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Time of aggregate destruction as a parameter of soil water stability within an agricultural hummocky moraine landscape in northern Poland

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Abstract. Slaking is a rapid wetting of soil aggregates that affects their stability in the face of the effects of water. The aggregate's stability has an indirect influence on soil functioning through its minimising of soil erosion. Testing slaking is very simple, does not need additional complicated equipment and could be done for any point. Testing was performed for natural air-dry aggregates (7–10 mm) sampled from the arable layers of four different types of soils within a young hummocky moraine landscape: Eutric Regosol (Protocalcic), Haplic Luvisol (Protocalcic), Albic Luvisol, Mollic Gleysol. The soil tests were performed on a soil-erosive catena located in Chełmno Lake District (Northern Poland) from the tops of hummocks and from the shoulder to bottom part of depressions.

The test results demonstrated a significant decrease in aggregate stability from Mollic Gleysol to Eutric Regosols (Protocalcic) – that is, from colluvial soils at depressions to completely eroded hummock-top soils. However, 75% of all aggregates in Eutric Regosols were unstable when time of aggregate destruction was less than 300 sec. Oppositely to Eutric Regosols laying on hummock tops, 70% of aggregates of Mollic Gleysols in depressions were water stable. The mean time for aggregate destruction for each soil from hummock-top to depression was 209 sec. for Eutric Regosol, 375 sec. for Haplic Luvisol, 616 sec. for Albic Luvisol and 772 sec. for Mollic Gleysol.

The main soil properties that affected the time of aggregate destruction are clay content (very strong negative correlation; r=–0.72); soil organic carbon content (strong positive correlation; r=0.69), and content of secondary carbonates (strong negative correlation; r=–0.69).

Key words:
young hummocky moraine landscape,
time of aggregate destruction,
aggregate stability,
spatial variation

Introduction

Young hummocky moraine landscape is typical for Northern Poland (Podgórski 2001). This area has a long history of land use based on progressive deforestation and intensive agriculture. Hence, the main factor in changing soil cover is anthropogenic denudation, which leads to significant transformation of soil profiles and forms a complex soil cover with a combination of non-eroded, eroded and colluvial pedons within small areas. The mechanism of anthropogenic denudation was discussed in detail in research by Sienkiewicz (1991, 1998), Podgórski (2001), Świtoniak and Bednarek (2014), Świtoniak (2014) and Doetterl et al. (2018). In young hummocky moraine landscapes, Świtoniak and Bednarek (2014) distinguish five classes of soil cover truncation based on the preservation of the original sequence of genetic horizons: (1) fully developed non-eroded soils, (2) slightly eroded soils, (3) moderately eroded soils, (4) severely eroded soils and (5) completely eroded soils.

The degradation of soils by erosion is one of the primary problems in present-day land management in such vulnerable landscapes as young hummocky moraine landscape. In 2021, the European Parliament adopted the Resolution on soil protection (2021/2548 [RSP]). It highlights the particular role of soils in the functioning of landscapes and societies and supports the opinion that healthy soils are essential for achieving a number of objectives, such as climate neutrality, the restoration of biodiversity, zero emissions for a non-toxic environment, healthy and sustainable food systems and a resilient environment. Particular attention is also paid to soil protection against erosion, which threatens 20% of all soils in the European Union. The condition of the soil structure could be considered as a tool for maintaining soil health in soil erosion control management.

Soil structure studies are based on estimating the role and function of soil aggregates and their mutual interactions. The role of aggregate stability in soil resistance to water erosion has been widely discussed in the scientific literature. The influence of aggregate stability on soil erosion was first determined by Middleton (1930). He was also the first to apply the method of sieving soil aggregates in water on a sieve column. Ellison (1947), Emerson (1954), Bryan (1968), Luk (1977) and many others (e.g. Barthes and Roose, 2002) further developed the issue of structure water resistance. Initially, studies of structure for erosion susceptibility were descriptive, but later studies led to the refinement of the method and the inclusion of a number of factors based on the quantitative assessment of the water resistance of aggregates (Kemper and Rosenau 1986; Le Bissonnais 1996; Fox and Le Bissonnais 1998; Márquez et al. 2004; Zhang and Horn 2001; Gumiere et al. 2009). Scientists argued that a structure with low water resistance increases the susceptibility of soils to erosion. Nevertheless, studies of soil structure, although numerous (e.g. Peng et al. 2015; Rabot et al. 2018), often omit spatial issues, are fragmentary in this respect, and do not allow for the reconstruction of a complete figure of structural changes in areas with complex soil cover. The work on soil structures focuses on separate soil varieties, and the use of a heterogeneous research methodology at different stages does not allow for comparison of results nor the creation of satisfactory maps of the spatial variability of structure properties (Rząsa and Owczarzak 2004).

The hypothesis of the study was based on the following assumptions:

1. soil aggregate stability varies among the different types of soils, depending on stages of soil truncation;
2. soil aggregate stability expressed as time of aggregate destruction connects with basic soil properties; and
3. data on real and calculated TAD might be used for creating digital maps.

The aim of the presented research was to determine the spatial variability of the time of aggregate destruction (TAD) of aggregates in different types of soils within a young hummocky moraine landscape in Northern Poland, to develop the linear regression model for the TAD parameter based on soil properties, and to create maps illustrating this parameter with the help of different technical and cartographic approaches. The research utilises a parameter of time of aggregate destruction (TAD, in seconds) based on the actual results of a slaking test and calculated data from a linear regression model. The results could be used for predicting soil erosion within a hummocky and undulating moraine plateau. The maps could be used by stakeholders in making decisions on the use of agrotechnologies and soil erosion control.

Study object

A detailed description of the experimental site and soil was given in a previous article (Radziuk et al. 2021).

The investigated area (Fig. 1) is located in Ryńsk Commune in the northern part of the Kuyavian-Pomeranian Voivodeship, Poland. Geomorphologically, it represents a hummocky and undulating moraine plateau, which is a very common landform within the Chełmno Lake District. Its general relief was formed during the youngest, Pomeranian phase of the Weichselian glaciation about 16–17 kyr ago (Fig. 1; Ehlers and Gibbard 2008; Marks 2012). The region surrounding the study object has been used intensively for agricultural purposes since the Middle Ages (Chudziak 1999). The study area is located in a warm, moderate, transitional marine–continental climate zone. The mean temperature in the past 20 years in the region was 9.3 °C, and the annual amount of precipitation in this period was 549.7 mm (CRU

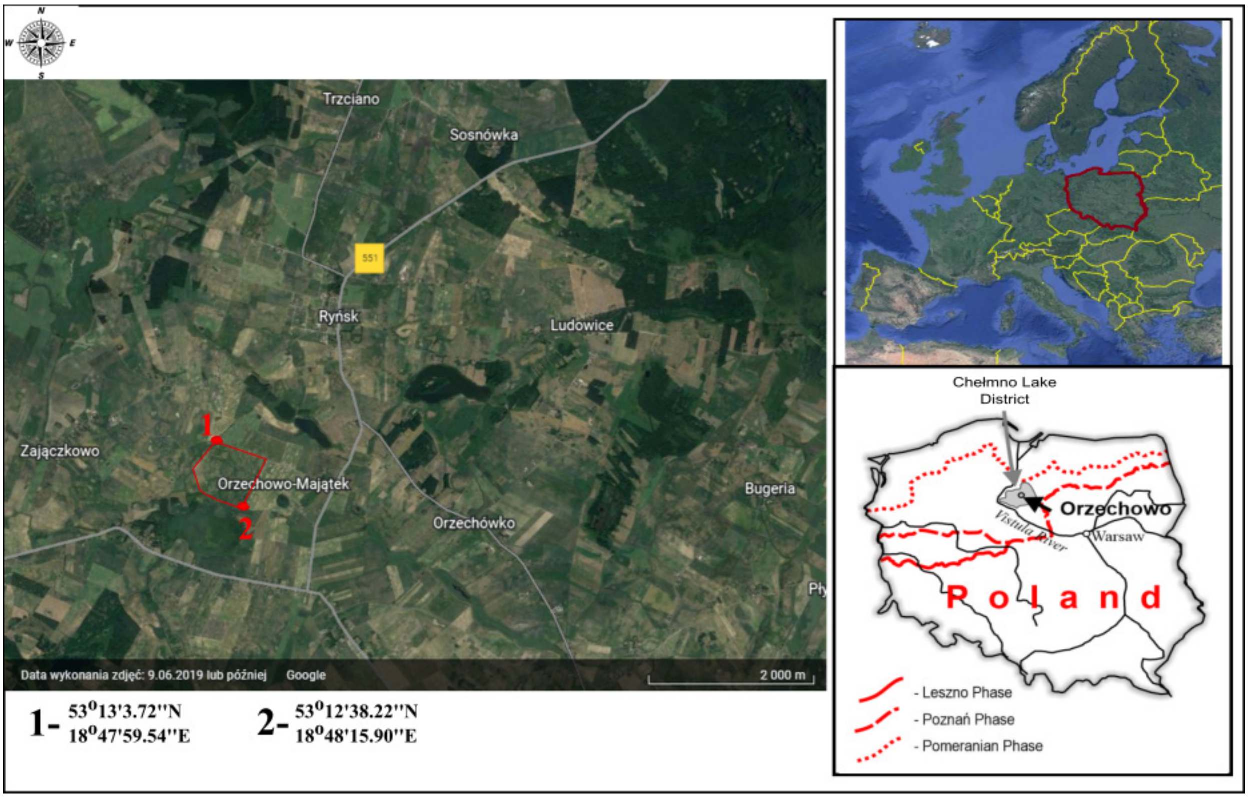

Fig. 1. Location of the experimental plot in Orzechowo (Northern Poland)

Time Series v4.04 2022). Total precipitation exceeds evaporability (precipitation–evaporation ratio >1) and that means the territory has a leaching regime of soil water. The experimental plot covers 0.394 km^2 and has been subjected to a regime of conventional tilling.

Study methods

Soil sampling and material preparation

Soil samples were collected in October 2019. On the experimental plot, a total of sixteen soil profiles along four slopes of the moraine hills were chosen, with the following division into four groups of four pedons each (designated A–D). Soil pedons were divided in groups based on stage of soil truncation: A – completely truncated soils – Eutric Regosol (Protocalcaric), B – strongly truncated Haplic Luvisol (Protocalcaric), C – slightly eroded Albic Luvisol or Mollic Gleysol, and D – soils with accumulation of colluvial material – Endogleyic Phaeozem or Mollic Gleysol. The location of each soil pit was precisely determined by GPS for further GIS analyses. The detailed description of soil types is given below in the part Soil cover of the experimental plot. Samples were collected from the arable layer using PVC cores of 10 cm in diameter and 10 cm in height, providing samples with a total weight of approximately 2.5–3.0 kg. All samples were handled immediately after returning from the field and dried in natural conditions without using an oven. Next, samples were sieved through a column with the following sizes of sieves: 10 mm, 7 mm, 5 mm, 3 mm, 1 mm, 0.5 mm and 0.25 mm. The aggregates of size 7–10 mm were separated out and then used for a slaking test.

Moreover, at 50 input points, surface samples were taken in different places of the experimental plot to create the input data network. The points were chosen based on an orthophotomap based on visible colour differences and ensured regularly spaced distribution. The choice of points for soil sampling was made randomly inside separate soil contours (Fig. 2). Samples from catenae were used both for the slaking test and for determination of main soil properties. Samples from additional input points were utilised only for determination of soil properties.

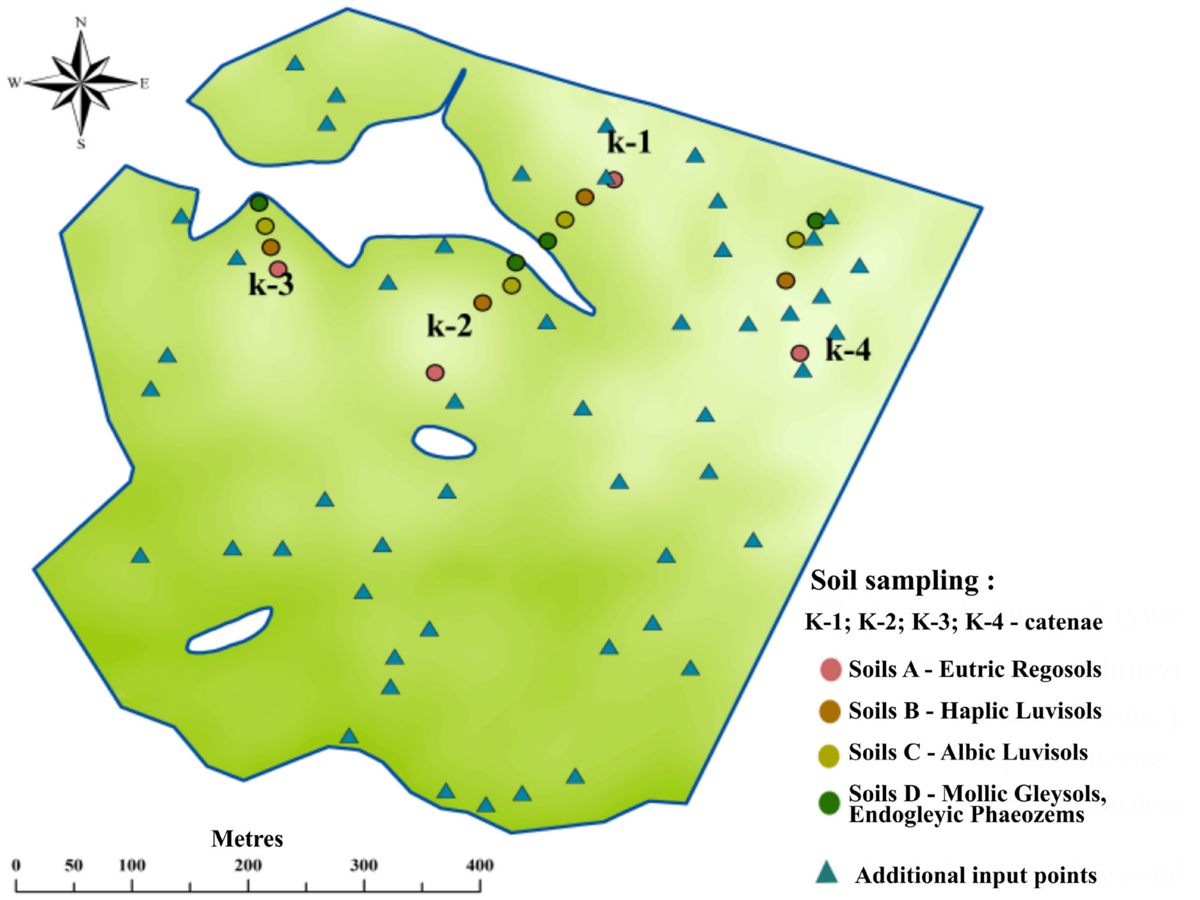

Fig. 2. Soil sampling points on the experimental plot in Orzechowo

Laboratory analyses

The slaking test was performed using a device developed at the Department of Soil Science of Academy of Agriculture in Poznań (Rząsa and Owczarzak 2004). The device consists of a plexiglass cubic container and two tensioned nylon threads stretched at a distance of 6 mm between two short sides. The stable aggregates are determined by measuring the time for total destruction of aggregates, placed on threads and covered with distilled water. For the analysis, aggregates of size 7–10 mm after dry sieving were used. This aggregate size was chosen for two reasons. Firstly, the size of aggregates should be bigger than the distance between the nylon threads in the device. Secondly, it should allow for aggregates of similar shape and mass. Aggregates of size >10 mm vary significantly by this criterion. Other sizes of aggregates are too small to be used in this test. Each soil sample was evaluated on the basis of measurements in two replicates of five aggregates per replicate. Water was then introduced through an additional side chamber to prevent artificial swirling of the fluid. The water was at a level of 1 cm above the aggregates. The time of aggregate destruction was calculated from the moment the aggregate's contacty with water until its total destruction, which was determined as the time at which the soil material fell to the bottom of the container. The result was the mean of ten aggregates and expressed in seconds. Water-stable aggregates were those that remained on the threads for 15 minutes (900 seconds) or more. The time of aggregate destruction of each soil type was determined as the mean value of 40 aggregates (10 aggregates for each soil from 4 catenae).

The basic soil properties were examined from catenae and additional input points material. The following analyses were done: texture by sieves and sedimentary aerometric method of Casagrande as modified by Prószyński (PN-ISO 11277:2005), secondary carbonates content using a Scheibler volumetric calcimeter, pH using a potentiometric method in water and KCl. The SOC content was investigated with the help of a Vario MACRO Cube CHN/CHNS Macro Elemental Analyser. Non-complexed clay and SOC were calculated from the equations suggested by Dexter with co-authors (2008). These characteristics were used for a general description of soils and statistical analyses (PAST 4.0), calculation of correlation and linear regression and further mapping the time of aggregate's destruction (sec.).

The cartographic work was made using various tools in the ArcGIS 8.0 software. Visualisation of spatial variation of time of aggregates destruction was made using the Spline interpolation tool (Urbański 2011). Another approach to visualisation involved attributing each soil polygon of the soil map a mean value of the studied parameter (time of aggregate destruction).

Results

Soil cover of experimental plot

The investigated soil profiles represent typical erosional catenae of young moraine plateaus with three main stages of soil truncation (groups *A, B, C*) and soils developed by accumulation of slope deposits (*D*) (Fig. 3, Table 1).

- *Soils A* – Eutric Regosol (Protocalcic) (IUSS Working Group WRB 2015) with minimum development of soil profile ACkp-Ck caused by strong erosion. Material from Ck occurs widely in the arable layer. The clay faction content is between 15 and 18% (sandy loams). The small amount of humus in ACkp is also connected with strong truncation of these pedons – the SC content is about 0.60%. At the same time, the surface horizons are rich in calcium carbonates (with C-$CaCO_3$ content reaching almost 0.80%. The subsoil is very similar to the surface plough horizon in terms of its morphology and basic characteristics, with the highest C-CaCO3 content of all studied soil varieties in the entire soil profile. Described Regosols can be found in 13 soil contours with a mean area of 50 m2. The total area share of these pedons is about 1% of the investigated soil cover (Fig. 3).
- *Soils B* – soils with Bt horizon partially involved the ploughing layer (ABtp). They covered mostly shoulder slopes in upper parts of hummocks. According to WRB (2015), they were mostly classified as Haplic Luvisol (Protocalcic). These soils occupy almost 0.1 km^2 and occurred in more than 40 soil contours. Due to excavation of argic horizons, these B soils have the highest clay content in the arable layer, with a mean value of 18%, and a minimal share of sand particles. In the subsoil (*argic* – Bt), the clay content can even reach 24.0%. The SOC amount is comparable to that of *Regosols* (very low) in the entire profile. Therefore, the high rate of clay content is responsible for the high value of maximum hygroscopicity – about 3.60% in the plough horizon and 4.21% in the subsoil.
- *Soils C* – due to their location within straight and bottom parts of slopes, these pedons were only slightly eroded or non-eroded. Some admixture of slope deposits is possible only in the arable horizon. This group includes Albic Luvisols (Ap-E-Bt-Ckg) and Mollic Gleysol (Luvic) (Ap-A-Eg-2Btkl). Additionally, *Soils C* prevail in the investigated area – they cover 58% of the study site (0.22 km^2). Because they form one soil contour, it can be treated as the "background" for the remaining soils. The highest content of sand fraction of all examined "C" profiles was 65.0%. Due to clay eluviation, *Soils C* are depleted of clay fraction in the upper part of pedons and exhibit a low pH rate in connection with the lack of calcareous material content. Also, we observed the highest value of maximum hygroscopicity among the groups. The soil organic carbon content in the arable layer increases in comparison with soils in the top and shoulder positions (group A and B). In the subsoil, C-SOC amount is low – similar to soils A and B described above.
- *Soils D* – soils with slope deposits thicker than the plough horizon (colluvium can be found in subsoil) occurred in landscape depressions and in the lower parts of slopes. This group contains Endogleyic Phaeozems and Mollic Gleysols according to WRB (IUSS Working Group 2015).

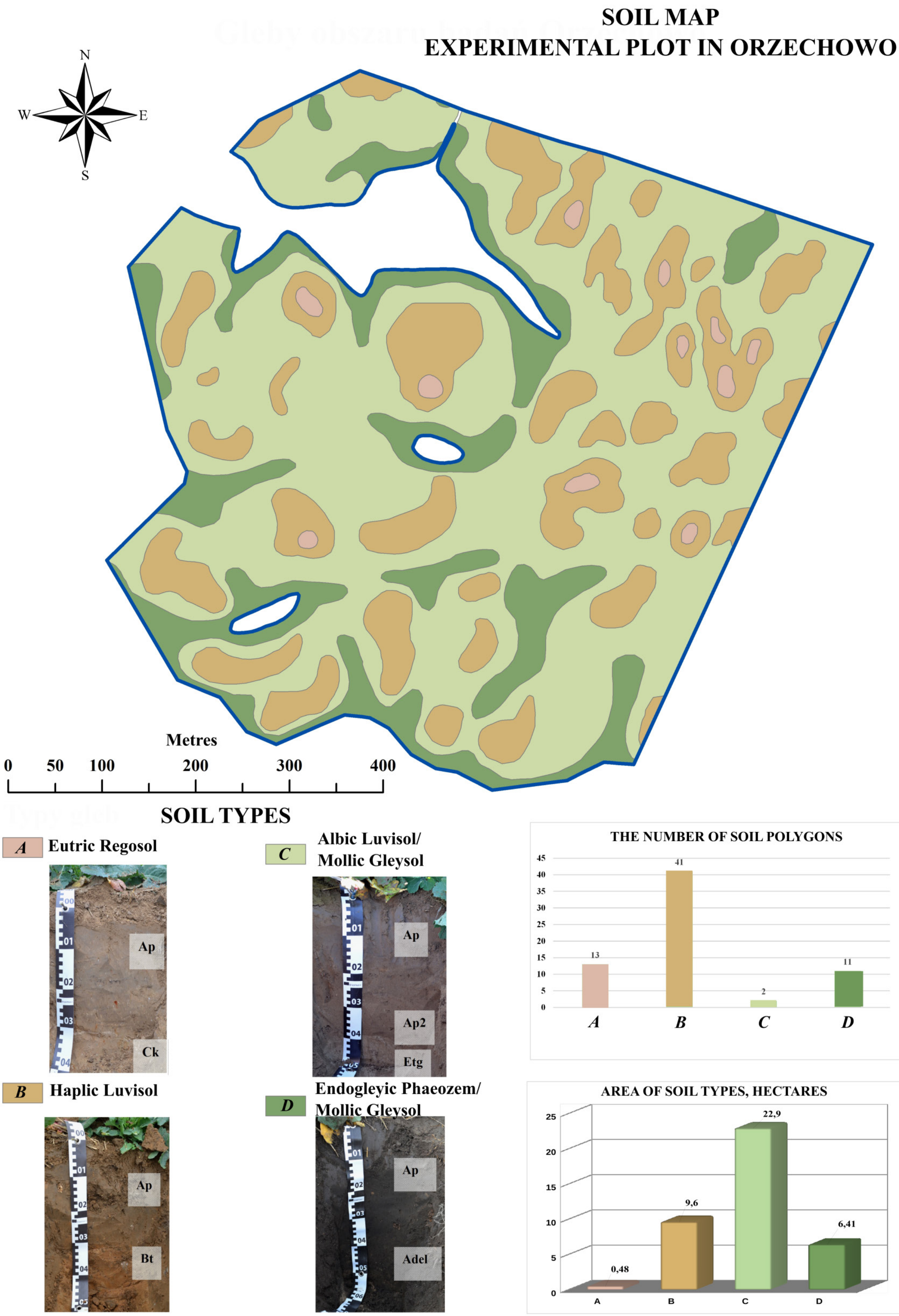

Fig. 3. Soil cover of the experimental plot in Orzechowo

Table 1. Basic soil properties under study (mean ±standard deviation)

Soil group	*Soils A*	*Soils B*	*Soils C*	*Soils D*
WRB classification	Eutric Regosol (Protocalcic)	Haplic Luvisol (Protocalcic)	Albic Luvisol / Mollic Gleysol	Endogleyic Phaeozem / Mollic Gleysol
Soil horizon sequence	ACkp-Ck	ABtp-Bt-Ck	Ap-E-Bt-Ckg/ Ap-A-Eg-Btkl	Ap-A-A2-Ab-Ckl
Sand (%)	59.30±4.0	56.3±4.3	66.0±4.1	60.0±3.9
Silt (%)	24.80±3.3	25.8±3.2	24.0±2.6	31.0±2.9
Clay (%)	16.80±2.1	18.0±2.2	10.0±2.2	9.0±1.6
pH_{KCl}	7.48±0.14	7.31±0.17	6.38±0.52	6.77±1.14
C-SOC (%)	0.62±0.09	0.77±0.11	0.93±0.16	2.35±1.34
$CaCO_3$ (%)	7.16±3.34	1.35±1.09	0.17±0.06	0.22±0.21
Non-complexed clay/SOC, %	10.5±1.4/0	10.3±1.5/0	0.6±2.2/0	0/1.5±1.4

Source: own elaboration

They can be found in 11 contours and their total area is 0.064 km². They have the highest soil organic carbon content of all analysed soil types, with significant heterogeneity between the particular soils. Also, it was established that these soils have relatively low content of clay fraction, although this does not affect the bulk density or maximum hygroscopicity. Within the study site, they are the only soils whose C-COS content increases from the plough horizon to the subsoil. The deeper horizons are also enriched in humus from primary (before slope processes started) A or even O horizons developed in the past under the strong influence of groundwater. At the same time, C-SOC content is quite diverse in both the plough horizon and the subsoil.

Assessment of TAD in laboratory conditions

Water saturation of soil material leads to the destruction of soil aggregates. The disintegration of aggregates under such static water conditions takes place in two phases: firstly, initial infiltration of water into the aggregate and its further slow swelling and disintegration. This process leads to extrication of soil materials and the filling of pore space with it. On the soil surface, in combination with the destructive action of raindrops and crusts being filled by water and soil particles, soil material can enter into surface runoff on the slopes (Rząsa and Owczarzak 2004).

In this study, the water stability of the aggregates was evaluated as time in seconds until the aggregates were completely destroyed. Rząsa and Owczarzak (2004) indicated that units were less resistant to water in the air-dry state than in the wet state. However, climatic changes with increasingly frequent periods of drought, combined with highly intensive but brief precipitation, can create conditions similar to laboratory ones necessary for the destruction of aggregates, soil adhesion and acceleration of the erosion process.

The results of the assessment of time of aggregate destruction (TAD, sec.) showed that all soils contain both stable and unstable aggregates in the arable layer (Table 2). Values of TAD were divided into four categories, of which the first (0–300 sec.) characterised very unstable aggregates and the last (>900 sec.) described water-stable aggregates. Regosols contain only 10% of stable aggregates, whereas non-eroded soils (Soils C and D) included more than 50%. At the same time, Regosols mainly have unstable aggregates and mean TAD of 209 sec. Another eroded soil, Haplic Luvisols, presented higher mean TAD of 375 sec. However, these soils also have mainly unstable structure with 77.5% of destructed aggregates in 600 sec. Soils B have 20% of stable aggregates.

Non-eroded soils and soils with colluvial materials demonstrated higher water stability of aggregates than did eroded soils. The percentage of stable aggregates (TAD >900 sec.) in Soils C was about half of the total number, and 70% for Soil D. The large rate of stable aggregates that non-eroded soil contained increased the mean value of TAD to 616 sec. in Albic Luvisols and 772 sec. in Endogleic Phaeozems and Mollic Gleysols.

Table 2. Rate of aggregates with different TAD (% of total number)

	Percentage of aggregates (% of total number) with different TAD				Mean TAD, sec.
	0-300 sec.	300-600 sec.	600-900 sec.	>900 sec.	
Soils A Eutric Regosols	77.5	12.5	0.0	10.0	209
Soils B Haplic Luvisols	50.0	27.5	2.5	20.0	375
Soils C Albic Luvisols	30.0	0.0	17.5	52.5	616
Soils D Endogleyic Phaeozems/ Mollic Gleysols	12.5	5.0	12.5	70.0	772

Source: own elaboration

Relations between TAD and basic soil properties of soils in hummocky moraine landscape

The empirical results confirm the hypothesis that anthropogenic denudation affects the time of aggregate destruction and aggregate stability. The differences between non-eroded and eroded soil types were statistically confirmed (ANOVA, Kruskal–Wallis test, $p<0.05$). However, it was a surprising conclusion that ANOVA does not confirm the difference between Soils A and Soils B ($p=0.26$). Despite visible variation of TAD values in Eutric Regosols and Haplic Luvisol, soil aggregates have the same low resistance to water impact. The general trend of low resistance of moraine parent materials to water impact was also emphasised in research by Rząsa and Owczarzak (2004), who studied different types of parent materials. Nevertheless, anthropogenic denudation was not the only explanation for such a significant difference between eroded and non-eroded pedons. Anthropogenic denudation can also be a major reason for changes in basic soil properties. That is why the interaction between basic soil properties and values of TAD was estimated using the Spearman's correlation (Table 3).

What can be clearly seen from the table is the high positive relations between TAD and SOC content. The other variables, such as clay and calcium carbonates contents, have high negative correlation with TAD. Sand and silt contents did not show close relations with TAD, based on values of the correlation coefficient.

A review of the literature shows that interaction between soil properties and aggregate stability was observed in different soils, but not related to each other within the boundaries of a landscape. Thus, the negative effect of secondary carbonates has been explained in detail by some authors for soils with a high content of free Ca^{2+} and Mg^{2+} ions (Meozzi 2011; Rengasamy and Marchuk 2011; Zhu et al. 2016). The authors found that carbonates not included in the soil complexes cause the swelling and subsequent rapid destruction of aggregates in water. In the case of Eutric Regosols (Protocalcic), this could be a negative factor influencing the low stability of aggregates due to the exposure of the material of the CK horizon as a result of anthropogenic denudation.

Some authors have pointed out the essential role of clay particles in the formation of water-stable aggregates (Hillel et al. 1998; Vaezi et al. 2008). In the presented study, clay content has a negative impact on TAD ($r=-0.72$). As the researchers note, clay is an essential component of aggregates, which is why its content is so important in the analysis of water stability of structure (Kay and Angers 2001; Blanco-Canqui and Lal 2010). The clay content has a positive effect on the forces holding soil particles in aggregates. However, sandy-loam soils are categorised as low-clay soils, in which clay is not able to form highly stable complexes with soil organic matter, and here clay content has a negative impact on water stability. This relation was observed

Table 3. Correlation matrix for studied variables

	Sand content, %	Silt content %	Clay content, %	SOC, %	pH_{KCl}	$CaCO_3$
Time of aggregate's destruction (sec.)	0.33	0.45	**-0.72***	**0.69**	-0.55	**-0.69**

** in bold – strong correlation (p <0.05)*
Source: own elaboration

by Yan et al. (2010) and Wuddivira et al. (2021). At the same time, clay particles not fixed in aggregates can be rapidly soluble in water and cause soil loss, especially in arable soils (Watts and Dexter 1997; Getahun et al. 2016). Therefore, it seems necessary to calculate the content of non-complexed clay, which identifies how much clay is not fixed in stable soil complexes. This is an essential parameter for Regosols and Haplic Luvisols with very low soil organic carbon content and relatively high clay content (Table 1). In spite of the small area (about 10% of the total area) occupied by eroded pedons at the experimental plot, they may be the main source of colluvial materials due to their low water resistance.

The observed increase in water resistance of aggregates in the soils studied is strongly positively correlated with the soil organic carbon content (r=0.69). However, in order to achieve good or very good water stability, the amount of carbon in the soil should be very high for mineral soils (more than 4%), which is quite well confirmed by the research of Levy and Mamedov (2002). These authors showed that there is a strong relationship between the water resistance of aggregates and the content of soil organic carbon (>3%), but in soils with low content (<2%) such correlations are much weaker and do not allow an unambiguous assessment of the leading role of organic carbon in the formation of water-stable aggregates (Levy and Mamedov 2002). The obtained empirical data on the water stability of aggregates also corresponded to the data presented by Owczarzaka and Rząsa (2006) for Podzols and Luvisols in the young moraine landscape in Poland. The authors showed that the high content of SOC increases the water resistance of dry aggregates in all size categories. The same relationship is also confirmed by other Polish studies (Orzechowski et al. 2011) concerning the high dependence of water stability on the SOC content, especially in colluvial soils. Some authors indicated that soil structure in colluvial soils in depressions was similar to that of non-eroded soils (Paluszek 1994, 2004).

Modelling of TAD

A strong correlation of TAD with some basic soil properties became the basis for the development of a linear regression model. The main goal of the model was to create the network of spatial points on the area of experimental fields and following mapping of the TAD values. The linear regression equation was designed based on empirical data from catenae (1) and further recalculated for additional input points.

$$TAD=734.230^{*}-21.003\cdot clay^{*}+95.112\cdot SOC^{*}-31.675\cdot CaCO_3^{*}$$

where: TAD – time of aggregate destruction [sec.]; clay – clay content [%]; SOC – soil organic carbon content [%]; $CaCO_3$ – calcium carbonates content [%]; * – statistically significant variable for the model with $p<0.05$.
Basic parameters of model: r=0.77; $p=2.6424\times10^{-9}$; d=3

The equation uses the widely defined soil properties and could be utilized in many places in young hummocky moraine landscape in Poland. The obtained regression equation explains 77% of the total dispersion (r=0.77).

According to the regression equation, the soil organic carbon content has a positive effect on

Table 4. Summary statistics for measured and calculated values of TAD (sec.)

	Calculated TAD from linear regression (50 additional input points)				Measured TAD (4 catenas, 16 points)			
	A*	B	C	D	A	B	C	D
Number of samples	10	10	20	10	4	4	4	4
Min	121.1	336.3	416.5	542.4	116.9	234.8	440.5	421.1
Max	293.2	491.7	748.1	900.0	646.2	519.9	817.5	900
Mean	226.0	425.2	629.0	728.3	208.8	374.6	616.2	771.8
Stand. dev.	58.5	54.4	64.6	105.5	244.8	116.5	175.7	234.0
Coeff. of variation	25.9	12.8	10.3	14.5	81.9	31.2	28.8	30.3

**A – Eutric Regosols; B – Haplic Luvisols; C – Albic Luvisols/Mollic Gleysols; D – Mollic Gleysols/Endogleyic Phaeozems* aggregate dispersion, and the remaining parameters influence TAD negatively, reducing the aggregate's resistance to water impact. The calculation of TAD at 50 input points with the help of the linear regression equation showed that the model better illustrates the mean values for each soil. The difference of the calculated mean values from the measured data ranged from 2 to 14%. However, there were significant differences in the values of the standard deviation and the coefficient of variation of the calculated TAD (25–45% and 24–47%, respectively, from the measured data). The data obtained from the linear regression equation show greater uniformity than actually measured, which is expressed in much lower values of the coefficient of variation (Table 4). However, such uniformity of data confirms that the natural heterogeneity of the soil structure is more significant that could have been predicted. The obtained equation gives 77% reliability of the described values and presents a satisfactory level of modelling.

Visualisation of TAD values

The first approach to visualisation of TAD values is attributing each soil polygon a mean value of TAD (Table 2). The approach is based on the soil map (Fig. 3) and is presented in Figure 4. This approach leads to all values of TAD being divided into four categories. The categories were created based on time (each 5 min or 300 sec.); the water-stable aggregates were determined as the category with TAD >900 sec. The smallest areas were occupied by Regosols with a TAD of less than 300 sec. They comprise ~1% of the research area. One quarter of the study area was occupied by Haplic Luvisols (soils B), which correspond to a mean TAD of 375 sec.

The largest area (over half of the experimental plot) was occupied by Albic Luvisols with mean values of TAD in the range 600–700 sec. (Table 5). The presented data visualisation method does not take into account the areas with high values of TAD. They are limited to the highest mean values of 700–800 sec. (Soils D). However, the study of single aggregates showed that the vast majority of aggregates in Soils D had a higher water stability. That is why this method of visualisation should take into account that problem. The mean weight value of TAD for the entire experimental plot of Orzechowo, calculated using the first approach is 576.5 sec. (Table 5).

Unlike the previous approach, Spline interpolation allows us to create an interpolation surface with a gradual transition between values. At the same time, the spatial differentiation of TAD takes place in a wider range – from the minimum 100 sec. to 900 sec. Soils with very unstable aggregates occupy

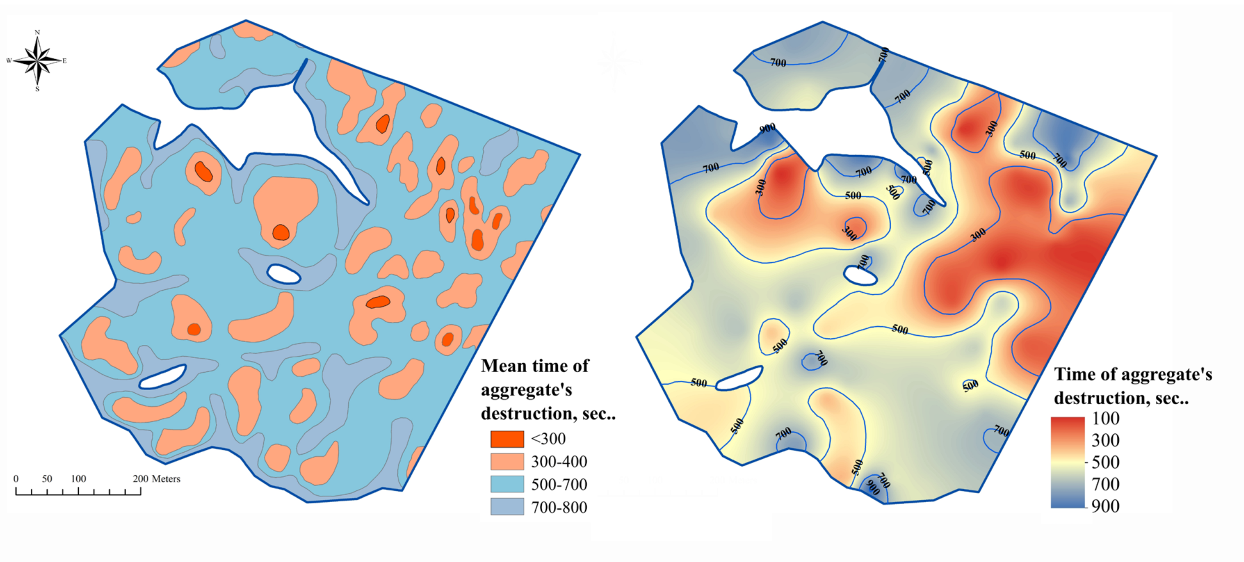

Fig. 4. Spatial variation of TAD (on the left side is based on soil map and attribution of soil polygons with mean values; on the right side – Spline interpolation (GIS)

Table 5. Areas with different values of TAD (sec.) depend on different approach to visualisation

Approach to visualisation	Areas with different values of TAD (sec.), % from total area							Mean weight value of TAD, sec.
	> 300	301-400	401-500	501-600	601-700	701-800	801-900	
Spline interpolation (GIS)	14.0	9.6	16.7	28.6	21.8	8.0	1.3	513.8
Mean value attributed the soil polygons (soil map based)	1.0	25.0	n.d.	n.d.	58.0	16.0	n.d.	576.5

the highest elevations in the eastern and north-eastern parts of the research area and on the tops of isolated hills. This is generally well correlated with the polygons where eroded soils were located. According to the data presented in Table 5, the area with TAD less than 300 sec. covers 14% of the research territory. Enclosed in one soil polygon, these soils require the use of technologies aimed at improving the quality of the structure not only within separate soil contours, but in the entire part of the field. The largest area is occupied by soils with TAD values of 500–600 seconds. These soils cover 28.6% of the total area. This is almost twice as much area as calculated using the first approach to visualisation. The areas with such values of TAD occupy surfaces between hills and kettle-holes, which correspond mostly to Mollic Gleysols and Endogleyic Phaeozems.

Soils with TAD of 800–900 sec. occupy only 1.3% of total area and are located at the field boundaries and in depressions. Spline interpolation perfectly emphasises the decrease in TAD from the hills to the kettle-holes. As was said before, a positive effect of the use of Spline interpolation is the creation of a map that more precisely shows the gradual natural variability of the structure feature under study, without sudden "drops" from one soil to another. The other advantage of the approach is that it is not necessary to classify the pedons, because the data obtained from the regression equation takes into account only the data on the basic properties of soils.

The mean weight TAD for entire area, calculated on the basis of Spline interpolation, was 513.8 sec. The value corresponds to the mean value obtained from the first approach. The difference is about 10%.

Conclusions

The conducted research confirmed that the eroded soils in the upper part of the slope are characterised by a very unstable structure, and also covers an area that must be taken into account during the planning of agrotechnical treatments. Eutric Regosols have three times lower water stability of aggregates than non-eroded and deluvial soils. Time of aggregate destruction changed from 209 sec. in completely eroded soils to 772 sec. in Mollic Gleysols / Endogleyic Phaeozems.

The main reason for poor aggregate stability in completely eroded and strongly eroded pedons is the combination of comparatively high clay particles content with actual low soil organic carbon content. These conditions lead to insufficient formation of stable clay–organic complexes and rapid slaking of soil aggregates.

The traditional approach does not ensure a gradual transition of data between adjacent soil contours, which is an unnatural phenomenon. However, it could be used for areas with low heterogeneity of soil cover. The major drawback of the approach is the sharp transitions of values between polygons, which cannot be eliminated by technical tools.

Spline interpolation showed more satisfactory results of TAD mapping. Based on empirical data and calculated data from linear regression modelling, this approach presented high correspondence of data with elevation of area and, indirectly, with location of eroded pedons.

The performed method of aggregate stability estimation could be recommended for wide use, due to its simplicity and lack of need for additional sophisticated laboratory equipment.

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Disclosure statement

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Author contributions

Study design: MŚ; data collection HR; statistical analysis: HR; result interpretation: HR, MŚ; manuscript preparation: HR, MŚ; literature review: HR, MŚ.

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