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Using Magnetic Susceptibility Mapping for Assessing Soil Degradation Due to Water Erosion

Ondřej JAKŠÍK[1], *Radka KODEŠOVÁ*[1], *Aleš KAPIČKA*[2], *Aleš KLEMENT*[1], *Miroslav FÉR*[1] *and Antonín NIKODEM*[1]

[1]*Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic;*
[2]*Institute of Geophysics of the CAS, Prague, Czech Republic*

Abstract

Jakšík O., Kodešová R., Kapička A., Klement A., Fér M., Nikodem A. (2016): Using magnetic susceptibility mapping for assessing soil degradation due to water erosion. Soil & Water Res., 11: 105–113.

This study focused on developing a method for estimating topsoil organic carbon content from measured mass-specific magnetic susceptibility in Chernozems heavily affected by water erosion. The study was performed on a 100 ha area, whereby 202 soil samples were taken. A set of soil samples was divided into 3 subsets: A (32 samples), B (67 samples), and C (103 samples). The mass-specific magnetic susceptibility using low (χ_{lf}) and high (χ_{hf}) frequency, and organic carbon content were measured at all soil samples. The contents of iron and manganese, extracted with a dithionite-citrate solution (Fe_d, Mn_d) and ammonium oxalate (Fe_o, Mn_o), were quantified in A and B samples. Models for predicting organic carbon content from magnetic susceptibilities were designed as follows: (1) subset A was used as the training set for calibration, and subsets B and C were used as the test sets for model validation, either separately (subset B only), or together (merged subsets B and C); (2) merged subsets A and B were used as the training set and subset C was used as the test set. Results showed very close correlations between organic carbon content and all measured soil properties. Obtained models relating organic carbon content to mass-specific magnetic susceptibility successfully predicted soil organic carbon contents.

Keywords: arable land; geomorphologically diverse areas; Chernozem; magnetic susceptibility; soil organic carbon; spatial variability

Soil degradation due to water erosion is one of the greatest problems of agricultural soils worldwide. To be able to map the extent of soil degradation and consequently propose actions for soil improvement, an effective approach is needed. Soil organic carbon content and its time fluctuations is one of the key features characterizing the given site and occurring processes. It is widely accepted as the main soil quality indicator (e.g. Reeves 1997) and therefore can be used for soil degradation assessment. Traditional laboratory techniques (dry combustion, wet oxidization) of soil organic carbon determination are usually labour intensive, time consuming, and require special instruments, which means they are not suitable for large sample collections (e.g. large areas or continual monitoring). Therefore, there is a need for fast, reliable, and cost-effective techniques. Many indirect methods have been developed recently. One alternative to estimate soil organic carbon as an indicator of soil erosion is VIS-NIR reflectance spectroscopy (e.g. Minasny *et al.* 2013; Vašát *et al.* 2015a).

Another possibility to assess soil material redistribution within the studied area is to measure magnetic properties of soils. This technique is capable of distinguishing topsoil, subsoil, and parent material based on different concentrations of ferrimagnetics, and thus providing quantitative information about soil redistribution within the study area. Magnetic properties of soils have been used in several stud-

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ies for assessing soil erosion and the consequent redistribution of soil materials. De Jong *et al.* (1998) studied the differences in magnetic susceptibility between topsoil and subsoil, and between soils of different slope positions, and showed that magnetic susceptibility mapping could be used to quantify soil redistribution in a cultivated field. A similar study was performed by Karchegani *et al.* (2011), who assessed soil redistribution following deforestation and intensive cultivation. Sadiki *et al.* (2009) applied magnetic susceptibility for soil degradation identification as well as for tracing the sources of sediments that are contributing increasingly larger sediment loads to the drainage network. Royall (2001) made use of mineral magnetic measurements to investigate soil erosion and sediment delivery in a small agricultural catchment in a limestone terrain. By using magnetic susceptibility, the rate of soil erosion can be estimated for a given period of agricultural land use (Jordanova *et al.* 2011, 2014). There is a wide range of other applications of magnetic properties for assessing soils, such as for hydric soil delineation (de Jong 2002; Grimley *et al.* 2004) or soil pollution assessment (e.g. Kapička *et al.* 2003, 2011; Magiera *et al.* 2006; Lu *et al.* 2007; Kodešová *et al.* 2011; Dlouhá *et al.* 2013).

Studies by Jordanova *et al.* (2010, 2014) and Jakšík *et al.* (2015) showed that in Chernozem regions, that are strongly influenced by water erosion, the organic carbon content of topsoil is closely related to ferrimagnetic particles content, and thus also to the mass-specific magnetic susceptibility. In these studies, while low contents of ferrimagnetic particles were found in the loess substrates, considerably higher ferrimagnetic particles content were documented in the mollic horizons. This was attributed to highly favourable conditions for the *in situ* formation of pedogenic ferromagnetic minerals in the mollic horizons of the Calcic Chernozem, where pedogenic acidification in the humic horizon accelerates weathering processes. Jordanova *et al.* (2010) suggested that the conditions were favourable for magnetite (maghemite) production due to the following reasons: (*i*) high organic carbon content, which provides suitable conditions for bacterial metabolism and impedes crystallization of goethite and hematite (Maher 1998; Cornell & Schwertmann 2003); (*ii*) repeated cycling of oxidation and reduction conditions (Mullins 1977; Thompson & Oldfield 1986); and (*iii*) possible presence of Fe-reducing bacteria (Fortin & Langley 2005; Weber *et al.* 2006; Behrends & Van Cappellen 2007). However, studies by Jordanova *et al.* (2010, 2014) and Jakšík *et al.* (2015) did not include the development of models that would have been validated on independent data sets. Therefore, the aim of this study was to test the hypothesis that mass-specific magnetic susceptibility can be used for estimating organic carbon content (i.e. to develop models on calibration data sets and validate on validation data sets) and via proving this hypothesis to provide an effective approach based on magnetic properties measurements for acquiring information about soil properties in topsoil.

MATERIAL AND METHODS

Study site. The study was carried out in South Moravia (Czech Republic). The region is known for uninterrupted agricultural use since the Holocene. The original soil unit in the wider area is a Haplic Chernozem (FAO 2014) developed on loess. The intensive agricultural exploitation in combination with terrain morphology has resulted in a highly diversified soil spatial pattern. Nowadays the original soil unit is preserved only on the top of relatively flat parts, and is gradually transformed by water erosion up to Regosols on the steepest slopes, while colluvial soils are formed in terrain depressions and at toe slopes due to sedimentation of previously eroded material. Soils within this area have been intensively investigated during the last several years (Zádorová *et al.* 2011a, b, 2013, 2015; Brodský *et al.* 2013; Vašát *et al.* 2014, 2015a, b; Jakšík *et al.* 2015). Studies concentrated on soil type mapping (with particular interest to delineate colluvial soils) (Zádorová *et al.* 2011b, 2013, 2015), determining relationships between terrain attributes and soil properties (Zádorová *et al.* 2011a, b; Jakšík *et al.* 2015), and using VNIR reflectance spectroscopy for estimating soil organic carbon content (Brodský *et al.* 2013; Vašát *et al.* 2015a, b) or extractable nutrients in soils (Vašát *et al.* 2014). On a relatively small set of soil samples (36) taken within a 6 ha area, Jakšík *et al.* (2015) documented that organic carbon content is closely related to iron content, and thus also to mass-specific magnetic susceptibility (measured using low (χ_{lf}) and high (χ_{hf}) frequency). To test the hypothesis that mass-specific magnetic susceptibility can be used for estimating soil organic carbon content of eroded soils, the set of soil samples and a similar procedure (i.e. dividing the set into several subsets), used by Vašát *et al.* (2015b) for validating methods for estimating C_{ox} using VNIR-DRS, was used also in this study. The area of the experimental field was 100 ha. In total, 202 spots were visited within this region following a judgment sampling design, which may be roughly described as a regular grid with varying spacing. The goal was to cover different landform elements (crest, slopes, and depressions) as evenly as possible. For detailed investigation a 6 ha subplot in the north-west part of the area was sampled with much higher density (Figure 1a – black triangles). From this dense sample grid, a subset was further detached to determine some specific, more demanding soil characteristics (Jakšík *et al.* 2015). As a result, we distinguished three subsets to be used for calibration and validation: subset A consisting of 32 samples (Figure 1b – black dots), subset B (Figure 1b – white dots) consisting of 67 remaining samples of the subplot, and 103 samples of subset C (Figure 1a – grey triangles) from the extended grid covering the whole study area. Samples were taken from topsoil (up to the depth of 20 cm).

Measured data. The collected soil samples were transported to the laboratory, air-dried, ground, and sieved through a 2 mm mesh. The low- (0.47 kHz) and high-frequency (4.7 kHz) magnetic susceptibility measurements were made in 10 ml plastic containers using the Bartington MS2B system (Bartington Instruments 2008), and expressed as mass-specific magnetic susceptibility. Next, the grain fraction ≤ 0.25 mm was extracted to determine soil organic carbon content (all soil samples) and content of iron and manganese (subsets A and B). Soil organic carbon content (C_{ox}) was measured using wet oxidation by acid dichromate solution followed by potentiometric titration of ferrous ammonium sulphate (Skjemstad & Baldock 2007). C_{ox} data were previously used in a study by Vašát *et al.* (2015b). The contents of iron and manganese extracted with a dithionite-citrate solution (Fe_d, Mn_d) and ammonium oxalate (Fe_o, Mn_o) were quantified according to McKeague and Day (1966) and Courchesne and Turmel (2007), respectively. Data (i.e. C_{ox} and different forms of Fe and Mn contents) for subset A were presented by Jakšík *et al.* (2015) and all data (subsets A + B) were applied in the study by Vašát *et al.* (2015b).

Statistical analysis. First, the basic statistics were evaluated and the Pearson's correlation coefficients and *P*-values were calculated to evaluate the relationships between different soil properties within different subsets and their combinations: A, B, C, A + B, A + B + C. Next, we used linear regressions (applied for selected sample sets) to obtain equations for predicting C_{ox} content from measured magnetic susceptibilities, which was used to predict C_{ox} content for the other sets of soil samples. We consider two different scenarios: (1) using subset A as the training set for calibration, and subsets B and C as the test sets for model validation either separately (subset B only) or together (merged subsets B and C) and (2) using merged subsets A and B as the training set and subset C as the test set. The goodness-of-fit

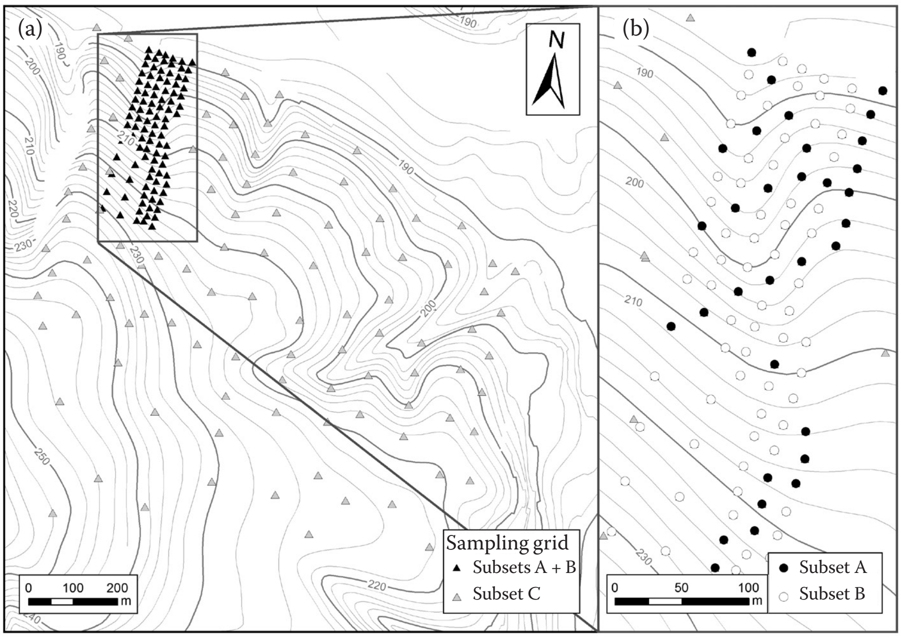

Figure 1. Study area with contour lines: (a) detailed subplot – black triangles (subsets A + B), extended grid – grey triangles (subset C), (b) detailed subplot: selected samples – black dots (subset A), remaining samples – white dots (subset B)

of each model was evaluated using the coefficient of determination (R^2) and residual mean square error (RMSE). Statistical analyses were performed using STATISTICA software Ver. 12 (Statsoft 2013).

RESULTS AND DISCUSSION

The soil organic carbon content within the studied area is showed in Figure 2. The figure clearly shows high C_{ox} diversification due to water erosion. The highest soil organic carbon contents were found in the relatively flat parts (crests), with only mild evidence of soil erosion. Conversely, the lowest contents were measured on steep slopes, where the signs of water erosion are the most significant. Sedimentation of previously eroded material (mollic horizon rich in organic carbon as well as exposed loess) in bottom parts (toe slopes, depressions) resulted in a moderate organic carbon content.

The descriptive statistics of all measured soil properties for each subset are shown in Table 1. Each data subset has similar soil properties distribution in terms of variation, and therefore can be used for mutual comparison of represented areas. The Pearson's correlation coefficients indicating relationships between all evaluated properties for different sets (A, B, C, A + B, A + B + C) are shown in Tables 2–6. Results show strong positive correlations between C_{ox} and all Fe and Mn forms. A very strong positive correlation was also found between soil organic carbon (C_{ox}) and mass-specific magnetic susceptibility at low (χ_{lf}) as well as high frequency (χ_{hf}). These findings correspond to similar studies previously published (Jordanova *et al.* 2010, 2014; Jakšík *et al.* 2015). Frequency dependent susceptibility (χ_{fd}), or difference in magnetic susceptibility ($\Delta\chi$) suggested by Jordanova *et al.* (2011) as a suitable factor for assessing the presence of ultrafine crystalline iron minerals in humic horizons (i.e. suitable conditions for natural crystallization of goethite and hematite), was not evaluated in this study because of statistically insignificant results previously published for this area (Jakšík *et al.* 2015).

The models for predicting soil organic matter content from mass-specific magnetic susceptibility (χ_{lf}) measured at low frequency (0.47 MHz) are shown in Table 7. Table 7 also shows R^2 and RMSE values for model calibrations and validations. The R^2 and RMSE values calculated for validation sets showed slight decreases and increases, respectively, in comparison to values calculated for calibration sets. However, they still indicate a very close correspondence between measured and predicted C_{ox} values. Both models of soil organic carbon prediction that were based on magnetic susceptibility outperformed even the model proposed by Vašát *et al.* (2015b), who utilized reflectance soil spectroscopy for the same sample sets. Results proved the hypothesis, that magnetic susceptibility measured in the laboratory can be adopted for soil organic carbon content prediction and used as an alternative approach for fast and cost-effective mapping and monitoring of soil modification due to water erosion within a region of interest. Even more time-

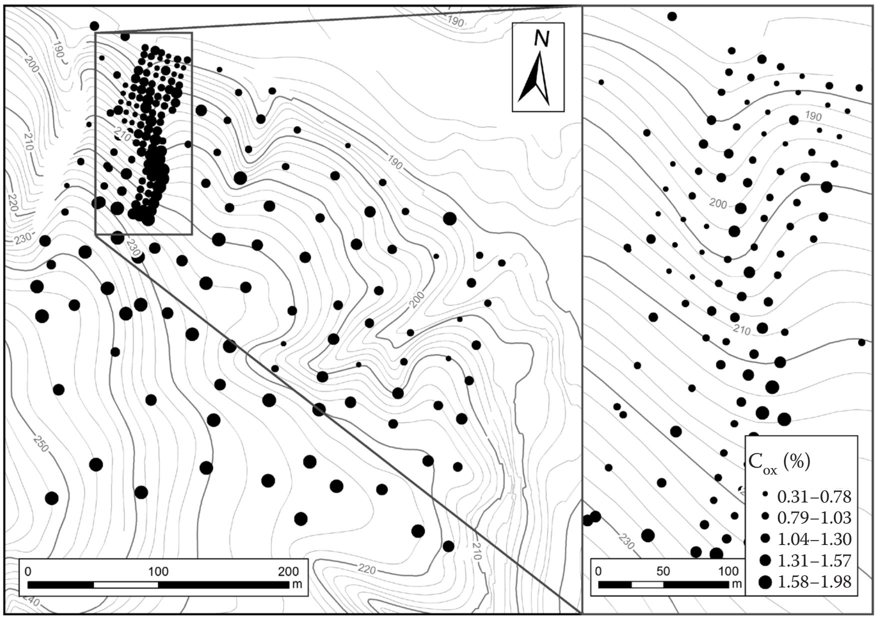

Figure 2. Soil organic carbon spatial distribution within the study area

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Table 1. Descriptive statistics of measured soil properties (mean, median, min, max, standard deviation (SD)) for calibration data sets: soil organic carbon – C_{ox}, mass-specific susceptibility for low (χ_{lf}) and high frequency (χ_{hf}), content of iron and manganese in ammonium oxalate extract Fe_o and Mn_o and dithionite-citrate extract Fe_d and Mn_d

Variable	Subset A (n = 32)					Subset B (n = 67)					Subset C (n = 103)				
	mean	median	min.	max	SD	mean	median	min	max	SD	mean	median	min	max	SD
C_{ox} (%)	1.08	1.01	0.58	1.98	0.35	1.06	0.99	0.50	1.84	0.31	1.26	1.29	0.31	1.92	0.36
χ_{lf} (10^{-7} m^3/kg)	3.46	2.92	1.51	7.80	1.68	3.46	3.01	1.44	7.47	1.57	5.04	5.14	1.23	8.62	2.07
χ_{hf} (10^{-7} m^3/kg)	3.21	2.81	1.48	7.01	1.50	3.21	2.78	1.55	6.73	1.38	4.59	4.69	1.17	7.74	1.83
Mn_d (mg/kg)	347.7	340.0	278.0	474.0	52.10	345.48	329.00	255.50	471	50.33					
Fe_d (mg/kg)	6803	6782	5076	8553	928.3	6910	6666	5080	9531	1134.63					
Mn_o (mg/kg)	1054	951.0	575.3	1953	373.1	1070	977.1	560.2	2261	386.94					
Fe_o (mg/kg)	229.03	195.70	147.64	418.96	79.58	225.52	197.84	144.20	404.52	71.19					
	Subset A + B (n = 99)					Subset A + B + C (n = 202)									
C_{ox} (%)	1.06	0.99	0.50	1.98	0.32	1.16	1.09	0.31	1.98	0.35					
χ_{lf} (10^{-7} m^3/kg)	3.46	3.00	1.44	7.80	1.59	4.23	3.72	1.23	8.62	2.01					
χ_{hf} (10^{-7} m^3/kg)	3.21	2.78	1.48	7.01	1.41	3.89	3.46	1.17	7.74	1.78					
Mn_d (mg/kg)	346.2	336.5	255.5	474	50.65										
Fe_d (mg/kg)	6875	6725	5076	9531	1068.7										
Mn_o (mg/kg)	1065	968.8	560.2	2261	380.7										
Fe_o (mg/kg)	226.7	197.8	144.2	419	73.62										

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Table 2. Correlation coefficients between measured soil properties: soil organic carbon (C_{ox}), mass-specific magnetic susceptibility using low (χ_{lf}) and high frequency (χ_{hf}), content of iron and manganese (in dithionite-citrate extract Fe_d, Mn_d and ammonium oxalate extract Fe_o and Mn_o) for subset A

Variable	C_{ox}	χ_{lf}	χ_{hf}	Mn_d	Fe_d	Mn_o	Fe_o
C_{ox}	1	0.9854***	0.9806***	0.9413***	0.5994***	0.9491***	0.8634***
χ_{lf}	0.9854***	1	0.9963***	0.9538***	0.6551***	0.9739***	0.8895***
χ_{hf}	0.9806***	0.9963***	1	0.9423***	0.6537***	0.9739***	0.8871***
Mn_d	0.9413***	0.9538***	0.9423***	1	0.6806***	0.9385***	0.8628***
Fe_d	0.5994***	0.6551***	0.6537***	0.6806***	1	0.7195***	0.6630***
Mn_o	0.9491***	0.9739***	0.9739***	0.9385***	0.7195***	1	0.9321***
Fe_o	0.8634***	0.8895***	0.8871***	0.8628***	0.6630***	0.9321***	1

$^{***}P < 0.001$

Table 3. Correlation coefficients between measured soil properties: soil organic carbon (C_{ox}), mass-specific magnetic susceptibility using low (χ_{lf}) and high frequency (χ_{hf}), content of iron and manganese (in dithionite-citrate extract Fe_d, Mn_d and ammonium oxalate extract Fe_o and Mn_o) for subset B

Variable	C_{ox}	χ_{lf}	χ_{hf}	Mn_d	Fe_d	Mn_o	Fe_o
C_{ox}	1	0.9340***	0.9350***	0.8316***	0.7567***	0.8505***	0.8375***
χ_{lf}	0.9340***	1	0.9960***	0.9049***	0.8184***	0.9150***	0.8890***
χ_{hf}	0.9350***	0.996***	1	0.9070***	0.8249***	0.9175***	0.8843***
Mn_d	0.8316***	0.9049***	0.9070***	1	0.8638***	0.8980***	0.8387***
Fe_d	0.7567***	0.8184***	0.8249***	0.8638***	1	0.8564***	0.7921***
Mn_o	0.8505***	0.9150***	0.9175***	0.8980***	0.8564***	1	0.9336***
Fe_o	0.8375***	0.8890***	0.8843***	0.8387***	0.7921***	0.9336***	1

$^{***}P < 0.001$

Table 4. Correlation coefficients between measured soil properties: soil organic carbon (C_{ox}), mass-specific magnetic susceptibility using low (χ_{lf}) and high frequency (χ_{hf}) for subset C

Variable	C_{ox}	χ_{lf}	χ_{hf}
C_{ox}	1	0.9165***	0.9168***
χ_{lf}	0.9165***	1	0.9994***
χ_{hf}	0.9168***	0.9994***	1

$^{***}P < 0.001$

Table 5. Correlation coefficients between measured soil properties: soil organic carbon (C_{ox}), mass-specific magnetic susceptibility using low (χ_{lf}) and high frequency (χ_{hf}) for subset A + B + C

	C_{ox}	χ_{lf}	χ_{hf}
C_{ox}	1	0.9283***	0.9286***
χ_{lf}	0.9283***	1	0.9985***
χ_{hf}	0.9286***	0.9985***	1

$^{***}P < 0.001$

and cost-effective non-intrusive approach could be proposed based on the assumption that magnetic susceptibility may be measured directly in the field using the field sensor MS2D (Bartington Instruments 2008). A strong correlation between the volume magnetic susceptibility measured in the field and mass-specific magnetic susceptibility measured in the laboratory was documented for subplot A + B by Kapička *et al.* (2013). We should however point out that successful application of the laboratory or field method for predicting soil organic carbon content requires soils consisting of two contrast horizons,

Table 6. Correlation coefficients between measured soil properties: soil organic carbon (C_{ox}), mass-specific magnetic susceptibility using low (χ_{lf}) and high frequency (χ_{hf}), content of iron and manganese (in dithionite-citrate extract Fe_d, Mn_d and ammonium oxalate extract Fe_o and Mn_o) for subset A + B

Variable	C_{ox}	χ_{lf}	χ_{hf}	Mn_d	Fe_d	Mn_o	Fe_o
C_{ox}	1	0.9519^{***}	0.9512^{***}	0.8698^{***}	0.6986^{***}	0.8873^{***}	0.8426^{***}
χ_{lf}	0.9519^{***}	1	0.9961^{***}	0.9213^{***}	0.7642^{***}	0.9358^{***}	0.8879^{***}
χ_{hf}	0.9512^{***}	0.9961^{***}	1	0.9188^{***}	0.7670^{***}	0.9378^{***}	0.8836^{***}
Mn_d	0.8698^{***}	0.9213^{***}	0.9188^{***}	1	0.8051^{***}	0.9117^{***}	0.8452^{***}
Fe_d	0.6986^{***}	0.7642^{***}	0.767^{***}	0.8051^{***}	1	0.8048^{***}	0.7552^{***}
Mn_o	0.8873^{***}	0.9358^{***}	0.9378^{***}	0.9117^{***}	0.8048^{***}	1	0.9300^{***}
Fe_o	0.8426^{***}	0.8879^{***}	0.8836^{***}	0.8452^{***}	0.7552^{***}	0.9300^{***}	1

$^{***}P < 0.001$

Table 7. Prediction of soil organic carbon (C_{ox}) using mass-specific susceptibility (χ_{lf}) at low frequency (0.47 kHz); model A calibrated on subset A (predictions for subsets B and B + C); model AB calibrated on subsets A and B combined (prediction for subset C)

	Regression equation	R^2	RMSE
Model A			
Calibration	$C_{ox} = 0.3764^{***} + 0.2030\ \chi_{lf}^{***}$	0.9710^{***}	0.0580
External validation B		0.8723^{***}	0.1150
External validation BC		0.8518^{***}	0.1872
Model AB			
Calibration	$C_{ox} = 0.4093^{***} + 0.1894\ \chi_{lf}^{***}$	0.9060^{***}	0.0969
External validation C		0.8400^{***}	0.1901

$^{***}P < 0.001$

i.e. mollic horizon and substrate of high and low ferrimagnetic particle contents, respectively.

CONCLUSIONS

The study presents magnetic susceptibility as a novel parameter for soil degradation assessment. The results showed that magnetic measurements taken within similar Chernozem regions could provide reliable, non-intrusive, and satisfactory information for determination and monitoring of soil organic carbon content. The main advantage of magnetometric techniques is in their relative simplicity as compared to standard laboratory techniques for evaluating ferrimagnetic particles content, and in this region related soil organic carbon content. Indirect magnetic measurements are highly effective, and therefore can be very useful for larger numbers of samples at study sites.

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Corresponding author:

Ing. Ondřej Jakšík, Ph.D., Česká zemědělská univerzita, Fakulta agrobiologie, potravinových a přírodních zdrojů, Katedra pedologie a ochrany půd, Kamýcká 129, 165 21 Praha 6, Česká republika; e-mail: jaksik@af.czu.cz