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Multilevel Soil Degradation Analysis Focusing on Soil Erosion as a Basis for Agrarian Landscape Optimization

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Abstract

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The article demonstrates a multilevel method of soil degradation analysis on land within South Moravia (Czech Republic (CZ)), in the Hodonín region, which is among the highest producing agricultural regions in CZ. The analysis takes a top-down approach, from a regional scale, through cadastres, to individual blocks of land. In the initial (rough) phase, selection was based on the Soil Degradation Model created for the Czech Republic, which classifies the extent of soil degradation to a cadastral level. Within the chosen region, the Čejkovice cadastre is the most burdened in terms of the combination of various degradation factors, and was therefore chosen for a further level of analysis in the form of remote sensing. The results of remote sensing and image classification identify areas with a high level of water erosion, which is the most significant degradation factor within CZ. Pedological research was then carried out in these identified areas. The results of both approaches were compared, and showed significant differences between erosional areas and depositional areas of slopes, which confirms their suitability for the given form of research and analysis. A combination of the given general (Degradation Model) and more detailed methods (erosion modelling, image classification and soil sample analysis) can find practical application in the optimization of farm production in the rural landscape.

Keywords: aerial photos; erosion/deposition; modelling; soil analysis; soil degradation

In both specialist and political circles there is currently considerable discussion on the issue of sustainable use of the landscape and considerate methods of agricultural production. One of the problems that has to be resolved in relation to this is soil degradation. At landscape level this degradation indicates an irreversible or irresistible system change to a landscape that affects the landscape system components (i.e., their geo-factors, land use and interlinkage), the natural and cultural capacity of the landscape in terms of structure, processes, and landscape functions (productive, ecological and social), or ecosystem services. In publications there is plenty of information about the worsening quality of soils and the limited resources for agricultural production. For example, Bini (2009) describes how accelerated soil degradation has affected as much as 33% of the Earth's land surface. The main degradation factors dealt with in our research, and which have a dominant position among worldwide soil degradation, are those of soil erosion, soil compaction, loss of organic matter, soil acidification, and soil contamination. In describing the problem of evaluating soil degradation in this article we particularly focus on water erosion in a specific location.

Soil degradation due to accelerated water erosion is the most serious degradation factor globally (Lal 2001) and also in Europe, where it has a negative influence on roughly 105 million hectares of land (European Environment Agency 2003) and is among the eight soil threats listed in the Soil Thematic Strategy for Soil Protection (Commission EC 2006).

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At the same time, erosion has become part of the EU environmental agenda due to the impact on food production, water resources, biodiversity, ecosystems and carbon stock decline (Lal 2005; Boardman & Poesen 2006). The current mean rate of soil loss from arable land in the EU is 2.67 t/ha/year and is 10% higher than the overall rate of soil loss (Panagos *et al.* 2015). It is also the biggest problem in the Czech Republic, where it threatens 51.57% of agricultural land in categories ranging from land susceptible to erosion, to most threatened land (Collective 2012). According to Verheijen *et al.* (2009) the extent of water erosion is the result of inappropriate management, but also the influence of climatic changes. In the Czech Republic water erosion is a much more serious problem than wind erosion, which threatens about 14.31% of agricultural land. A further serious problem within Europe is the low content of organic matter in soils (Rusco *et al.* 2001).

In the Czech Republic (CZ) there is a tradition of relatively long-term evaluation of soil characteristics and soil degradation, which was utilized in the creation of the Soil Degradation Model of CZ (Šarapatka & Bednář 2015). This model gives information on degradation threat from water erosion, wind erosion, acidification, loss of organic matter, contamination and soil compaction at cadastral level. Another way of evaluating degradation threat is by means of modelling, especially modelling of water erosion, which is the most serious degradation factor in CZ.

A specific problem of agricultural soils in CZ is the size of land blocks, which may even exceed 100 ha. There lies an opportunity of evaluating the manifestation of erosion processes by aerial measurement images. By classical methods of research, such investigation would be very demanding, in terms of both time and money. Digital analysis of aerial measurement images is therefore a suitable alternative for evaluation of erosion/deposition processes. There are plenty of examples of application of remote sensing data which concern many scientific fields.

Elaboration of aerial images and their production on a local scale is addressed by Aber *et al.* (2010). The publication also deals with interpretation and image analysis, and the use of aerial images in various scientific disciplines, including mapping and soil degradation. Information on aerial photography and soil is also given in a publication by Pane and Kiser (2012). Practical use of aerial images in the study of gully erosion is presented by Marzolff and Poesen (2009). Similar use of aerial images and their interpretation in relation to erosion on volcanic soils is made by Servenay and Prat (2003). The method of detection of extensive erosion in the form of so-called erosional areas which was used in our research follows on from these publications, which come to similar conclusions. In addition, our research also gives an analysis of soil samples taken in the erosional and depositional parts of slopes. This adds to, and in the results it confirms the results of the image analysis of aerial photographs of selected blocks of land suffering from extensive soil erosion.

The aim of our research was to propose and verify the method of progressive analysis of landscape degradation, from a national level down to a level of individual blocks of land, using processing techniques appropriate to the individual scale. This method should also be easily applicable and beneficial in analysis, planning and optimisation of landscape in other countries.

MATERIAL AND METHODS

Study area. On the basis of results from the Soil Degradation Model (Šarapatka & Bednář 2015) the study focused on the cadastre of Čejkovice (Figures 2–4), which suffers a considerable negative influence of water erosion, in particular, as well as other degradation factors (loss of organic matter). This cadastre is located roughly 40 km SE of the regional capital of Brno in the Hodonín district. The cadastre has an area of 2506 ha and the surrounding countryside is gently undulating in character and is intensively exploited for agriculture (ca 80% of cadastre). On the dominant chernozem soils, which form 87% of the cadastre's agricultural land, the signs of erosion/deposition are distinctly evident locally on steeper slopes in exposed areas, both in soil profile and on the surface. In some places the A-horizon is completely washed away, in which case we can talk of a transformation into regosols. Climatically, the land lies within a warm area with average annual temperature of 9.2°C, and annual precipitation of 532 mm.

For analysis of soil degradation we used three levels of elaboration, from a nationwide viewpoint using the model which we proposed, through the cadastral level with a calculation of erosion threat via the erosion models right to the level of farm land using remote sensing and pedological research. Figure 1 illustrates the whole process starting with the selection of endangered cadastres according to Degradation Model, then preparing maps of potential water

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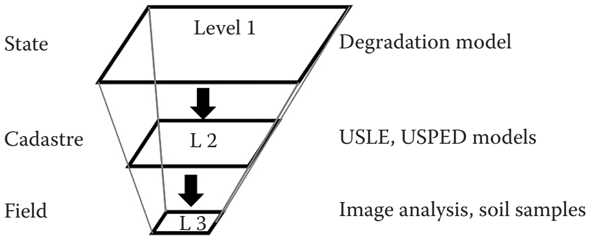

Figure 1. Process of three level analysis including methodology used

erosion threat by means of commonly used methods of Universal Soil Loss Equation (USLE) and Unit StreamPower-based Erosion/Deposition (USPED) modelling, and finally selection of individual fields for further processing according to level 2 results.

Soil Degradation Model (Level 1). The primary data source for our research was the results of the Degradation Model of CZ from all 13 037 cadastral areas within the Czech Republic. The model provides data on the susceptibility of land to certain types of degradation (water and wind erosion, soil compaction, loss of organic matter, acidification and contamination) (Šarapatka & Bednář 2015) and is the first level of evaluation of the following chosen area (Figure 2).

The model defines the aggregation index of Total Degradation Threat (TD) as:

$$\mathrm{TD} = W_{\mathrm{LOM}}\mathrm{LOM} + W_{\mathrm{ACI}}\mathrm{ACI} + W_{\mathrm{HMI}}\mathrm{HMI} + W_{\mathrm{WAE}}\mathrm{WAE} + W_{\mathrm{WIE}}\mathrm{WIE} + W_{\mathrm{COM}}\mathrm{COM}$$

where:

LOM – loss of organic matter
ACI – soil acidification
HMI – heavy metal intoxication
WAE – water erosion
COM – soil compaction
W_x – corresponding values of degradation factors

Values were determined on the basis of PCA analysis, which is suitable to use in the case of the majority of all variables (degradation factors) being mutually correlated, as described in an article by Šarapatka and Bednář (2015). The resulting TD index value is within a range from 0 (no threat) to 1 (maximum threat).

For each of the cadastres the Degradation Model also provides information on the level of threat from individual degradation factors (see above).

Figure 2 shows the area we studied, for our research an area was expertly chosen in South Moravia, specifically the Hodonín district.

The choice of land for the second phase of analysis was made on the basis of land being threatened by at least two degradation factors in the highest category of threat. The other criterion was the acreage of arable land (Figure 3).

Erosion modelling (Level 2). In order to estimate potential water erosion and identify erosional/depositional areas in the cadastre, chosen on the basis of results of the Degradation Model, the USLE and USPED models were chosen, and using GIS software ArcGIS 10.2 produced by the ESRI company, the resulting raster maps of erosion threat were produced, using methods specified in published guidelines (Janeček *et al*. 2012) and a handbook by Mitasová and Mitas (1998).

The input data for calculation was freely available hypsographic data – DMR 4G (ArGIS Online) with a pixel definition of 5 × 5m, the land block database (LPIS) and the BPEJ (SPÚ) database.

The aim of this phase was to choose locations for detailed research using the methods of aerial

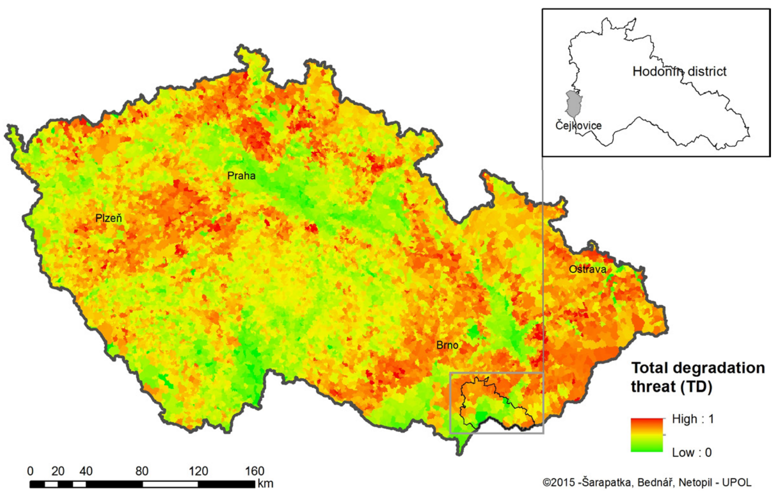

Figure 2. Results of the Soil Degradation Model for the Czech Republic with the area of interest, the Čejkovice cadastre, marked (Šarapatka & Bednář 2015)

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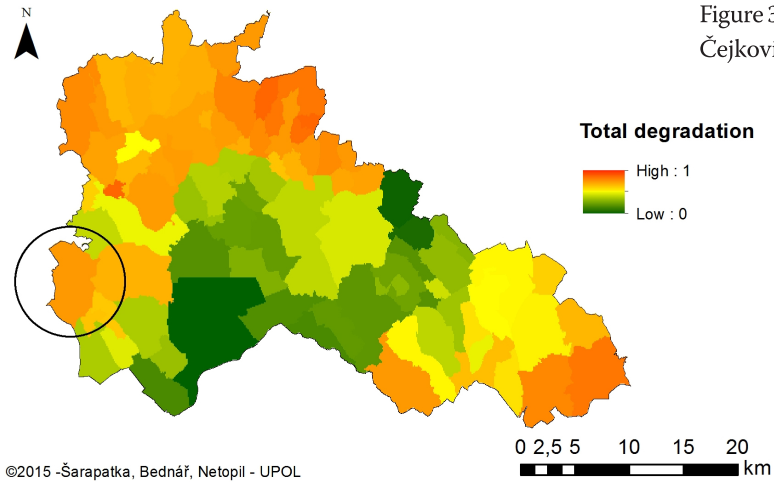

Figure 3. Total soil degradation in Hodonín district, CZ; Čejkovice research area is marked by the circle

photography and control soil-sampling in situ. The following criteria were chosen: level of potential erosion threat to the land block, size of land block and availability of aerial photographs from the appropriate time period (outside the vegetation period) with clearly evident signs of erosion activity.

Remote sensing analysis (Level 3). Our research was based on digital aerial measurement images which capture the current state of land under investigation. Aerial images were taken in 2003 using an analogue camera and colour photographic material and then digitalized on a photogrammetric scanner (14 micrometers per pixel) to have a seamless colour orthophotographic map of CZ produced, by the company Geodis Brno s.r.o., to a scale of 1 : 20 000 (spatial definition of 50 cm/pixel). Images were available in data format as TIFF or JPEG files in the layout of 1 : 5000 scale national maps derived (SMO-5, grid system S-JTSK/Krovak East North). The main method of evaluation of the extent of erosion was unsupervised image classification, which was carried out by means of the ERDAS Image programme, the Classifier module and the Unsupervised Classification (Isodata) tool.

For our study we chose chernozem soils, where the spectral characteristic is most influenced by the content of organic matter, followed by soil humidity, texture and composition of mineral content of the soil (Lillesand *et al.* 2007). The increased content of organic carbon leads not only to the actual name of the soil type, it also significantly shows in the dark colour of the humous A-horizon, or in radiometric information in aerial photographs. If the original soil profile is disturbed (erosion), often down to the soil-forming substrate (loess), a distinct colouration is also evident in the photographs. Erosional areas are significantly lighter than various dark areas of undisturbed, transitional or only partly disturbed chernozem profile/topsoil horizons.

Interpretation of the results of unsupervised image classification was carried out in the Erdas Image program by means of the Interpreter module and GIS analysis instrument. Individual spectral classes/categories were reclassified with regard to the level of disruption to soil by erosion, and thus classes of information were created which were subsequently combined into three thematic final classes: stable/depositional, transitional, eroded based on pedological interpretation of images, as previously stated. The first category included areas undisturbed by erosional and depositional areas. The second category included areas where the soil profile was partially disturbed by erosion, and the third included areas heavily affected by erosion. The resulting interpretation of the aforementioned categories was based on knowledge of the manifestation of erosion in the soil profile. Use was also made of selected forms of analysis of the soil samples taken.

Field measurements, water erosion models and statistical evaluation. A control evaluation and study of chosen basic soil characteristics, from undisturbed soil samples taken by means of a Stitz GmbH dynamic sampling probe, was carried out in the locations evaluated via image analysis (see above). On the basis of image analysis and interpretation of its results, one sample was always taken from the erosional area of the slope and one sample from the depositional area. Locations for deep sampling of soil profile were selected on the basis of a map of erosion-affected areas (Figure 4). GPS equipment was used for localisation in the field (Magellan Mobile Mapper 6). Within selected blocks of land

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with signs of erosion six undisturbed deep probes of soil profile were taken to a depth of one metre. Subsequently the undisturbed soil profiles were divided into 60 soil samples measuring 10cm. After laboratory preparation and processing, analysis was carried out on selected soil characteristics, i.e. basic soil characteristics, such as texture (pipette method), C_{org} (wet oxidation followed by titration), pH/$CaCl_2$ and $CaCO_3$ content (gasometric measurement of CO_2) (Page *et al.* 1982; Klute & Page 1986) and spectral reflectance, which was measured with an X-Rite SP62 portable spectrophotometer (X-Rite, Inc., Michigan, USA). The aim was to make a physically based quantitative comparison of topsoil and subsoil horizons of the samples taken. The choice of analytical method was generally based on the aforementioned prerequisite that the erosion-disturbed soil-profile has a weak or non-existent humus horizon, and on the surface there is, to a certain extent, a presence of soil-forming loess substrate, which is significantly lighter than a humus chernozem A-horizon. The analysis was intended to show the difference between erosion-disturbed soil profiles of erosion and depositional areas, or even areas completely undisturbed by erosion, within the land block. Soil samples were taken (Figure 5) including both erosional and depositional areas in a network of sampling locations relevant to the representative collection of samples (Zbíral & Honsa 2010). The aim of this level of evaluation was to verify the results of image analysis of aerial photos and the state of the soil profile in erosional and depositional areas.

The results obtained from sample analysis were statistically evaluated by means of the STATISTICA programme (StatSoft, Ver. 12, 2013) with testing of the difference between groups (parametric comparison).

RESULTS AND DISCUSSION

Soil Degradation Model. According to the Soil Degradation Model of CZ (Šarapatka & Bednář 2015) the Hodonín district is particularly threatened in its northern and eastern parts, as shown in Figures 2 and 3. Most of the cadastres are threatened by water erosion, which is typical for this region. For further research in the form of remote sensing, land was chosen in Čejkovice cadastre, which includes the greatest area of arable land (1604 ha). In terms of overall TD values, Čejkovice is within the category of moderately to highly threatened land (TD = 0.65) and, besides water erosion, loss of organic matter is also a problem in this area.

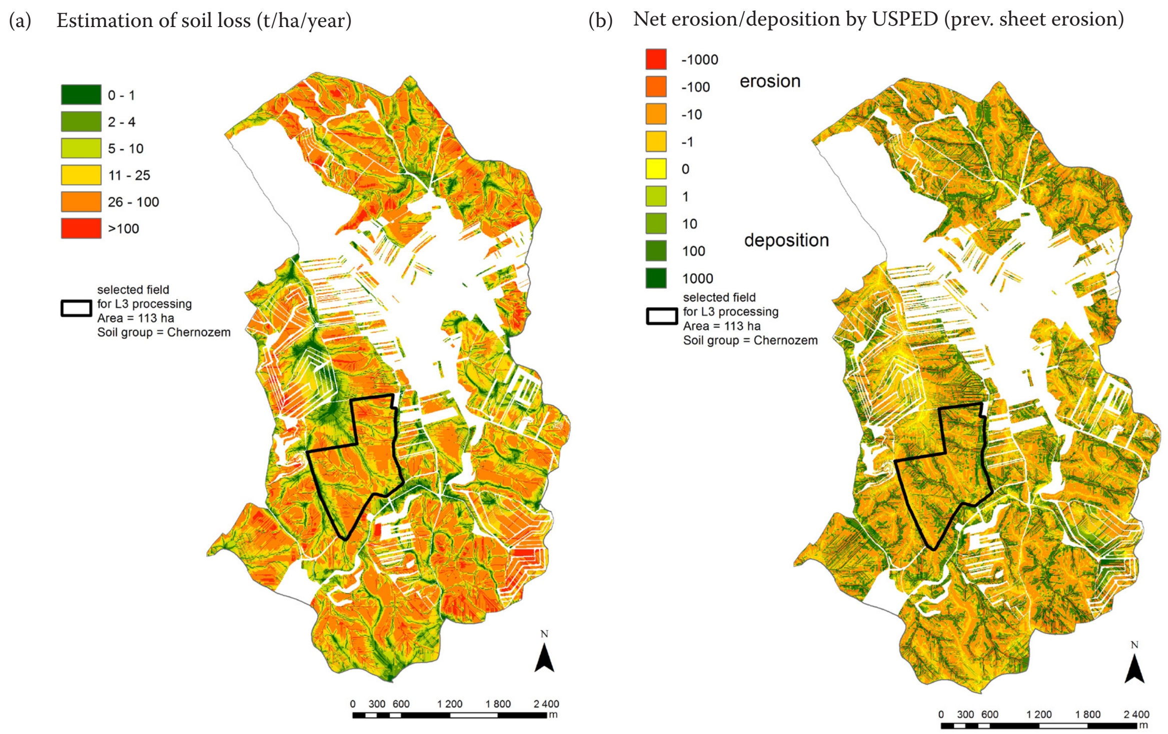

Figure 4. Results of erosion analysis with the specific land block marked erosion USLE model (a) and USPED model (b) of Čejkovice area

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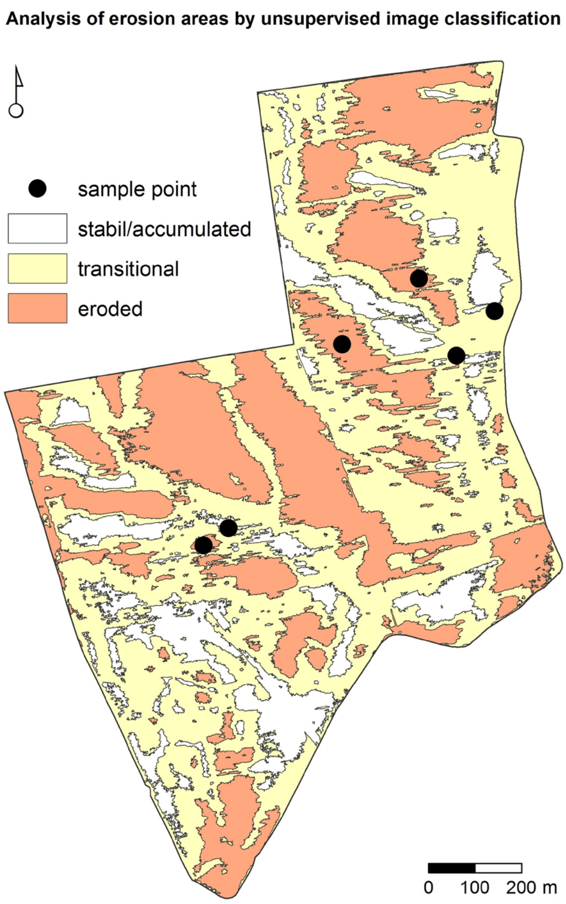

Figure 5. Unsupervised image classification of aerial image including its interpretation – Čejkovice cadastre

Erosion modelling. In order to estimate potential water erosion and identify erosional/depositional areas in the Čejkovice cadastre, raster maps of erosion threat, with a pixel resolution of 5 × 5m, were created on the basis of USLE and USPED methods. Zonal analysis of land blocks allowed average values of erosion threat to be attributed to individual blocks. Along with the land block size and available aerial images, these average values were the basis for selection of land blocks for subsequent processing by means of spectral analysis. The results of erosion modelling and the chosen land block for the next phase of processing are shown in Figures 4a, b.

Remote sensing analysis. We have addressed the intensity of water erosion in chosen localities in model form with the aim of verifying models used in CZ (especially USLE) with the application of image analysis, as well as control soil samples from erosional and depositional localities. This meets the requirements described by Cerdà *et al.* (2013) to develop scale-explicit understanding of erosion, to overcome existing flaws in methods applied, and to understand the process of erosion, transport and deposition.

Table 1. Average values of selected observed soil chemical characteristics in depositional and erosional areas of slopes

Horizon and characteristics	Erosional area	Depositional area	*P* (2-tailed)
Topsoil horizon (m)	0–0.3	0–0.4	
C_{org} (%)	0.62	1.09	0.000
Carbonates (%)	17.14	4.40	0.000
pH/$CaCl_2$	7.75	7.59	0.080
Subsoil horizon (m)	0.3–1.0	0.4–1.0	
C_{org} (%)	0.20	0.41	0.000
Carbonates (%)	15.94	13.59	0.156
pH/$CaCl_2$	7.82	7.82	0.930

The results stated above (Figure 5) confirm the great potential of aerial photography in pedology (erodology), for research in both small and large-scale landscape.

Specifically, this archive and current source of information can be used to detect areas of erosion in the intensively-farmed landscape. It creates an interdisciplinary link between photogrammetry (orthorectification), geoinformatics (image analysis – classification) and soil science (interpretation of image/surface of soil profile). Systematic aerial photography began in the Czech Republic in the late 1930s. The images served primarily as control material for the creation of topographical maps, and nowadays they have various uses, for example in research into erosion processes in the landscape. The basic prerequisite in observing the development of erosional areas by means of aerial photography is, in terms of soil science, the significant difference between the topsoil and subsoil horizons. These characteristics also project into radiometric information in aerial photos which is utilised in classification algorithms of software specialising in image analysis.

Field measurements and water erosion models. The resulting values of selected analysis of soil characteristics shown in Table 1 were averaged, within statistical processing, for depositional and erosional areas of slopes. In the depositional soil samples, on the basis of varying characteristics, a topsoil horizon was set at a depth of 0–40 cm, followed by a subsoil horizon from 40–100 cm. In the erosional sample, on the basis of the studied characteristics, a topsoil horizon was set at a depth of 0–30 cm and a subsoil horizon from 30–100 cm.

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The resulting average values showed distinct differences between soil samples in the depositional and erosional areas of slopes (Table 1).

A high content and quality of organic carbon (humus) is the basic diagnostic characteristic of the chernozem A-horizon. The distinct difference between content of organic carbon in the topsoil layers in the depositional and erosional samples clearly shows the disturbance, and even total washing away of the humous A-horizon in locations of so-called erosional area, while the opposite applied in little-disturbed locations and depositional areas. Each hectare of an average bulk density of 1.35 t/m^3 in the topsoil horizon contains, in the erosional part of the slope, 25.1 t C to a depth of 0.3 m, whereas, in the depositional part it is 58.9 t C to a depth of 0.4 m, i.e. 44.2 t to a depth of 0.3 m.

The erosion processes are intensive in the studied area and the depth of the colluvial horizon may be even greater than the samples taken to a depth of 1m (Zádorová *et al.* 2013). This is indicated by the average C_{org} content we determined in the subsoil horizon in the depositional area of the slope, showing a value of 0.41%. This indicates that it is a mixed horizon consisting of mollic humous horizons with a soil-forming substrate, loess.

The changes in content of soil organic matter correspond with the results of studies summarised by Kirkels *et al.* (2014). Soil organic carbon (SOC) is susceptible to erosion due to its greater presence in the surface layer and low bulk density. Light fractions are preferentially transported over longer distances; this includes clays and labile SOC (Lal 2003; van Oost *et al.* 2009). Deposition may occur in various areas of land, with potential storage in colluvial, alluvial or waterlogged sites (Liu *et al.* 2003). Other soil characteristics, such as compaction, nutrient content and bacterial biomass, also relate to loss of organic matter (Gregory *et al.* 2009; Hirsch *et al.* 2009; Johnston *et al.* 2009). Overall reduction in the organic matter content of soil also relates to global climatic changes. Therefore, in recent years there has been intensive discussion of the potential of SOC sequestration, which is addressed e.g. in a study by Lugato *et al.* (2014), who state that protection of soil against erosion must be an integral part of SOC management.

A further typical characteristic of chernozem soil profile under Central European climate, is the leaching of carbonates from the topsoil horizon, and an increase in the subsoil horizon. In evaluation of surface layers of erosional samples, values are similar to the subsoil horizon of depositional samples. From this it transpires that increased values of carbonates in erosional areas of slopes relate to the resulting level of organic carbon. The average pH levels across the soil profile, rounded up to one tenth of a point, show a difference only in the topsoil horizon of the depositional sample. This can be put into context with the significantly lower content of carbonate in this part of these samples. These results are in agreement with the conclusions of Jakšík *et al.* (2015), who state an opposite trend for $CaCO_3$ than for C_{org} due to loess exposition at the eroded parts. Their study also finds no statistically significant differences in pH between the erosional and depositional areas, as values reflected the combination of C_{org} and $CaCO_3$ content. The spectral reflectance measurement was based on the assumption that the dark chernozem topsoil horizon would have greater absorption of radiation than the subsoil, which in contrast would have greater reflectance of radiation, which also proved to be true in the depositional samples. In the erosional bores the difference in reflectance between the topsoil and subsoil horizons was roughly half that found in the depositional bores, and the erosional profiles even looked distinctly lighter and more like the subsoil horizon of the depositional profiles. Changes in organic matter content are also confirmed by the results of subsequent additional reflectance measurement, where statistically significant differences were found in topsoil horizons of erosional and depositional areas of slopes, i.e. at $P < 0.001$. Reflectance was also statistically significant between the topsoil and sub topsoil horizons in erosional and depositional areas of slopes, which helped to identify the boundary between these two horizons.

Erosion processes also have an influence on the physical characteristics of soil, such as aggregate stability, bulk density a penetration resistance (Stavi & Lal 2011). One of the observed parameters in our study was also the assessment of grain according to the same rules for division of soil samples. The results of grain measurement, between topsoil and subsoil horizons of the depositional and erosional samples showed that erosion processes were particularly apparent in the finest fractions, in which statistically significant differences were found between erosional and depositional areas of slopes. In the topsoil horizon these differences were recorded as $P < 0.001$ in the finest fraction smaller than 0.001 mm. Similarly, in the subsoil horizon, in comparison of the entire profile from 0 to 1 m, these differences were recorded

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at significance level of 99% for fractions < 0.01 mm, < 0.001 mm, and for both fractions together. These results prove that erosion processes transported mainly particles with active surfaces, both the clay fraction and organic matter, thus changing the proportion of these in the soil. Some research reports (Ampontuah *et al*. 2006; Shi *et al*. 2012) describe a tendency towards the deposition of coarser particles – silt up to 63 μm, due to the fact that finer aggregate particles are more resistant to disturbance and wash-off. In our case, with severe soil degradation along with mineralization of organic matter, there is greater damage to aggregate stability and clay particles can be transported more easily. These particles can be deposited not only in lower parts of slopes, but sediment can also accumulate in various fluvial settings, which is described for the Moravia region e.g. by Sedláček *et al.* (2016). According to their research the proportion of clay and organic matter is greater in oxbow lakes and meanders than in reservoirs.

CONCLUSION

The study developed an evaluation of the state of erosion-threatened land which accounts for approximately half of the arable acreage in CZ. The approach described is a model solution, which, within the principles of ecological engineering (Constanza 2012), is also applicable in other regions outside the Czech Republic, and, in landscape planning and projection of management systems, can lead to sustainable use of the agricultural landscape, both in terms of its productive and non-productive roles.

The analysis described in this article is important not only for evaluation of the degradation of agricultural land, but also as the basis for a scenario of the influence of degradation processes on the production of cultivated crops. There is a lack of published information about the reduction of crop yield, for example we can draw on the publication by Oldeman (1998), who calculated that global cropland production was 12.7% lower than it would have been without degradation; Pimentel *et al*. (1993) who estimate that global production is 15–30% lower as a result of all the various effects of soil erosion. Montanarella (2007) states that, for land within Europe, the total cost of soil degradation, on the basis of available data, would be up to 38 billion Euro annually for EU25. A study on this theme was published by Telles *et al*. (2011). An important element on the selected erosional and depositional areas will be our own research, which will allow the calculation of lost yield in wider areas of South Moravia as an agricultural production area of the Czech Republic.

The study proved the effectiveness of the chosen form of analysis of land threatened by soil degradation by means of several instruments at various levels of focus, from the rough Degradation Model to image classification from aerial images and to analysis of soil samples.

The use of remote data in the study and evaluation of the erosion/accumulation process proved to be highly effective. Mapping erosional areas, specifically by means of aerial measurement images is still an undervalued approach which has its own specifics. A very important factor is the choice of location affected by erosion, where there is a distinct difference in the spectral manifestation of the topsoil and subsoil layers of the soil profile, which was the case in the observed chernozems. Of equal importance is the date of the images, i.e. the bareness of the soil surface. Detection of erosional areas via image analysis and subsequent soil science interpretation was verified by control analysis of selected soil characteristics within the observed erosion profile. Depositional areas, transitional areas or areas undisturbed by erosion are not clearly distinguishable on the analysed images.

The limiting factor for the detection of erosional and depositional areas is the quality of aerial images, which is also influenced by soil type and the time of year the photos were taken. In this study the problem of evaluating soil degradation was elaborated on chernozem soils with varying spectral manifestation of individual diagnostic horizons. In subsequent research we also intend to focus on other soil types where the spectral differences are less evident. This research is also important from the point of view of the repeatability of the chosen approach. This is now possible, especially on chernozem soils, not only within the Czech agricultural land fund, but analysis of erosional areas by means of aerial images can also be utilised in other countries where remote data is available.

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