps were converted to the raster with spatial resolution of 5 m per pixel, which gave a total number of 21,032 pixels for the whole field. The comparison of soil characteristics was made with these maps using multiple regression analysis. The spatial data processing and their analysis were made in geographical information systems (GIS) ESRI ArcGIS 9.2. The maps are presented in the Czech national coordinate system S-JTSK, in meters.



a) b)

Fig. 4. Maps of soil sampling points, a) 2004 – 50 m regular grid (214 soil samples for agrochemical analysis), b) 2005 – irregular grid (40 soil samples for textural analysis)



a) b)

Fig. 5. Maps of EC measurement points from EM-38, a) 2004 (n = 1771), b) 2005 (n = 2800)

RESULTS AND DISCUSSION

The basic statistical characteristics of point datasets obtained from the soil sampling analysis and EC measurement are presented in Table 1. The coefficient of variation demonstrates high variability in the datasets, particularly in Ca, Mg contents, results of EC measurement and P content. The lowest variability is found for sand, clay content and pH value. In the case of the EC data, on the contrary, the dataset contained a high number of data with higher variability. Though the pH value had a lower coefficient of variation, the range from 4.40 to 7.93 shows a very high heterogeneity of the soil environment within the field from the agronomic point of view.

Table 1. Descriptive statistics of EC and soil characteristics calculated from point datasets

Parameter	EC_04 (mS m^{-1})	EC_05 (mS m^{-1})	Clay (%)	Silt (%)	Sand (%)
Mean	9.07	9.15	33.55	15.50	50.95
Median	7.20	7.20	33.00	15.00	51.00
Std.	5.55	6.26	4.56	3.14	5.68
Variance	30.78	39.21	20.82	9.85	32.25
Min	1.40	0.20	23.00	10.00	39.00
Max	31.4	49.9	44	23	67
Set size (n)	1771	2800	40	40	40
CV (%)	61.20	68.43	13.60	20.24	11.15

Parameter	pH	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Humus (%)
Mean	6.47	58.18	146.14	177.93	3856.20	3.24
Median	6.85	46.00	138.00	137.50	2570.00	3.23
Std.	0.95	36.41	37.13	121.96	4602.09	0.52
Variance	0.90	1325.56	1378.71	14874.0	21179225	0.27
Min	4.40	13.00	90.00	53.00	641.00	1.63
Max	7.93	196	395	948	33670	4.77
Set size (n)	214	214	214	214	214	214
CV (%)	14.64	62.58	25.41	68.54	119.34	15.95

Table 2 shows basic statistical characteristics that were calculated from continuous maps. The use of the ordinary techniques with the nugget variance calculation in interpolation process led evidently to a decrease in variability of the examined soil characteristics in contrast to values of coefficients of variation from the original point datasets. The ordinary kriging with nugget variance calculation has a character of a smoothing method when the local extremes are eliminated. However, the mean value remains on the same level as the original dataset.

Table 2. Descriptive statistics of EC and soil characteristics from interpolated maps (n = 21032)

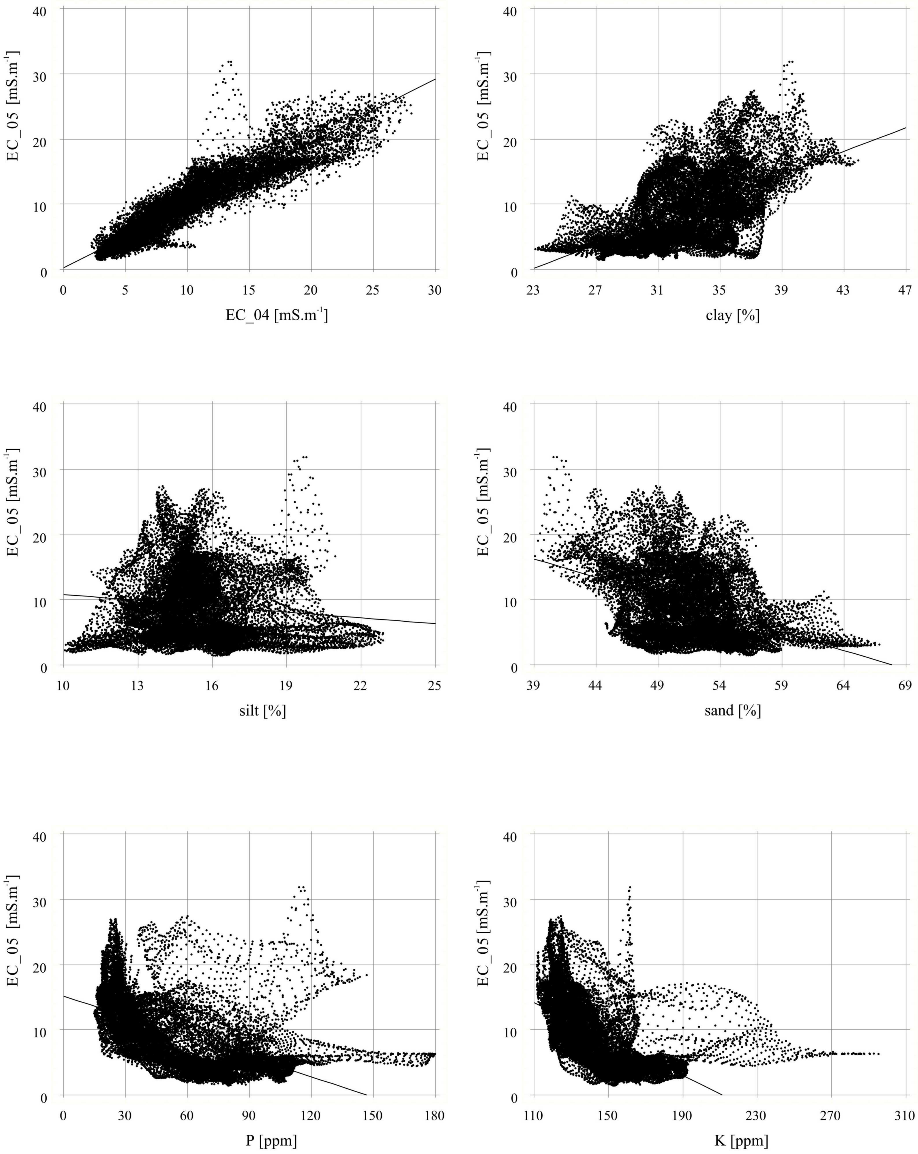
Parameter	EC_04 (mS m^{-1})	EC_05 (mS m^{-1})	Clay (%)	Silt (%)	Sand (%)	PH	P (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	Humus (%)
Min	2.24	1.42	23.09	10.05	39.07	4.75	14.82	111.37	76.29	806.00	2.12
Max	28.06	31.82	43.93	22.89	66.84	7.82	179.74	295.18	472.99	18316.20	4.64
Mean	9.20	9.13	32.96	15.48	51.56	6.47	57.88	145.68	177.09	3848.37	3.25
Std	5.20	5.36	3.28	1.99	3.89	0.74	30.23	22.49	73.25	2685.56	0.44
CV (%)	56.56	58.73	9.96	12.86	7.55	11.40	52.23	15.44	41.36	69.78	13.48

The correlation between different dates of EC measurements, EC_04 and EC_05, was $r^2 = 0.936$ (Tab. 3 and Fig. 6). This very close relationship shows a high stability of measurement results from a short-time point of view even in different year seasons (spring 2004, autumn 2005). In the data of EC measurement, there are identical spatial patterns (Fig. 7). Even the range and mean value of both measurements are similar. Dobers (2002) confirms that EC differences appear independently of the year season – the EC values are highly correlated by different times in the same fields. Likewise, similar results were obtained by Schmidhalter *et al.* (2002). They reported that areas with different soil conditions measured by EC are invariable from a short-time point of view, only the absolute values are changing.

Table 3. Correlation coefficients (r^2) between EC and examined soil characteristics (n = 21032)

	EC_04	Clay	Silt	Sand	PH	P	K	Mg	Ca	Humus
EC_05	0.936	0.548	–0.110	–0.406	0.596	–0.579	–0.584	0.673	0.318	0.595

All correlation coefficients are significant at $\alpha = 0.01$.



EC_05 [mS.m-1]
EC_04 [mS.m-1]
clay [%]
silt [%]
sand [%]
P [ppm]
K [ppm]

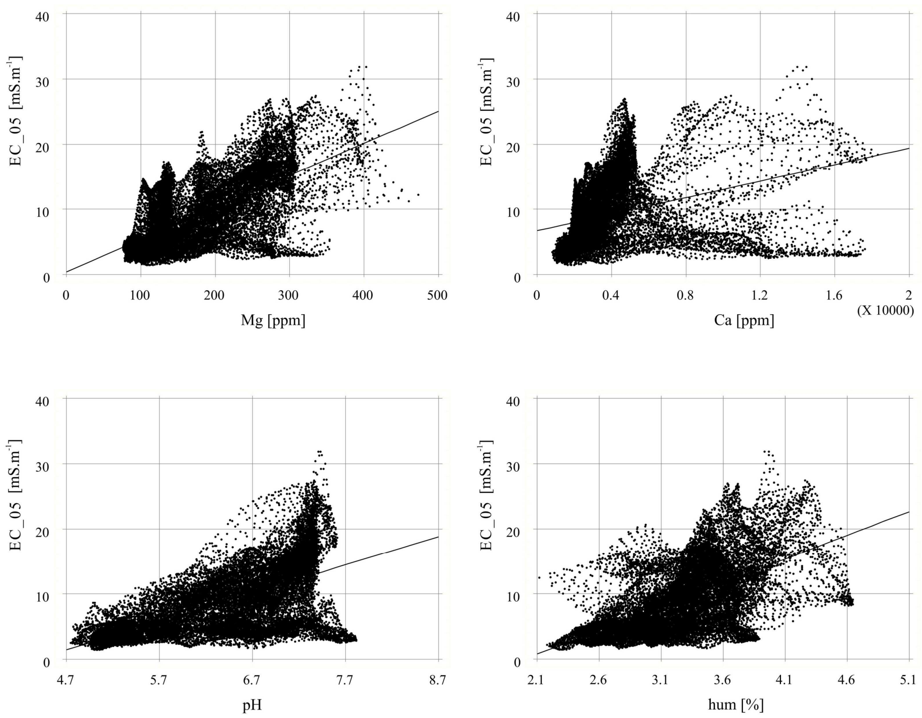


Fig. 6. Scattergrams of correlated characteristics

The comparison of EC_05 and results of the soil textural analysis shows a moderately strong relationship to clay content (r^2 = 0.548), a relatively weak relationship to silt content (r^2 = –0.110), and a moderate relationship to sand content (r^2 = –0.406). These results show a positive effect of clay content. Its low content causes a significant negative correlation with EC_05 on sandy loam. The results confirm that the soil texture belongs among important factors influencing EC. Under some conditions, lower EC values can mean a soil with a higher content of sand category, while higher EC values correspond with clay-rich soils. Schmidhalter *et al.* (2002) mention in their study a possibility of direct use of EC maps in the precision agriculture process in heterogeneous fields in arid regions. This could be, for instance, variable soil cultivation based on soil texture discovered by EC mapping. More complicated interpretation is in the case of the assessment of silt content effect on EC. Rhoades (in Dobers 2002) recommends that the soil texture should not be considered independently of soil moisture. The author shows an example of silt which has negligible EC, similar to that of sand

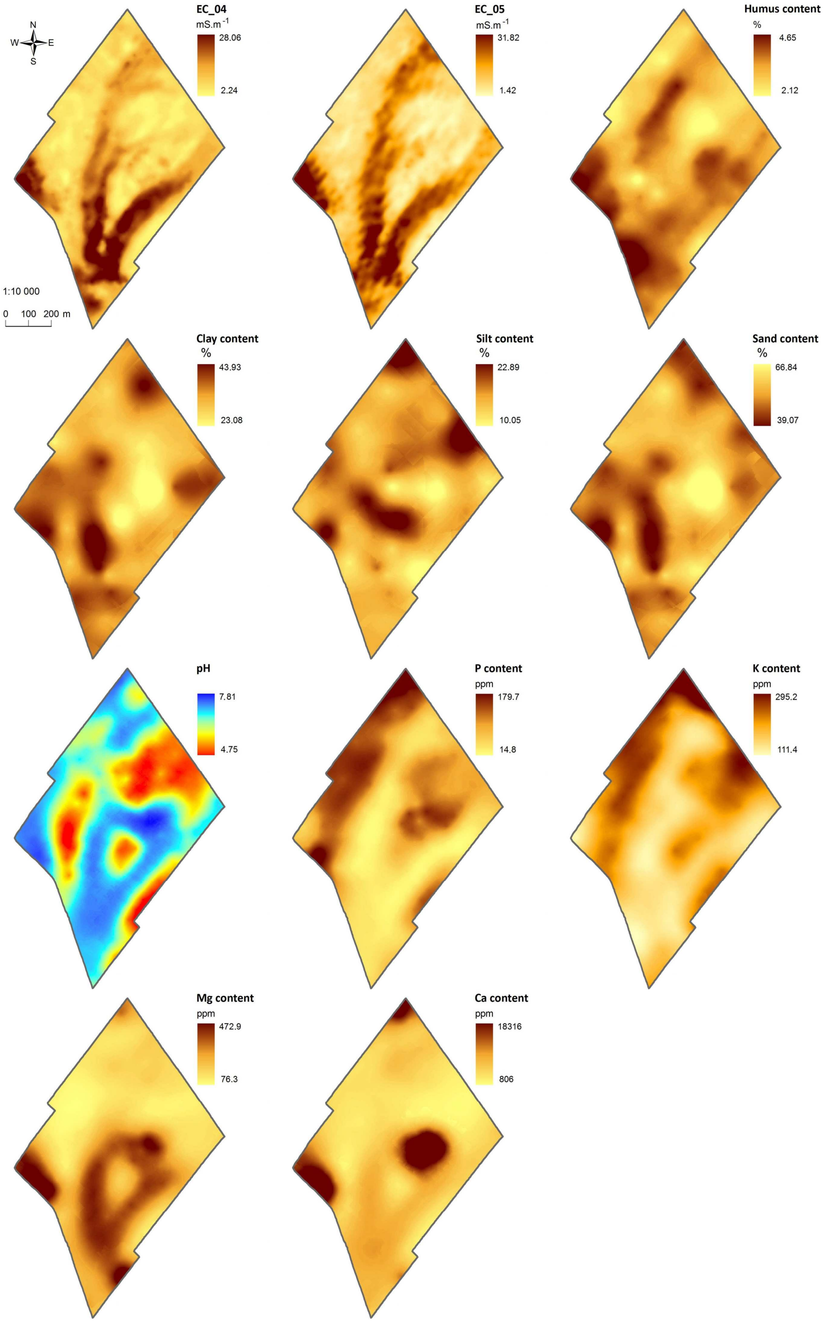


Fig. 7. Maps of soil characteristics constructed from point datasets using ordinary kriging

in contrast to clay under arid conditions. However, if silt is wet, it is easy to distinguish it from sand because of its smaller particle size.

The humus content ($C_{ox} \times 1.724$) correlated with EC_05 in a moderately strong positive way ($r^2 = 0.595$). It is the third highest correlation among the examined soil characteristics following Mg content ($r^2 = 0.673$) and pH value ($r^2 = 0.596$). In some studies, the organic matter content is classified as an additional factor of EC because it affects the saturation percentage and bulk density (Corwin and Lesch 2003). On the other hand, Lück *et al.* (2000) consider a higher content of organic matter in soil to be better for water holding capacity of soil; water holding capacity influences EC values through increase in soil moisture. To prove these hypotheses, a detailed survey aiming at the referred soil physical properties (soil moisture, bulk density, etc.) has to be performed.

Correlation analysis of agrochemical properties showed weak or moderately strong correlations with EC_05. The strongest correlation was found for Mg content ($r^2 = 0.673$), the weakest one for Ca content ($r^2 = 0.318$). The increase in Mg, Ca content and pH value led to higher EC values. In contrast, negative correlations were found for P and K contents. Regardless the correlation direction, except Ca content, the results could be considered balanced. Probably, the EC measurement did not directly detect the nutrient content in soil. It is possible that EC responds to some physicochemical soil properties which are in direct relationship with the nutrient content and pH value. Nevertheless, EC reacts to these characteristics of the given location and enables to determine areas with significantly different soil conditions which are mapped in detail by soil sampling and consecutive laboratory analysis. This procedure, when the locations of soil sampling points are arranged irregularly across the field on the basis of preliminary mapping of soil conditions, is called directed sampling.

The greatest potential of geospatial EC measurement in precision agriculture consists in providing reliable spatial information for directed soil sampling to identify and characterise the spatial variability of edaphic properties influencing crop yield. Directed soil sampling based on EC enables to characterise spatial variability in soil properties correlated to EC with a significant reduction in the number of sampling points in comparison to grid sampling (Corwin and Plant 2005).

CONCLUSIONS

1. The results confirm that from a short-time point of view the EC measurement can be considered to be stable. When measurements are made in the same field during different year seasons, it is necessary to normalize the EC values on the basis of

constant soil temperature and to take into account the soil moisture. These factors connected with meteorological conditions are of crucial effects on EC.

2. Comparison of EC and results of soil particle size analysis confirms that soil texture is another factor influencing EC. Moderate relationship of clay and sand content suggests suitability of the EC measurement for mapping differences in the soil texture. Therefore, the EC maps can be used as input information in variable soil tillage, especially under arid conditions. This indicates that to identify and characterise soil texture components using EC, additional monitoring of soil moisture is also necessary.

3. Finding moderately strong relationships and balance for almost all of the examined agrochemical characteristics (P, K, Mg content and pH value) represents their close relationship to the basic factors influencing EC rather than their direct effect on EC. However, it does not mean that under these conditions it is not possible to use EC mapping to estimate the content of the examined nutrients in soil. For better interpretation it is necessary to make another investigation into soil moisture, soil salinity and CEC.

4. The results show that the method of soil EC measurement is a suitable tool for the mapping of spatial variability of soil conditions in the field. Direct use of EC maps in precision agriculture is not very common now because of complex influence of a lot of local soil conditions, which is difficult to interpret. Information is used mainly for directed sampling when locations of soil sampling points are determined based on preliminary knowledge of field heterogeneity – EC maps. Finally, in contrast to traditional grid sampling, reduction in soil samples and at the same time keeping the level of soil map details and interpretability can be expected.

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MAPOWANIE WARUNKÓW GLEBOWYCH W ROLNICTWIE PRECYZYJNYM

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S t r e s z c z e n i e. W pracy przedstawiono weryfikację metody pomiaru przewodnictwa elektrycznego (EC) do oceny przestrzennej zmienności właściwości gleby w rolnictwie precyzyjnym. Weryfikacja została przeprowadzona na 53-ha polu doświadczalnym zlokalizowanym na Południowych Morawach w Republice Czeskiej. Pomiary EC prowadzono przy użyciu aparatu EM-38 (Geonics Ltd, Canada) w latach 2004 i 2005. W tym samym czasie pobierano próbki wierzchniej warstwy gleby na potrzeby analiz agrochemicznych, obejmujących zawartość P, K, Mg, Ca, próchnicy, wartości pH, oraz do analizy tekstury gleby. Stwierdzono silną korelację pomiędzy latami prowadzenia pomiarów EC ($r^2 = 0,936$), co potwierdza stabilność metody pomiarów EC z krótko-okresowego punktu widzenia. Silne związki pomiędzy EC a zawartością frakcji ilastej ($r^2 = 0,548$) oraz piasku ($r^2 = -0,406$) potwierdzają wpływ tekstury gleby na wartość EC. Ponadto, prawie wszystkie badane charakterystyki agrochemiczne (zawar-tość P, K, Mg oraz wartość pH) jak i zawartość próchnicy, wykazywały stosunkowo zrównoważone, umiarkowanie silne korelacje z wartością EC. Wskazuje to, że pomiar EC gleby jest odpowiednim narzędziem do mapowania w polu zmienności przestrzennej warunków glebowych. Informacje te mogą być stosowane głównie do ukierunkowanego pobierania próbek glebowych, gdy lokalizacja miejsc próbkowania określona jest na podstawie wstępnej znajomości niejednorodności pola – mapy EC. W przeciwieństwie do tradycyjnego pobierania próbek opartego na regularnej siatce punktów, w zastoso-waniu tej metody można oczekiwać zachowania poziomu szczegółowości map przy znaczącej redukcji liczby ilości pobieranych próbek glebowych.

S ł o w a k l u c z o w e: przewodnictwo elektryczne gleby, zmienność przestrzenna, rolnictwo precyzyjne