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Which quality indicators reflect the most sensitive changes in the soil properties of the surface horizons affected by the erosion processes?

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Abstract: Soil erosion, especially water erosion, is one of the most widespread types of soil degradation, not only worldwide, but also within the Czech Republic, where it endangers more than a half of the agricultural land. In addition to farming, the landscape structure has a significant impact on soil erosion in the conditions under study, where, especially in the post-war period, the collectivisation of large-scale arable land was accompanied by the abolition of the associated landscape elements. The agricultural production area of South Moravia is one of the most endangered areas in the Czech Republic, therefore, it was selected for our research, whose main objective was to verify the sensitivity of the selected physical, chemical and biochemical characteristics to identify the changes in the soil properties in the erosion processes at the identified erosion areas. The testing was carried out within a period of 5 years in 60 locations with Chernozems with cultivated corn. To assess the quality of the soil properties, indicators of soil quality from the physical, chemical and biological – biochemical groups were selected. The results of the analyses and the subsequent statistical evaluation showed that the chemical characteristics, especially those related to the quantity and quality of the organic matter, were the most sensitive to the changes in the soil properties. From the biochemical indicators, some enzymes, particularly dehydrogenase and acid phosphatase, reacted sensitively. The physical characteristics were not significantly affected by the erosion processes.

Keywords: physical, chemical and biochemical characteristics; soil; soil quality indicators; water erosion

Erosion is generally considered to be a major cause of arable land degradation (Li et al. 2007) and it is associated with changes in the soil properties, significantly affecting crop yields, and also worsening the hydrological and other non-productive soil functions. From a long-term prospective, it can lead to a gradual change in the hydrological regime in the landscape (Boardman & Poesen 2006). Water erosion is not only a major global problem, it also endangers more than 50% of the soil in the Czech Republic, with an estimated land loss due to erosion being at 21 million tonnes of topsoil per year (Collective

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2018). Within the land, erosion leads to the land shifting from the convex parts of the slopes and to its accumulation in the concave parts (Govers et al. 1994; Lobb et al. 1995; Sensoy & Kara 2014) and part of the material is taken away from the agricultural land with extensive damage. An incorrect economic activity is often irretrievably damaging the land, where its amount that is taken away can exceed the amount of land created by the natural processes by many times (Verheijen et al. 2009).

The erosion-influenced slopes occur both in the area and in the concentrated runoff to transfer the soil particles, to lose carbon and other nutrients, and to influence many soil properties (Cheng et al. 2010). A number of studies have described the greater adsorption of nutrients and agrochemicals on finer soil particles with their subsequent transfer (Ghadiri & Rose 1993; Padmalal et al. 1997). Other negative manifestations of the erosion related to crop production can include limited rooting, a decrease in the available water resources, reduced soil fertility and adverse physical conditions. (Ebeid et al. 1995). In connection with these physical properties, for example, Jankauskas et al. (2007) or Arriaga (2003) described the increasing erosion intensity with the increasing bulk density. The shift and redistribution of a significant proportion of organic matter and nutrients into the lower parts of the slopes is also serious (Polyakov & Lal 2004a; Chaplot & Poesen 2012). The research has confirmed that soil erosion can change not only the physical and chemical properties of the soil, but also the biological properties, such as the microbial composition, the abundance of individual edaphons or the enzyme activity (Xu et al. 2010; Hiltbrunner et al. 2012). According to the research, these biological characteristics may respond to changes in the environmental conditions more sensitively and sooner than the other soil parameters (Lynch et al. 2004; Odlare et al . 2008). The activity of the microorganisms in the soil plays an important role in biotransformation, nutrient cycles and in the enzyme activity (Zhang et al. 2009; Burns et al. 2013). Thus, these activities can be a useful tool for assessing the functional diversity of the microbial communities in the soil or in the organic matter transformation (Kandeler et al. 1999).

Nutrients in the soil, especially N and P, but the organic matter also, are subject to losses due to water erosion. An increase in the proportion of smaller particles is observed in the eroded material, resulting in an increase in the proportion of the minerals and organic colloids and, therefore, the sediment becomes richer in nutrients (Bertol et al. 2003). Soil erosion also preferentially removes fresh and more labile C-rich materials from the topsoil (Wang et al. 2014). Most of the eroded soil is known to be relocated near source areas and basins (Smith et al. 2005). The eroded and subsequently settled C can be stabilised by the interaction with minerals, thereby reducing the C-deposited mineralisation in the soil profile (Wang et al. 2013). Wang et al. (2013) also found out higher concentrations of the dissolved organic carbon at the deposition sites.

From the brief review above, the effect of erosion processes on the physical, chemical and biological properties of soils is evident. In this context, the aim of our research was to verify which of these selected indicators reflects the most sensitive changes in the soil properties in the erosion and accumulation processes.

MATERIAL AND METHODS

Location selection and sampling the soil samples. The research took place between the years 2012 and 2016 in the area of South Moravia, CZ on Chernozems (IUSS Working Group WRB 2015). The selection of the localities in the selected cadastral areas are as follows: Krumvíř (48.9890058N, 16.9102728E), Horní Bojanovice (48.9497050N, 16.8001464E), Hustopeče (48.9408467N, 16.7376211E), Ostrožská Nová Ves (49.0043386N, 17.4363183E), Ostrožská Lhota (48.9755900N, 17.4675133E), Syrovín (49.0258231N, 17.2639311E), Vracov (48.9752289N, 17.2109967E), Velké Bílovice (48.8492886N, 16.8922736E), Čejkovice (48.9059197N, 16.9423033E) and Hovorany (48.9549308N, 16.9934561E). This selection occurred using the ESEU maps (evaluated soil – ecological units) and according to the erosion threat of the land modelled assistance using the Universal Soil Loss Equation (USLE/RUSLE) (Wischmeier & Smith 1978). Moreover, 60 sampling locations with the designation C (control with minimal manifestations), E (erosional parts) a D (depositional parts) were gradually selected on the individual blocks of the arable land with a cultivated crop – maize using the USPED (Unit Stream Power – Based Erosion Deposition) model (Mitášová et al. 1996; Mitáš & Mitášová 1998).

The soil samples for the chemical and biochemical analyses were taken from the 0–20 cm horizons using a probe rod from the company Eijkelkamp according to

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the International Standard (ISO 10381-1, 2002). The collected mixed samples specified for the chemical analysis were air dried and sieved (2 mm size) (ISO/DIS 11464, 2004). For the biochemical analysis, the non-dried samples were sieved as soon as possible and analysed (ISO 10381-6, 2009).

The soil samples were taken from the topsoil at a depth of 5–25 cm to determine the physical characteristics. For sampling, Kopecky rollers (100 cm^3) were used. 8 intact samples were taken from all the sampling locations. The same samples were used to determine the grain size as for the chemical analysis of the soils.

Soil samples analysis. The selected soil characteristics were determined according to the following procedures:

From the physical characteristics, the bulk density, the total porosity, the maximum capillary water capacity and the minimum air capacity were determined after sampling into the Kopecky rollers. The physical properties were determined using the standard method of Zbíral and Honsa (2010). The stability of the soil aggregates was determined by wet sieving (Kandeler 1996).

In the study of the chemical characteristics, the content of the available phosphorus and calcium was determined using the extraction solution according to Mehlich III, followed by atomic absorption spectrophotometry, atomic emission spectrophotometry and photometry (Mehlich 1984; Zbíral & Honsa 2010). Total organic carbon (C_{ox}) content was determined by the soil oxidation with a chromsulfuric mixture and the colour intensity was then measured by spectrophotometry (ISO 14235, 1998; Zbíral et al. 2011). Total nitrogen (N_{tot}) was determined by the oxidation of nitrogen peroxide in a concentrated sulfuric acid environment. After mineralisation, distillation into boric acid was carried out and the crude protein content was determined by titration with H_2SO_4 (ISO 11261, 1995; Zbíral el al. 2011). The soil reaction was determined as pH/H_2O (ISO 10390, 2000; Zabíral & Honsa 2010). The humus fractions were determined by a modified procedure (Kononova & Běličková 1961), where the C of all the humus substances was determined by evaporation of the pyrophosphate leachate and the C content of the humic acids was determined after the dissolution of NaOH.

In the study of the biochemical characteristics, the enzymatic activities were determined by means of a colorimetric ending. The cellulase activity was determined using CM-cellulose as a substrate (Schinner & von Mersi 1990). The phosphatase activity was measured using p-nitrophenyl phosphate as a substrate (Tabatabai & Bremner 1969). The dehydrogenase activity was determined using a triphenyltetrazolium chloride substrate (Ross 1970). For the determination of the urease activity, the soil samples were incubated with a urea solution (Tabatabai & Bremner 1972). To determine the protease activity, the soil samples were incubated with casein (Ladd & Butler 1972).

Statistical evaluation. The results of all the analyses were evaluated by the STATISTICA statistical program (Ver. 12.0, 2013), in which, the basic characteristics of the groups were performed. Evaluation of the statistically proven differences among the groups was performed by the Mann-Whitney U test. Furthermore, the influence of the slope parts on the measured environmental characteristics was evaluated from the obtained data. The individual parts of the slope entered the analysis as independent variables (control, erosion and accumulation) and the physical, chemical and biological properties of the soil were used as the dependent variables. The data were analysed using the linear redundancy analysis (RDA) direct model. Furthermore, the significance of the individual independent variables using a forward selection method was also tested. The significance of the RDA model and the individual variables was tested by the Monte Carlo permutation tests (Lepš & Šmilauer 2000). All the analyses were performed in the CANOCO 5 programme.

RESULTS AND DISCUSSION

Water erosion causes changes in the physical and chemical properties of the soil, including changes in the soil structure, organic matter content, calcium carbonate content, and nutrients (Kosmas et al. 2001; Li & Lindstrom 2001; Šarapatka et al. 2018). These changes were also covered by our research, where we statistically processed the results of analyses of the physical, chemical and biological – biochemical properties for the individual parts of the slopes – control, erosion and accumulation.

Although the results of the analyses and their basic statistics presented in Table 1 indicate the differences in the studied characteristics among the slope parts, the statistically significant differences between the slope positions after the use of the Mann-Whitney U test shown in Table 2, however, show only differences in some of the characteristics, most of which

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were recorded between the erosional and depositional part of the slope (8 – incl. enzyme activity – out of the 22 studied characteristics), followed by differences between the control and erosional parts of the slope (7 – incl. enzyme activity – out of the 22 studied characteristics). The least statistically significant differences were between the control and depositional parts (only two statistically significant differences). It is, thus, possible to state that these parts of the slopes (control and depositional) are similar in the studied characteristics.

In addition, from the chemical characteristics, the N_{tot} content was statistically significant between the erosional and depositional part of the slope (0.13 and 0.16%, respectively), the C CHS – content of the humic substances (0.25 and 0.40% respectively), C HA – the content of the humic acids (0.10 and 0.21%, respectively), C : N (15.04, respectively 12.98), the Ca content (7561.43 and 5951.14 mg/kg, respectively), with which it is related to the pH/H_2O (7.67 and 7.56, respectively), and statistically significant differences in these parts of the slopes of the P content available (40.86 and 62.43 mg/kg, respectively). These results are consistent with some other published studies (Polyakov & Lal 2004b, Nie et al. 2013), which report that erosion results in the faster loss of organic carbon, nitrogen and phosphorus. For these reasons, the deposition area is considered as a carbon repository (Zhang et al. 2013). The soil fertility and productivity are also dependent on the nutrient content and circulation of the organic matter (Steiner et al. 2007; Bhattacharyya et al. 2010). However, not only the amount of soil organic mat-

Table 1. The values of the studied physical, chemical and biochemical soil properties in the individual parts of the slopes

Soil characteristics	C – control part			E – erosional part			D – depositional part		
	average values	median	SD	average values	median	SD	average values	median	SD
Bulk density (g/cm^3)	1.65	1.61	0.22	1.72	1.60	0.25	1.59	1.56	0.15
Particles 2.00–0.05 (mm)	23.06	23.46	6.65	25.09	24.18	7.17	30.28	27.02	15.21
Particles 0.05–0.002 (mm)	49.21	48.65	6.99	50.31	50.73	6.51	46.43	50.57	11.98
Particles < 0.002 (mm)	27.74	27.66	4.92	24.75	25.27	3.81	23.31	23.28	5.17
Maximum capillary water capacity (% vol.)	36.44	36.36	5.89	37.73	36.89	6.21	36.74	36.52	3.67
Total porosity (% vol.)	39.71	39.31	4.36	41.36	40.94	5.39	40.96	40.71	4.00
Minimal air capacity (%)	5.94	5.97	3.13	5.54	5.96	2.29	6.96	7.37	2.98
Soil airiness (% vol.)	11.27	10.58	4.07	12.67	11.63	5.32	15.07	11.25	7.29
Water stability of soil aggregates (%)	33.14	29.53	18.97	28.61	23.56	14.76	30.02	29.29	12.69
pH/H_2O	7.52	7.69	0.46	7.67	7.78	0.42	7.56	7.61	0.31
C_{ox} (%)	2.26	2.23	0.39	1.98	2.01	0.36	2.13	2.07	0.49
N (%)	0.16	0.16	0.03	0.13	0.13	0.03	0.16	0.17	0.02
C CHS (%)	0.37	0.39	0.16	0.25	0.24	0.11	0.40	0.40	0.20
C HA (%)	0.19	0.20	0.11	0.10	0.09	0.07	0.21	0.22	0.12
C : N	14.64	13.84	2.46	15.04	14.81	2.43	12.98	12.58	1.91
Ca (mg/kg)	6 587.93	6 940.00	2 212.53	7 561.43	8 107.00	2 107.22	5 951.14	6 118.50	1 541.42
P (mg/kg)	76.82	51.00	71.39	40.86	32.50	28.36	62.43	54.00	28.81
Dehydrogenase (µg TPF/g DW/16 h)	4.11	3.68	2.70	3.15	3.32	1.65	4.37	3.84	2.45
Acid phosphatase (µg NP/g DW/h)	283.90	261.93	132.30	226.48	187.17	124.59	256.46	218.94	115.93
Urease (µg N/g DW/2 h)	984.79	982.11	453.41	857.55	856.33	322.64	988.33	1 034.16	298.84
Cellulase (µg GE/g DW/24 h)	123.87	111.60	69.18	115.50	101.81	60.28	114.69	103.94	63.82
Protease (µg tyr/g DW/2 h)	90.58	78.83	58.93	94.26	91.54	59.24	90.50	93.96	59.52

CHS – content of the humic substances; HA – humic acids; TPF – triphenyl formazan; NP – nitrophenol; GE – glucose equivalents; tyr - tyrosine equivalents; SD – standard deviation

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Table 2. The statistically proven differences between the slope parts (Mann-Whitney U test)

	pH/H_20	C_{ox}	N_{tot}	C CHS	C HA	C : N	Ca	P_{avail}
Erosional vs. depositional part	X		X	X	X	X	X	X
Control vs. erosional part	X	X	X	X	X			X

C_{ox} – total organic carbon; N_{tot} – total nitrogen; P_{avail} – available phosphorus; CHS – content of the humic substances; HA – humic acids; there are statistically proven differences in the dehydrogenase activity between the erosional and depositional parts of the slopes in the biochemical characteristics, in the acid phosphatase activity between the control and erosional part of the slopes; there were no statistically proven differences between the slope parts for the physical characteristics

ter, but also its quality is important in terms of soil quality (Liu et al. 2006). The lower pH and higher calcium content in the erosional parts of the slopes are indicative of the intense erosion processes, and the blending of the surface horizons remains as a soil-forming substrate (Šarapatka et al. 2018). The effect of the erosion processes on the calcium content is confirmed by the published results of similar studies, which further report that the yields tend to be the lowest in the eroded areas where the calcium substrates are exposed and are low in organic matter (Stewart et al. 2002; Cox et al. 2003).

In the biochemical characteristics, there was a statistically significant difference in the dehydrogenase activity (3.15 and 4.37 μg TPF/g DW/16 h, respectively). A statistically significant difference was observed in the activity of the acid phosphatase in the activity of the soil enzymes, between the control and erosional part of the slopes (283.90 and 226.48 μg NP/g DW/h, respectively). The increased acid phosphatase activities were also observed in the depositional part of the slope compared to the erosional part (256.46 and 226.48 μg NP/g DW/h, respectively), but this difference was not statistically proven at $P < 0.05$. There is a similar situation with C_{ox}, when it was (2.26 and 1.98% respectively) between the control and erosional part of the slope. There was also a difference between the depositional and erosional part of the slope, but it was not statistically proven (2.13 and 1.98%, respectively).

The process of the conversion of the organic matter into the soil environment takes place with the participation of the soil microorganisms and their associated enzymes (Schimel & Bennett 2004). The effect of the erosion on the enzymatic activity, also confirms these results, where we experienced higher enzymatic activity in the deposition areas compared to the erosional parts of the slopes. These results are confirmed by, for example, the study by Garcia & Hernández (1997), which demonstrated the lower biological activity in the dehydrogenase and catalase in degraded soils.

Although there were some differences in the physical characteristics between the slope parts (Table 1), these were not statistically proven and require a follow-up monitoring, although in all three parts of slope, the results indicate some disruption to the soil environment (e.g., high bulk density, low porosity). The results of the granular composition of the soil indicate a certain homogenisation of the soil environment and the possible removal of fine soil particles outside the monitored locations, as described, for example, by Stone et al. (1985).

To determine which characteristics are most sensitive to the ongoing erosion, the RDA analysis was chosen. Figure 1 includes all the physical, chemical and biological characteristics of all the studied parts of the slopes. This model proved to be significant ($F = 2.5$; $P = 0.004$) and helped to explain the 5.8% variability. We repeatedly performed this analysis, also omitting the control part of slope, again with a similar significant result ($F = 3.6$; $P = 0.002$), with the explained variability being 6.3%.

Subsequently, analyses were carried out separately for the individual groups of the characteristics (physical, chemical and biological), again for all parts of the slopes and then only for the erosion and accumulation parts, the results of which were very similar, as in the analyses without omitting the control part of the slope. Taking the individual characteristics, the model of the chemical properties significantly occurs ($F = 6.2$; $P = 0.004$), which explained the 13.3% variability (Figure 2). From this, it can be seen that the erosional part of the slope indicates a higher C : N ratio and Ca content, suggesting a less decomposed and humified portion of the organic matter, as well as the de-eroded surface horizons of the outflows with a higher Ca content. The amount and quality of the organic matter expressed by C_{ox}, N_{tot} and the C humus substances and the humic acids, as well as

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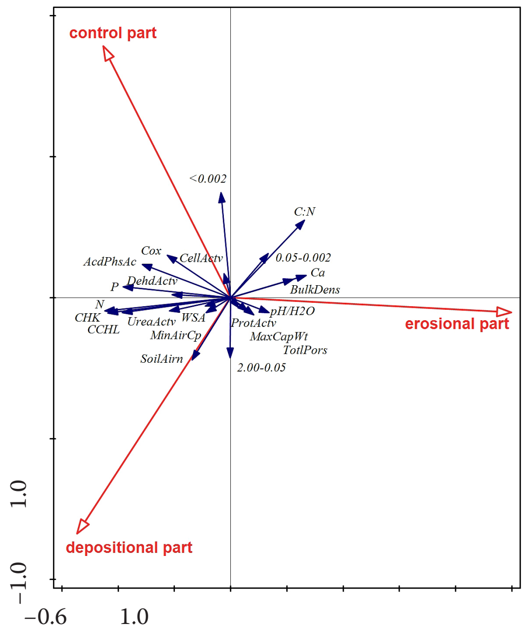

Figure 1. The redundancy analysis (RDA) ordination diagram describing the relationship among the individual slope parts and all the soil characteristics

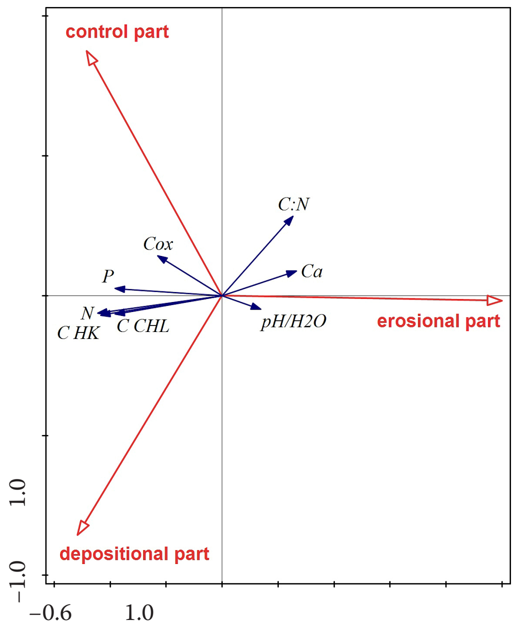

Figure 2. The redundancy analysis (RDA) ordination diagram describing the relationship among the individual slope parts and the soil chemical characteristics

the higher levels of the available nutrients (expressed herein as the acceptable P content) were increased approaching the depositional parts of the slopes.

The biological – biochemical properties (Figure 3) do not come out as being significant as a whole (F = 1.5; P = 0.14), but the significant erosion of the slope (F = 2.6; P = 0.038) was found when testing the individual independent variables. From this analysis, there is an apparent negative correlation to the erosional part of the slopes with higher enzyme activi-

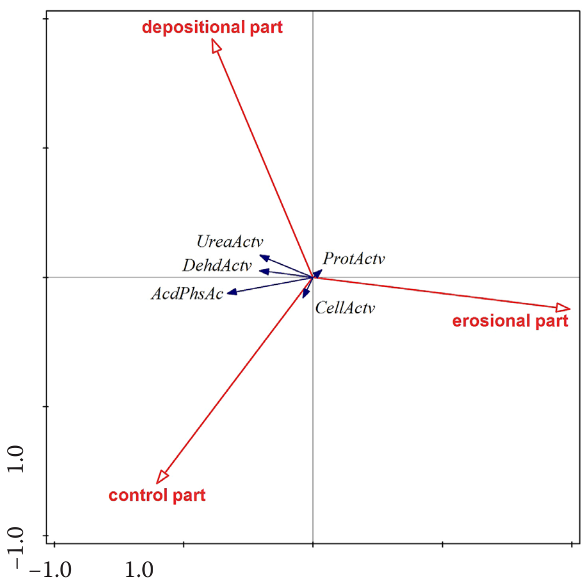

Figure 3. The redundancy analysis (RDA) ordination diagram describing the relationship among the slope parts and the soil biological characteristics

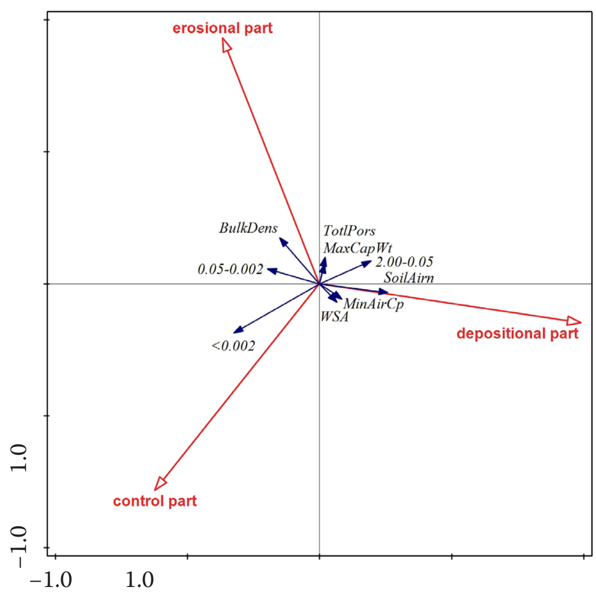

Figure 4. The redundancy analysis (RDA) ordination diagram describing the relationship among the slope parts and the physical soil characteristics

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ties either in the depositional or control parts of the slopes. This corresponds to the results of the Mann-Whitney U test. For the physical properties (Figure 4), only the depositional part ($F = 2.1$; $P = 0.048$) in the overall non-significant model ($F = 1.3$; $P = 0.24$) came out as significant. In this model, only the smallest particle size < 0.002 is the least affected.

To determine the main factors influencing the soil quality, the selected physical, chemical and biological – biochemical characteristics were analysed by the RDA analysis. This analysis showed that the chemical characteristics, where the organic matter together with the basic nutrients, and the related activity of the soil enzymes seem to be the main influence on the course of the erosion. In the Feiza et al. (2008) study, it was found that the soil organic matter, and, in particular, the organic carbon contained therein, is an important indicator of the quality on the eroded soils and is composed of a wide range of compounds that decompose at different rates depending on their chemistry, temperature, humidity, biota, soil minerals and aggregation. Therefore, as a recommendation for further soil degradation testing, it would be a good idea to focus more closely on the above-mentioned properties related to the organic matter and to study their interconnection in details and the physical properties should be extended to study more horizons with the possible dating of these changes in these heavily affected areas.

CONCLUSION

The study on water erosion in the locations with Chernozems of South Moravia confirmed the negative effect of the water erosion on the physical, chemical and biochemical properties of the soils with different intensive influences of individual properties. The characteristics related to the quantity and quality of the organic matter and the supply of the available nutrients – phosphorus – were the most affected. This was also related to the activity of the selected soil enzymes, especially dehydrogenase and acid phosphatase. The activity of these enzymes is correlated to a number of other soil characteristics, e.g., the organic matter (Šarapatka & Kršková 1997). The situation is more complicated with the physical properties where there was no statistically significant difference between the individual slope parts, which may be related to long-term erosion processes and shading of the horizons. Even the deposition parts of the slopes are covered with material from the C horizon of the erosion parts. These long-term intensive erosion processes are described by Zádorová et al. (2013). The follow-up research, with an emphasis on the physical properties, should be extended to study more horizons with the possible dating of these changes in these heavily affected areas. More detailed knowledge of the impact of the erosion processes on the soil environment in these intensively farmed areas, which also affect the production and non-production functions of the soil, is important for deciding on the optimal land use both on the local and national levels and for adjusting the rules of the EU Common Agricultural Policy within the Cross-Compliance checks.

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