

## Article

# The Effect of Erosional Transformation of Soil Cover on the Stability of Soil Aggregates within Young Hummocky Moraine Landscapes in Northern Poland

Hanna Radziuk \*  and Marcin Świtoniak 

Department of Soil Science and Landscape Management, Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University, 87-100 Toruń, Poland

\* Correspondence: anka.radziuk@gmail.com

**Abstract:** Aggregate stability is a crucial factor in predicting the development of the erosion process, and it is particularly important in landscapes with high heterogeneity of soil cover, such as young hummocky moraine uplands. The objective of the presented work was to estimate the influence of erosion on the properties of aggregates and analyze the variation of aggregate stability under different erosion-related alterations of soil cover. The conducted research indicates that erosion has led to a deterioration of the quality of soil structure in the upper parts of the slopes, which in turn may intensify the slope processes leading to faster truncation of the pedons. Both the differentiation of the soils themselves and the stability of the aggregates were very strongly linked to erosive transformations. The tops of the hills and the upper parts of the slopes are covered with completely or strongly eroded soils in which the aggregates have the least favorable characteristics. Due to the smallest amount of humus and the highest clay content, the soils have the largest share of soil clods, which are aggregates larger than 7 mm that may have formed in dry conditions (soil drought). The plow horizons of most eroded Eutric Regosols and strongly eroded Luvisols have very poor water resistance, similar to that of the subsoils. The main factor determining the low aggregate stability of Eutric Regosols is the number of secondary carbonates that lead to a rise in soil dispersion. Strongly eroded Haplic Luvisols have a low resistance to water due to relatively high clay content (20–26 percent). The higher stability of aggregates in soils with colluvial materials (Albic Luvisols, Mollic Gleysols, Endogleic Phaeozems) depends mainly on soil organic carbon content. The results showed the necessity for adaptation of land management practices to real condition and heterogeneity of soil cover.



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**Keywords:** aggregate stability; hummocky landscape; erosional transformation; soil aggregate distribution; soil structure

## 1. Introduction

Soil is a basic, complex, multifunctional and living integral element of the ecosystem of key environmental and socio-economic importance, which plays a fundamental role in many aspects: food security and the elimination of hunger, carbon sequestration and biomass production. Efficiently functioning soil is also the reservoir of biodiversity resources, preventing floods and droughts. The European Parliament Resolution on soil protection (2021/2548 (RSP)), which was adopted in 2021, highlights the particular role of soils in the functioning of landscapes and society. Particular attention is given to soil protection against erosion, which threatens 20 percent of all soils in the European Union [1]. Soil erosion control is one of the primary objectives in the current management of arable land. In some vulnerable landscapes, such as the moraine uplands, common in the northern hemisphere, water erosion together with anthropogenic denudation has significantly altered the original soil cover. The high potential risk of erosion development is associ-

ated with intensive soil use in recent centuries, from the Middle Ages to the present, and systematic deforestation accompanied by excessive rainfall [2].

The intensity of water erosion is most often explained by specific parameters of the basic properties of soils, such as texture, chemical composition, and organic matter content. Soil structure is also an important indicator. On the one hand, the soil structure, the spatial arrangement of elementary particles of the solid phase of soils, arises as the integration of all soil elements and also largely determines the intensity of the development of erosion processes. On the other hand, the soil structure and its properties are the result of thousands of years of soil-forming, geomorphological and geological processes, and the process of erosion and anthropogenic denudation greatly accelerates their flow. From a practical point of view and in connection with the growing understanding of the role of soil and its health in all processes occurring in the landscape, caring for the structure and awareness of its spatial variability within separate areas is an investment in the future of agriculture [3]. To monitor the condition of the soil, information on its susceptibility to erosion becomes necessary in landscapes with a complex soil cover, such as the young hummocky moraine landscape. Soils in such landscapes are often conventionally cultivated, regardless of the varying maturity of the heterogeneous soil cover within a single field, the ability to store water in different soil types, the active pore space and the ability to accumulate decay. This lack of awareness results in soil degradation, loss of soil fertility and general pollution of the environment, in particular surface water.

Soil aggregate stability is one of the key factors in the understanding of the soil erosion process [4,5]. A comprehensive body of literature exists on the subject of soil aggregate stability and its impact on soil erodibility under a variety of soil and weather conditions [6–10]. The impact of aggregate stability on water is also linked to environmental problems [5] that include pollution [11,12], soil properties and processes, infiltration capacity, hydraulic conductivity, solute transport, carbon cycle, plowing, erodibility, and soil degradation. Some authors [13] argue that research into soil aggregate stability is essential as it helps better explain the actual susceptibility of the topsoil to erosion. Exploration of soil aggregate stability is a necessary element of land-use planning and erosion control management in vulnerable agricultural landscapes [14]. Additionally, it could be a primary step in some models that describe the potential erosion, where this characteristic is used as a proxy for soil erodibility [15].

The theory of soil aggregate stability is based on the examination of the process of aggregate disintegration or the factors that stabilize aggregates. As noted by Le Bissonnais [16], the typical mechanisms of aggregate destruction are slaking, breakdown by differential swelling, mechanical breakdown by raindrop energy, and physicochemical dispersion. The relative importance of these mechanisms depends on the rainfall and the physical and chemical properties of soils. Stabilizing factors are primarily related to soil characteristics, which may be affected by agricultural practices. Aggregate stability generally increases with the content of clay and organic matter in the soil, but a significant universal equation applicable to all types of soils and conditions has not been established [6,17]. Other parameters such as soil microorganisms and their activities and the presence of cations (including  $\text{Ca}^{2+}$  and  $\text{Fe}^{2+}$ ) are also involved in soil aggregation and stabilization [4,18]. Over the past two decades, there has been a significant increase in the investigation of factors that influence aggregate stability, with a focus on soil organic matter e.g., [5,19–21] and soil particle-size distribution. Aggregation is described as a product of external and internal factors [4] with a high degree of SOC impact on the process [22,23]. In landscapes, soil aggregate stability is typically a function of a particular soil. Considering the spatial differentiation of this parameter for a given area, researchers commonly calculate it as an integral sum of the individual soil varieties on the plot. As some authors point out [24], aggregation is controlled by different mechanisms in different soil types, which explains the spatial differentiation of the property.

Previous studies on aggregate stability do not take into account the variability resulting from the erosive transformation of the soil cover of young hummocky moraine landscapes,

they are limited and fragmented. However, they might be an essential tool for land management and soil erosion control. The need to obtain such information was a case of the presented study. The presented investigation was based on the hypothesis that in hummocky landscapes with highly heterogeneous soil cover, soil aggregate stability depends on the position of the soil on the slope and is linked to its erosional transformations—different stages of soil truncation or colluvium accumulation. The objective of our work was to analyze the variability of aggregate stability based on the wet-sieving analysis and to determine the relations between the basic soil properties of erosional transformed soils and aggregate stability in the hummocky moraine landscape. The present article is first-step research into the spatial differentiation of these phenomena in a hummocky morainic landscape. We explored the qualities of the soil structure for the examination of soil erodibility and further spatial interpretation.

## 2. Description of the Experimental Plot and Soil Cover

The object of study is located in the territory of the young glacial landscapes that are most common in Northern Eurasia and Canada. A complex pattern of generally short, steep slopes extending from prominent knolls to rounded depressions or kettles is typical of these areas. Human activity is the main factor in the contemporary development and alteration of the soil cover within these areas—especially in the case of hummocky moraine uplands [25,26]. The choice was caused by the observation that young moraine landscapes are predominant in the northern part of Poland. The relief and soils were being heavily transformed by settlements, communications networks and exploitation of mineral resources that occurs locally [27,28]. However, the most common transformation process in hummocky areas was human-induced erosion, also referred to as anthropogenic denudation [29]. This process led to the exposure of deeper genetic horizons in eroded, truncated soils and the accumulation of colluvial material in lower topographical locations. As a consequence, a complex system of soil mosaics that change intensively along with the slopes was formed [30–37]. Moreover, even small and homogeneously used agricultural plots may combine soils that exhibit a significant variability of the properties and colors in the surface horizons [38,39]. In the young-glacial landscape in Poland, distinguished five classes of soil truncation based on the preservation of the original sequence of genetic horizons were distinguished: (1) fully developed soils, (2) slightly eroded soils, (3) several eroded soils, (4) strongly eroded soils, (5) completely eroded soils (Figure 1). The authors assume that initially all clay soils were formed as Luvisols with A(p)-Bw-Et-2Bt-2C(k), horizon's sequence [35].

1. Fully developed soils—mostly Neocambic Luvisols—with a full sequence of genetic horizons A(p)-Bw-Et-2Bt-2C(k).
2. Slightly eroded—soils are characterized by the lack of Bw horizons.
3. Severe degree of erosion—eluvial zone is only visible in form of a more sandy texture of Ap horizons. Just under plowing period the Bt argic occur.
4. Strongly eroded soils—characterized by a complete lack of eluvial material Arable layers contain mainly material derived from the original argic Bt enrichment horizons.
5. Completely eroded—soils that have no diagnostic horizons (and simple sequence—Ap-Ck) on the basis of morphology it is impossible to determine from what original type of soil they were formed. The surface genetic horizons of these soils are made up of clay and have very little organic matter. The organic carbon content is significantly reduced in such “flat” soils compared to non-eroded soils, and the arable layers are enriched with calcium carbonate as a result of the prominence of parent rock in soils of this group [35].

Figure 1 illustrates the special aspects of soil formation in a young hummocky moraine landscape under anthropogenic denudation.

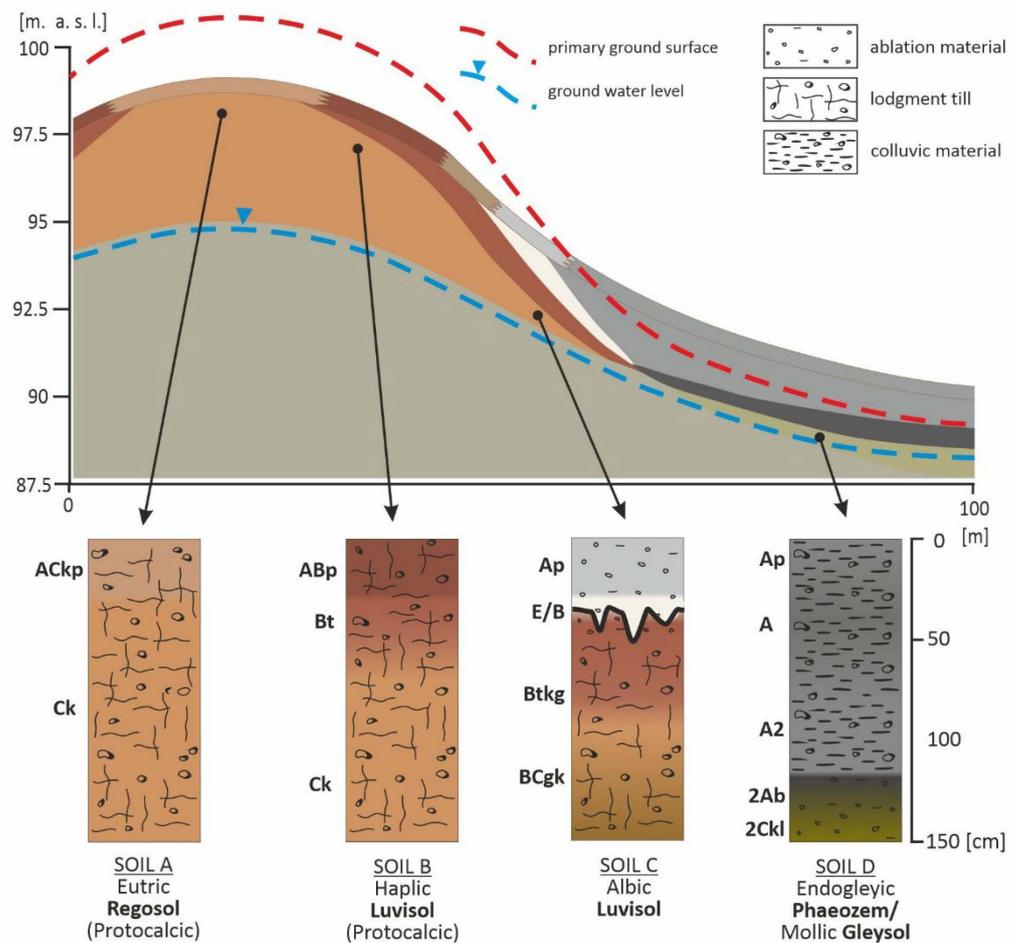
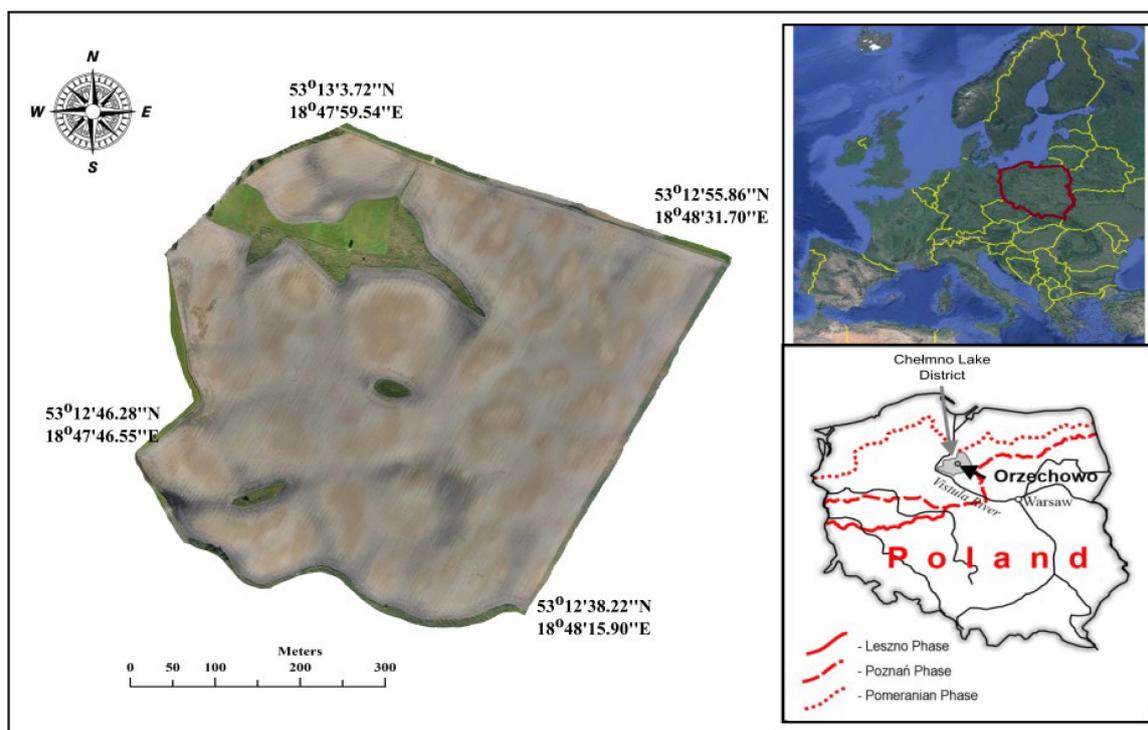


Figure 1. An erosion catena within the Orzechowo experimental plot.

The experimental plot with an area of 0.394 km<sup>2</sup> (Figure 2) is located in the northern part of the Kuyavian-Pomeranian Voivodeship, near Orzechowo village. It represents the hummocky and undulating moraine plateau of the Chełmno Lakeland, formed during the Pomeranian phase of the Weichselian glaciation of 16–17 kyr ago (Figure 2) [40–42]. The variability of topsoil colors visible in satellite photos was chosen as the main criterion [39]. It manifests the differentiation of soil cover in terms of anthropogenic denudation. In general, this part of the moraine plateau has been used intensively for agricultural purposes since the Middle Ages [43]. The contemporary land-use practice is conventional tillage, including deep plowing (30 cm). The entire area of the plot was used uniformly in recent years. In the autumn–winter season of 2018–2019, the surface was covered by winter oilseed rape. According to the Köppen–Geiger Climate Classification, the investigated area has a moist and cool temperate climate within a fully humid zone with temperate and warm summers [44]. The average annual air temperature is about 8 °C. The average annual precipitation is 540 mm. Soil drought events have occurred in the region in six out of the last ten years [45].

Soil processes in the young hummocky moraine landscape are closely related to the relief of the territory. Analyses of maps of relief and slope gradient show a significant heterogeneity of geomorphological conditions (Figure 3c,d). The main landform of the research area is a plateau. The altitudes change from 87.5 m a.s.l. to 103.3 m a.s.l. and the territory generally has an inclination from northeast to southwest. Several hummocks rising about 4–5 m above the surrounding area are visible in the central and northeastern parts of the experimental plot. More than half of the area (53.1 percent) lies in the 90–95 m altitudes, and an additional 36.9 percent are 95–100 m a.s.l. The area below 90 m a.s.l. occupies 7.8 percent, and above 100 m occupies 2.2 percent. Additionally, the relief of the

experimental plot is characterized by several small, closed depressions located in the south and northwest parts that accumulate water and sediments from surrounding hummocks and form a specific feature of the landscape. Despite a seemingly insignificant decrease in altitude in kettle holes—less than 5 m—these values influence soil processes and change soil cover from Luvisol to Mollic Gleysol and Phaeozems. The largest and flat-bottom depression is in the northern part of the experimental field and has an area of 0.02 km<sup>2</sup>.



**Figure 2.** Location of the experimental plot in Orzechowo (Northern Poland).

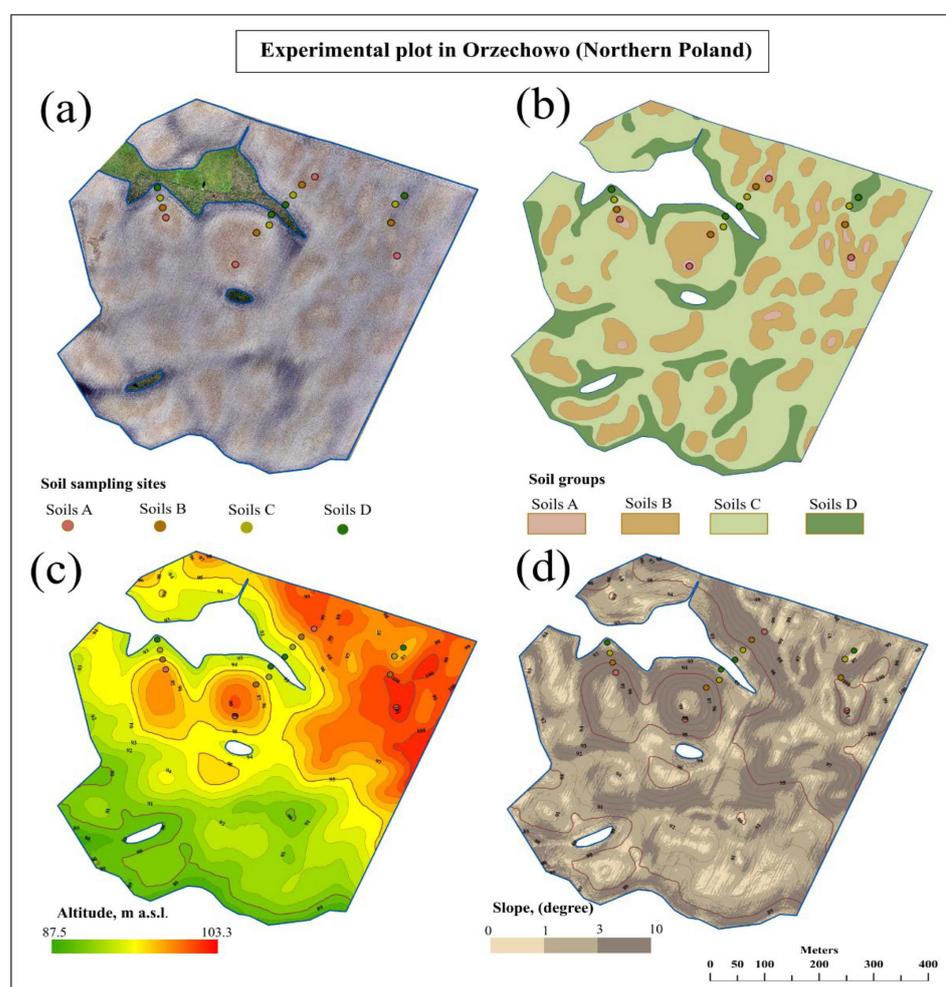
In this study, the analysis of the slope gradient has an additional character and utilizes it for determining the location of areas exposed to erosion. The USDA reports that erosion processes occur already at slopes from 1° [46]. One of the first researchers of anthropogenic denudation in Poland indicated that “pushing the soil through the plough” begins with a slope gradient of 3° [47]. About half of the experimental plot—52.3 percent—lies on very gentle slopes between 1° and 3°. About 10 percent of the area is occupied by flat or almost flat areas. However, the flat places do not form an uninterrupted contour and they are spread over the entire area. The area with a slope gradient from 3° to 10° occupies 37.9 percent. These are the areas most exposed to both water and anthropogenic erosion.

At the experimental plot, a total of sixteen soil profiles along four slopes of the moraine hills were chosen. The particular toposequences represent typical erosional catenas of young moraine plateaus with different stages of soil truncation (soil groups A, B, C) or colluvial soils (D) (Figure 3a,b; Table 1):

- Soils A—completely truncated pedons with no diagnostic horizons (ACKp-Ck) on the tops of the hummocks with slope inclination higher than 3° —Eutric Regosol (Protocalcic) [48]. Clods of parent materials (from Ck) occur widely in the arable layer. Clay content in ACKp horizons is about 15 to 18 percent (sandy loams). The surface horizons are also characterized by the low content of soil organic carbon (SOC)—about 0.6 percent. At the same time, the plow layers are rich in calcium carbonates (with C-CaCO<sub>3</sub> up to 0.79) derived from parent materials (Ck). The subsoil is very similar to the arable layer in terms of its basic properties. These soils form 13 soil contours with a mean area of 50 m<sup>2</sup>. The total area of soils A within the experimental plot is 0.05 km<sup>2</sup> or about 1 percent of the total area of the field (Figure 3b). They are easy to

determine on the basis of an orthophotomosaic—their light brown color comes from a significant  $\text{CaCO}_3$  content in ACkp horizons.

- Soils B—strongly eroded pedons with an illuvial material in the surface horizons (ABtp) which cover the shoulder slope position with high inclination ( $3\text{--}10^\circ$ ). Mostly classified as Haplic Luvisol (Protocalcic) [48] with a sequence ABtp-Bt-Ck of horizons. They occupy  $0.096\text{ km}^2$  within 41 soil contours which are mostly in the shape of rings around soils A or in an oval shape in summits of hills. The concentration of iron in Bt gave them clearly visible dark brown colors. On the study plot, this group generally has the highest clay content of all the plowing layers, with a mean value of 18 percent. In the subsoil (argic—Bt), clay content increases to 24.0 percent. The SOC content is similar to that of soils A in the entire profile. Therefore, the high rate of clay content is responsible for the high value of maximum hygroscopy—about 3.60 percent in the plow horizon and 4.21 percent in the subsoil.



**Figure 3.** Characteristic of the experimental plot in Orzechowo (Northern Poland): (a) orthophotomosaic; (b) soil map; (c) relief of the territory; (d) slope gradient.

- Soils C—pedons slightly changed by truncation located in the lower and bottom part of the slope with inclination  $1\text{--}3^\circ$ . In some places, admixture of slope deposits is possible (translocation zone on slope) in the arable horizon. This group is the most diverse from Albic Luvisols with a horizon sequence of Ap-E-Bt-Ckg to Mollic Gleysols (Luvic) (Ap-A-Eg-2Btkl) [48]. The group covers 58 percent of the total area ( $0.22\text{ km}^2$ ), in the form of one soil contour visible as a light gray background within the orthophotomosaic. In soils C, the greatest content of sand particles of all examined profiles was observed, (65.0 percent). Soils C have an eluvial zone in the uppermost parts of profiles, and

therefore are depleted of clay particles (which is a specific feature of this group) and exhibit relatively low pH values in connection with the lack of calcareous material content. Moreover, we observed the highest value of maximum hygroscopy among the groups. The soil organic carbon content increases in comparison with soils in the top and shoulder positions and exhibits a significant spread in values, although C-SOC does not increase significantly in the subsoil and close to other soils.

- Soils D—soils developed from thick colluvial deposits (visible in the plow and under-plow horizons) in the depressions (kettle holes) in the landscape. This group mostly belongs to Endogleyic Phaeozems (Colluvic) and Mollic Gleysols (Colluvic) according to WRB [48]. These soils are included in 11 contours with a dark gray color in orthophotomosaics and their total area is 0.064 km<sup>2</sup>. The main difference from the previous groups is the higher thickness of colluvial materials with relatively high soil organic carbon content. Due to the differentiation of buried material (which was incorporated during plowing into colluvial material) significant heterogeneity between the particular soils was noticed. Moreover, it was established that these soils have very low clay content, although it does not affect the bulk density and maximum hygroscopy. Soils D constitute a single category with increasing C-SOC content from the plow horizon to the subsoil. The deeper horizons contain organic matter from the original humus (or even organic) horizons developed in the past under the strong influence of groundwater, now covered with slope materials. At the same time, C-SOC content is quite diverse in both the plow horizon and the subsoil.

**Table 1.** Basic properties of the soils under study.

Soil Group		Soils A	Soils B	Soils C	Soils D
WRB name		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 (%)	1	59.3 ± 4.0	56.3 ± 4.3	66.0 ± 4.1	60.0 ± 3.9
	2	55.3 ± 5.4	55.7 ± 2.2	64.5 ± 8.3	59.5 ± 4.0
Silt (%)	1	24.8 ± 3.3	25.8 ± 3.2	24.0 ± 2.6	31.0 ± 2.9
	2	30.5 ± 3.1	21.0 ± 1.4	21.5 ± 2.1	31.5 ± 2.4
Clay (%)	1	16.8 ± 2.1	18.0 ± 2.2	10.0 ± 2.2	9.0 ± 1.6
	2	15.0 ± 2.0	24.0 ± 0.8	15.0 ± 7.6	10.3 ± 3.7
pH <sub>KCl</sub>	1	7.48 ± 0.14	7.31 ± 0.17	6.38 ± 0.52	6.77 ± 1.14
	2	7.56 ± 0.03	6.77 ± 0.34	6.17 ± 0.66	6.49 ± 1.04
C-SOC (%)	1	0.62 ± 0.09	0.77 ± 0.11	0.93 ± 0.16	2.35 ± 1.34
	2	0.14 ± 0.14	0.23 ± 0.06	0.43 ± 0.22	2.52 ± 1.19
CaCO <sub>3</sub> (%)	1	7.16 ± 1.3	1.35 ± 0.45	0.17 ± 0.16	0.23 ± 0.16
	2	12.8 ± 2.3	0.29 ± 0.30	0.14 ± 0.16	0.27 ± 0.08
Non-complexed clay/SOC, %	1	10.5 ± 1.4/0	10.3 ± 1.5/0	0.6 ± 2.2/0	0/1.5 ± 1.4
	2	13.8 ± 3.1/0	21.7 ± 0.3/0	10.6 ± 9.8	0/1.5 ± 1.2
Bulk density (kg × kg <sup>-3</sup> )	1	1.64	1.54	1.62	1.56
	2	1.88	1.78	1.58	1.75

1—plow horizon, 2—subsoil.

The diagnosis of erosive transformations also allows for the reconstruction of the soil cover. Before the period of increased erosion, the soil cover of higher elevations was dominated by Luvisols or Retisols (currently area covered by groups A, B, C) and in ground

depressions (nowadays soils D) soil affected by groundwater occurred—e.g., Gleysols, Gleyic Phaeozems and Histosols [49].

### 3. Methods

#### 3.1. Soil Sampling and Preparation

To estimate the soil properties, 32 undisturbed soil samples were collected (in October 2018) from 16 profiles encompassing the plow horizon (0–30 cm) and the subsoil (35–45 cm), making it possible to determine the parameters of the soil structure and the basic soil properties as described below. The sample collection was carried out 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, all samples were sieved through a column with the following sizes of sieves: 7 mm, 5 mm, 3 mm, 1 mm, 0.5 mm and 0.25 mm. Having obtained the different categories of aggregates, all of them were weighted separately, including those smaller than 0.25 mm, and finally, all these individual size categories of aggregates were tested.

Additionally, 32 disturbed soil samples were taken from the same locations to determine the particle size distribution, pH, Soil Organic Carbon (SOC) and secondary carbonate content. The samples included all aggregate sizes corresponding to their share in the total mass. The aggregates were crushed and sieved through a 2 mm sieve (separating the skeleton fraction from the fine earth fraction) to measure selected soil properties. Soil texture was determined using sieves and the Casagrande sedimentary aerometric method (PN-ISO 11277:2005). Soil pH was measured using a 1:2.5 (*w/v*) ratio of soil to water ( $\text{pH}_{\text{H}_2\text{O}}$ ) and a 1 M KCl ( $\text{pH}_{\text{KCl}}$ ) solution using an inoLab Level 1 pH meter. Secondary carbonate content was measured using a Scheibler volumetric calcimeter. The SOC content was investigated with the help of a Vario MACRO Cube CHN/CHNS Macro Elemental Analyzer. Non-complexed clay and SOC were calculated from the equations, suggested by [50]. The analyses were conducted at the Laboratory for Environmental Analysis (Nicolaus Copernicus University in Toruń, Toruń, Poland).

#### 3.2. Soil Structure Examination

Soil aggregate distribution in the soils (%) was determined using air-dry samples between the 7 mm, 5 mm, 3 mm, 1 mm, 0.5 mm and 0.25 mm sieves to provide the following ranges of aggregate sizes: more than 7 mm, 7–5 mm, 5–3 mm, 3–1 mm, 1–0.5 mm, 0.5–0.25 mm and less than 0.25 mm. After dry-sieving, the content of water-stable aggregates was determined using the Baksheev device. To assess aggregate stability, the prepared aggregates were placed in the sieve column within a cylindrical container (Baksheev device) filled with water. The cylinder was hermetically closed, and the samples were sieved for 15 min (angle: 45°, length of one cycle: 1 min). Each aggregate fraction was placed in the corresponding sieve as follows: the >7 fraction in the 7 mm sieve, the 7–5 mm fraction in the 5 mm sieve, the 5–3 mm fraction in the 3 mm sieve, the 3–1 mm fraction in the 1 mm sieve, the 1–0.5 mm fraction in the 0.5 mm sieve, and the 0.5–0.25 mm fraction in the 0.25 mm sieve. After each test, the residual aggregates were collected, dried at 105 °C and weighed [51,52].

The size fractions of water-stable aggregates were as follows: >7 mm, 7–5 mm, 5–3 mm, 3–1 mm, 1–0.5 mm, 0.5–0.25 mm and <0.25 mm. The material retained was quantified in each sieve with the exception of the aggregates in the <0.25 mm range, where the result was obtained by calculating the difference between the total weight of the aggregates taken for analysis and the sum of the remaining fractions.

Individual aggregate sizes were used separately instead of the cumulative samples (which were not examined). For the test, a 25 g soil sample for the >7 mm aggregate size and 10.0 g soil samples for other fractions except the <0.25 mm fraction were used. These variations were due to the unique properties of the aggregates: the weight of a single aggregate in the >7 mm fraction was often greater than 20 g, while other sizes sometimes

did not provide enough material to take a 25 g sample. To obtain comparable data, we performed a final calculation of percentages. Based on the practice that each soil group (A through D) consists of four pedons, we interpreted our data as four-time replicated. The analyses were conducted at the Laboratory for Environmental Analysis (Nicolaus Copernicus University in Toruń, Toruń, Poland).

### 3.3. Soil Aggregate Stability Evaluation

Soil aggregate stability was evaluated as a set of different parameters on the basis of data from the laboratory assessment of the aggregates. Since the wet-sieving method has a limitation in that it does not take into account all mechanisms of aggregate breakdown in field conditions, we decided to calculate as many of the parameters as possible from the data. The parameters involved different approaches; therefore, we examined the individual sizes of the aggregates from different positions.

Soil aggregate stability was determined for the purposes of the article by using the following parameters:

- Mean weight diameter after dry-sieving ( $MWD_{dry}$ , mm) and wet-sieving ( $MWD_{wet}$ ) [16], calculated according to the next Equation (1):

$$MWD = \sum (n; I - 1) WiXi \quad (1)$$

where  $Wi$ —the percentage of aggregates in the whole sample;  $Xi$ —mean aggregate's diameter calculated from the difference of top and bottom sieves  $(Xi + Xi - 1)/2$ ;  $n$ —the number of sieves.

- Percentage of water-stable aggregates larger than 0.25 mm ( $WSA > 0.25$ , %);
- Percentage of water-stable aggregates greater than 1 mm ( $WSA > 1$ , %);
- Percentage of aggregate destruction (PAD) [53] under wet-sieving, calculated according to the next Equation (2):

$$PAD = (m_d - m_w)/m_d \cdot 100 \quad (2)$$

where PAD—the percentage of aggregate destructed (%),  $m_d$ —mass of aggregates more than 0.25 mm after dry-sieving;  $m_w$ —mass of aggregates more than 0.25 mm after wet-sieving.

In the presented study, the individual sizes of the aggregates were tested, which is why the mean weight aggregate stability calculation method was utilized to determine the values of the parameters for the entire soil layer [54]. The authors proposed to calculate the characteristics as a sum of the values obtained by multiplying the proportional coefficient by the value of the parameter for each aggregate size.

### 3.4. Statistical Analyses

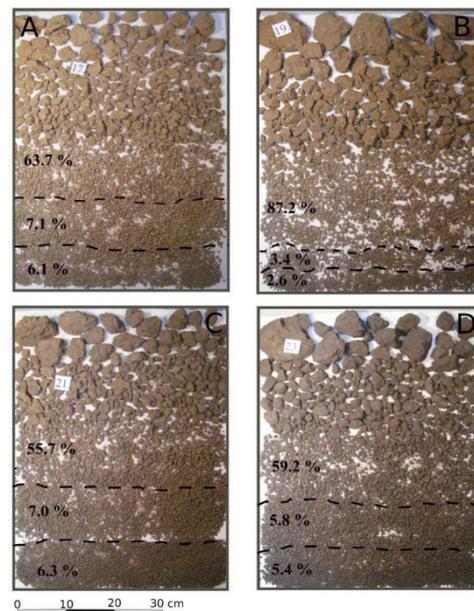
Statistical analyses were performed using Statistica Trial 8.0 and PAST 4.0 software. The significance level of the data was set to 5 percent. The standard error of the treatment was calculated by means of one-way analysis of variance (ANOVA). The Kruskal–Wallis H test for interpretation, based on normality tests for each set of data (Shapiro–Wilk test) was utilized. Multiple comparisons of the soils in terms of soil aggregate stability and basic soil properties were performed using the bubble plot and factor analysis methods. Linear correlation analyses (Pearson coefficient) were performed to quantify the relationships between the standard soil properties and aggregate stability.

## 4. Results

### 4.1. Soil Aggregate Distribution in Different Soils within a Hummocky Landscape

Aggregate distribution in dry conditions (Figure 4, Table 2) and after wet-sieving (Table 2) shows considerable variation. The soil structure in dry conditions is mainly represented by soil clods (aggregates larger than 7 mm). This tendency was observed in

all soil groups, both in the arable layer and in the subsoil. The content of dry aggregates of this size category ranges from 47.4 to 84.7 percent in the plow horizons and from 63.5 to 82.3 percent in the subsoil. Our research found a significant difference in the share of soil clods between soils in shoulder positions (soils A and soils B) and soils in lower parts of the slope. The most severely eroded soils A and the strongly eroded soils B have the highest content of the largest aggregates in the dry state. As regards other aggregate sizes, no significant differences were found between the soil groups in either the plow horizon or the subsoil.



**Figure 4.** Soil aggregate distribution in air-dry conditions (plow horizon, aggregates >3 mm) for different soils: (A)—Soils A; (B)—Soils B; (C)—Soils C; (D)—Soils D.

**Table 2.** Soil aggregate distribution in the plow and subsoil layers of the soils under study (mean values, %).

	Soil Aggregate Distribution, %								MWD	MWD <sub>dry</sub> /MWD <sub>wet</sub>
	>7	7–5	5–3	3–1	1–0.5	0.5–0.25	<0.25			
<b>Plow Horizon</b>										
Soil A	<u>68.9</u> *	<u>5.8</u>	<u>5.1</u>	8.2	<u>4.6</u>	3.5	<u>3.9</u>	<u>6.6</u>	5.2	
	1.1	1.3	2.7	12.2	18.3	25.1	39.3	1.2		
Soil B	<u>84.7</u>	<u>4.0</u>	<u>2.8</u>	4.2	<u>1.8</u>	1.1	<u>1.4</u>	<u>7.6</u>	6.0	
	1.3	1.0	3.0	13.2	19.9	25.3	36.3	1.2		
Soil C	<u>47.4</u>	<u>8.4</u>	<u>7.7</u>	<u>12.2</u>	<u>7.4</u>	<u>7.5</u>	<u>9.4</u>	<u>5.2</u>	2.7	
	4.8	2.3	5.4	16.6	19.6	25.2	26.1	1.9		
Soil D	<u>61.1</u>	<u>6.5</u>	<u>5.7</u>	<u>9.2</u>	<u>5.6</u>	<u>5.3</u>	<u>6.6</u>	<u>6.1</u>	2.6	
	10.6	2.7	5.7	19.0	20.7	24.7	16.6	2.5		
<b>Subsoil</b>										
Soil A	<u>72.3</u>	<u>6.3</u>	<u>5.2</u>	<u>6.6</u>	<u>3.1</u>	<u>3.0</u>	<u>3.5</u>	<u>6.9</u>	7.6	
	0.1	0.3	1.3	9.0	15.5	26.4	47.4	0.9		
Soil B	<u>82.3</u>	<u>4.5</u>	<u>3.5</u>	<u>4.0</u>	<u>1.8</u>	<u>1.5</u>	<u>2.4</u>	<u>7.5</u>	8.4	
	0.0	0.3	1.3	9.4	15.2	26.4	47.4	0.9		
Soil C	<u>73.3</u>	<u>4.3</u>	<u>3.5</u>	<u>5.5</u>	<u>3.0</u>	<u>3.7</u>	<u>6.7</u>	<u>6.8</u>	6.9	
	0.8	0.3	1.5	11.7	21.1	28.4	36.2	1.0		
Soil D	<u>63.5</u>	<u>6.6</u>	<u>6.3</u>	<u>8.3</u>	<u>4.3</u>	<u>4.0</u>	<u>7.0</u>	<u>6.2</u>	3.3	
	4.5	2.7	7.4	25.6	24.2	21.3	14.3	2.0		

\* over the line—dry-sieving; under the line—wet-sieving.

However, the tendency in the distribution of water-stable aggregates was different than described above. Soil clods, the main size category, exhibited minimal soil resistance to water. The percentage of aggregates larger than 7 mm dropped dramatically after water sieving: from 68.9 percent and 84.7 percent in soils A and soils B, respectively, to 1.1–1.3 percent in both groups. Soils D with their thick colluvial layer showed the highest share of resistant aggregates—around 10 percent in the plow layer. Soils C occupied an intermediate position with 4.8 percent of water-stable aggregates larger than 7 mm. In the subsoil, aggregates of this size category were destroyed without differences between the soil groups.

Additionally, in the plowing horizons and the subsoil, all aggregates larger than 3 mm were equally disaggregated without differences between the soils found on the slopes (Soils A, B and C). An increase in water-stable aggregates was observed in sizes of less than 3 mm. Generally, all soils had a very similar content of water-stable aggregates in sizes of 1–0.5 mm and 0.5–0.25 mm.

Aggregate stability can be estimated from the ratio of MWD in dry and wet sieving. A smaller difference in MWDs indicates higher stability of the soil aggregates [55]. Despite the similar distribution of aggregates in different soils, changes in mean weight diameter at dry-sieving and wet-sieving presented, in obvious ways, that soils in middle-slope and toe-slope positions have a more stable structure in plow horizons. Moreover, the aggregate stability of subsoil in Soils D was slightly worse than in plow horizons: the ratio of  $MWD_{dry}$  to  $MWD_{wet}$  was 3.3 and 2.6, respectively (Table 2). The highest value of the MWD's difference was in Soils B—strongly eroded Haplic Luvisols (Protocalcic)—both in plow horizon and subsoil.

#### 4.2. Water Stability of Aggregates in Different Soils

The description of soil stability as a complex of parameters could contribute to the study of soil behavior after contact with water and to the prediction of the development of the processes mentioned above. An assessment of soil aggregate stability is presented in Table 3. Some of the parameters used, for example  $MWD_{wet}$ , have a well-developed classification. Others ( $WSA > 0.25$ ,  $WSA > 1$ , PAD) are more intuitive and could be interpreted on the basis of absolute values.

**Table 3.** Aggregate stability parameters (based on wet-sieving) for different soil groups in a young hummocky moraine landscape (mean values  $\pm$  standard derivation).

Soil	Layer *	$MWD_{wet}$ (mm)	$WSA > 0.25$	$WSA > 1$	PAD, %
A	1	1.2 $\pm$ 0.15	59.7 $\pm$ 10.4	7.1 $\pm$ 3.0	37.9 $\pm$ 10.8
	2	0.9 $\pm$ 0.06	54.7 $\pm$ 8.7	1.9 $\pm$ 0.8	43.2 $\pm$ 9.4
B	1	1.2 $\pm$ 0.34	65.7 $\pm$ 9.3	8.9 $\pm$ 7.4	33.4 $\pm$ 9.4
	2	0.9 $\pm$ 0.06	48.8 $\pm$ 7.5	2.1 $\pm$ 1.0	50.0 $\pm$ 7.4
C	1	1.9 $\pm$ 0.49	67.3 $\pm$ 3.6	15.6 $\pm$ 6.2	25.6 $\pm$ 3.9
	2	1.0 $\pm$ 0.31	58.5 $\pm$ 10.4	2.5 $\pm$ 2.3	36.6 $\pm$ 15.0
D	1	2.5 $\pm$ 0.98	82.0 $\pm$ 3.4	22.1 $\pm$ 16.0	12.1 $\pm$ 6.1
	2	2.0 $\pm$ 0.79	79.7 $\pm$ 2.3	15.6 $\pm$ 12.0	14.3 $\pm$ 4.3

\* 1—plow horizon, 2—subsoil.

For all parameters, we observed a general deterioration of aggregate stability from the plow horizons to the subsoil. Moreover, very poor soil stability was typical of the subsoil in all slope soils, without any differences in relation to the slope position. This absence of differences was supported by the results of the statistical analyses ( $p > 0.05$ ). Another common feature was the essentially similar values of soil stability parameters for soils A and soils B. These soils have very poor stability despite differences in basic chemical

properties (soils A have a high secondary carbonate content). Refs. [56,57] emphasized in their research that poor aggregate stability corresponds to significant potential erodibility.

**MWD<sub>wet</sub>.** Mean weight diameter (MWD<sub>wet</sub>) is widely utilized in the assessment of soil stability and spatial distribution. According to Le Bissonnais (1996), soils can be categorized into five stability classes based on the MWD<sub>wet</sub> value. An MWD<sub>wet</sub> of >2 mm corresponds to very stable material, values in the range of 2–1.3 mm correspond to stable aggregates, values in the range of 1.3–0.8 mm correspond to medium stability, values in the range of 0.8–0.4 mm correspond to unstable material, and an MWD of <0.4 mm corresponds to very poor stability. The same classes have also been used by other scientists [6].

According to the classification described previously, we could characterize colluvial soils (soils D) as very stable materials in both studied layers (plow layer and subsoil). The aggregates in the plow horizons of soils C are characterized as stable. However, the subsoil in this group and also both horizons in soils A and soils B could be described as medium-stability materials. There are no differences between the completely eroded Eutric Regosol (soils A) and the strongly eroded Luvisols (soils B) in terms of MWD<sub>wet</sub> values. However, soils C show the most substantial difference in MWD<sub>wet</sub> values from the plow horizons to the subsoil. It is an unexpected result that demonstrates the high vulnerability of these soils. Disturbance of the plow layer and inclusion of the subsoil in plowing entail a high potential risk of an abrupt decrease in aggregate stability (Table 3).

For all soils, the difference between the plow horizons and subsoils was confirmed statistically ( $p < 0.05$ ). Additionally, significant variability between soils D and other soil groups and between soils C and soils A/B was revealed as a result of analysis of variance (ANOVA). Surprisingly, all subsoil horizons have  $p > 0.05$  that point at the equally negative tendency to decrease in soil aggregate stability in the subsoil without difference among soil groups.

**WSA > 0.25.** As for the total amount of water-stable aggregates, we expressed it by means of WSA > 0.25. The data showed that the total amount of water-stable aggregates in the plow horizons exceeded 50 percent. Soils D contain the largest amount of water-stable particles, with a mean value in excess of 80 percent. Similar data for delluvial (colluvial) soils in a hummocky landscape in Poland were described by some polish authors [58]. The article referenced above emphasizes the differentiation of materials in colluvial soils without a decrease in the amount of water-stable aggregates. At the same time, in our study, soils B and soils C have similar mean values, which could be evidence of similar stability of materials. However, we observed a significant fluctuation of data for soils B, whereas, for soils A, the data were more homogeneous. The subsoil of soils B exhibited the lowest values of water-stable aggregates—below 50 percent. Generally, the soils on the slopes are very similar to one another in the plow horizons. However, there is a considerable difference between the eroded and colluvial soil varieties in the subsoils.

**WSA > 1.** Our main estimation of aggregate stability was based on the WSA > 1 ranges proposed by Paluszek [59] that included five classes: very poor aggregate stability (WSA > 1 < 7 percent); poor aggregate stability (WSA > 1 7–15 percent); medium aggregate stability (WSA > 1 15–25 percent); good (WSA > 1 25–40 percent) and very good aggregate stability (WSA > 1 >40 percent). Generally, a vast majority of the soil samples (85 percent) were characterized by poor or very poor water stability with WSA > 1 less than 15 percent (Table 3). Moreover, approximately half of all soil samples had very poor overall stability. According to this classification, the most strongly and completely eroded soils (A and B) typically had the lowest stability parameters. At the same time, only two samples taken from colluvial soils—with less than 10 percent of clay content and very high SOC content—were ranked as having good or very good water stability.

**PAD.** The last indicator, considered in this paper, is PAD (%), which quite obviously presents the percentage of aggregates that have disintegrated due to the action of water (Table 3). Analysis of the data shows that the PAD values vary considerably depending on the type of soil and the degree of soil truncation. The least stable structure is characterized by the subsoils of soils A, B and C. The highest PAD values were reached in the subsoil of

soils B—50 percent. On the other hand, among the subsoils, the worst water resistance is characterized by the eroded soils (A and B), for which the PAD reaches 33.4–37.9% percent. Soils D have a better water resistance of structure with a PAD of 12 percent in the arable layers and 14 percent in the subsoil.

#### 4.3. Interaction between Soil Properties and Aggregate Stability in Hummocky Landscape Soils

The correlation matrix (Table 4) illustrates the most general specifications of soil aggregate stability in soils within the experimental plot. The analysis shows that the parameters of aggregate stability are positively correlated with soil organic carbon content and negatively with the content of clay.  $MSA > 1$  and  $MWD_{wet}$  are strongly correlated with SOC content— $r^2 = 0.85/0.86$ . These two parameters are widely utilized in aggregate stability assessment and our conclusion is grounded in their analysis.

**Table 4.** Pearson’s correlation matrix: interactions between soil aggregate stability and soil properties.

Parameters of Aggregate Stability	Content of Particles, %			C-SOC, %	pH <sub>KCl</sub>	CaCO <sub>3</sub> , %
	Sand (2.0–0.05 mm)	Silt (0.05–0.002 mm)	Clay (>0.002 mm)			
$MSA > 1$	+	+	−0.53	0.85	-	-
PAD, %	−0.46 *	−0.40	0.78	−0.75	+	0.48
$WSA > 0.25$	0.42	0.44	−0.77	0.72	+	-
$MWD_{wet}$	+	0.41	−0.63	0.86	-	-

Correlation: very strong positive and negative ( $r^2 = \pm 0.8–1.0$ ); strong positive and negative ( $r^2 = \pm 0.60–0.79$ ); moderate positive and negative ( $r^2 = \pm 0.40–0.59$ ); \* Correlation is significant with  $p < 0.05$ .

The parameter PAD has a negative meaning, decreasing aggregate stability with its rise. It has a strong positive correlation with clay content and a strong negative one with SOC content. PAD is a sole parameter that has a moderate positive correlation with secondary carbonate content. Moreover, PAD is moderately negatively correlated with sand and silt content.  $WSA > 0.25$  is a parameter, opposite to PAD, so it correlated with the same soil properties with the same forces.

## 5. Discussion

Despite the wide body of literature that exists, the study of water stability of aggregates in different conditions has still been very important. As some authors noticed, aggregate stability is a very flexible parameter and knowledge about it changing in different landscapes needs to be evaluated [60–62].

The study presented in this paper was based on the hypothesis that in hummocky landscapes with heterogeneous soil cover soil aggregate stability depends on the position of the soil on the slope and is linked to its erosional transformations (anthropogenic denudation), that is the different stages of soil truncation or colluvium accumulation. Prior studies that have noted the importance of the examination of aggregate stability as a part of spatial characteristics of soil cover did not take into account such complicated areas as the young hummocky moraine landscapes in the European boreal zone. However, more and more research studies have made attempts to access aggregate stability in different landscapes and carry out the differences in aggregate stability on a regional scale [61–64]. In contemporary research, the prediction of soil aggregate distribution in a landscape is based on available soil data, which is why the expansion of additional data can be an important task in such areas as a young hummocky moraine landscape. Our study complements research in this type of landscape in data on the stability of the soil structure to destructive water impact.

Our analysis of soil aggregate distribution showed a predominance of soil clods (>7 mm) in dry conditions. This could be an indication of negative processes in the soils, such as compaction and hardsetting beginning by the reason of intensive agricultural use.

This conclusion of our research also supports evidence from previous observations [65–69]. According to the obtained data, the highest content of clods in the dry state is characteristic of strongly and completely eroded soils (A and B) where truncation led to the excavation of illuvial horizons and parent materials and removal of sandier in textured material from eluvial zones [35,70,71]. In eroded pedons from group B with surface, ABtp horizons share of clods exceeds 80 percent in plow horizon and subsoil. It is almost two times higher in value than was obtained for Ap horizons in non-eroded soils (group C) located in lower slope parts. The dominant share of such large aggregates may negatively affect the growth of crops, especially in the initial stages of growth (Figure 5).



**Figure 5.** The weaker wheat growth fully coincides with the extent of eroded soils with ABtp and ACkp surface horizons (groups A and B).

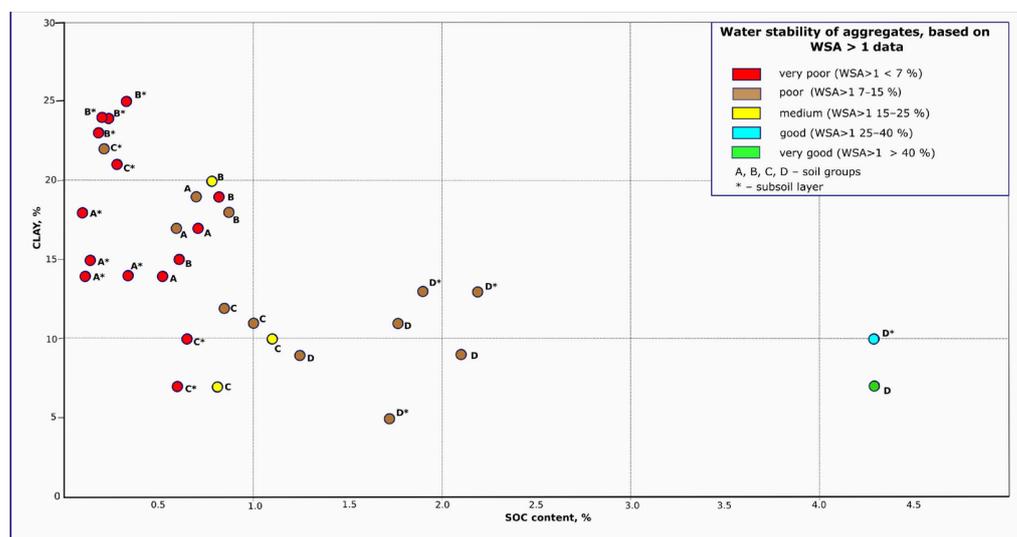
The slight resistance of soil clods to water impact is broadly supported by the work of other studies in this area [9,72]. Soil clod formation is very specific in soils and has a significant influence on the water stability of aggregates due to a slight connection between particles in clods. As the authors emphasize, the most serious problem for soils with a significant amount of soil clods in the arable layer is the inability to withstand mechanical stress, such as tilling. All these reasons point to the formation of exceedingly negative soil structural conditions in soils of experimental plots, especially in periods of droughts. Including parent materials into the plow layer also contributes to the form of soil clods from the materials with low organic carbon content and additional clay. The tendency for a convergence of the properties of the soils in the plow layer to those of the subsoil, reported in our study, collaborates with earlier findings [9,72]. At the same time, our study found the emphasizing role of smaller fractions in the total aggregation in wet conditions, consistent with the literature [59,69,72].

The presented studies confirmed the very low water resistance of large aggregates in all groups of soils (Table 2). Nevertheless, the clods from strongly eroded soils with reduced humus content in surface horizons had the lowest resistance. In groups A and B, the content of clods decreased to approximately 1 percent and the values of aggregate destruction (PAD) were highest. Moreover,  $WSA > 1$  is the lowest in soils from groups A and B (Table 3). Values below 10 percent indicate nearly two times lower content of such water-stable aggregates compared to non-eroded (C) and colluvial (D) soils. Small differences in  $WSA > 0.25$  between groups A, B and C may result from a significant share of sand grains in the mass of aggregates of this size. Therefore, this parameter cannot be interpreted unequivocally.

The research presented data on aggregate stability for each soil in an experimental plot. The current study was carried out on a local microscale, and it allowed us to find that in a young hummocky moraine landscape the aggregate stability changed significantly within a very small distance. Our catenae had a length of about 100 m and soil aggregate stability, performed by  $MWD_{wet}$ , changed from medium-stable to stable at this distance. Contrary to expectations, our study did not find a difference in aggregate stability between Eutric Regosols (Protocalcic) and Haplic Luvisol (Protocalcic) despite the different stages of trun-

cation. All parameters of aggregate stability were very close in values without a statistically confirmed difference. This is also consistent with our previous observations, which showed that Eutric Regosols (Protocalcic) (Soils A) and Haplic Luvisol (Protocalcic) (Soils B) had the same erodibility K-factor, calculated by EPIC model [73]. A possible explanation for this might be that these soils have very similar soil organic carbon content (less than 0.8 percent) and an additional negative factor, specific in each soil group: secondary carbonates in the case of Soils A; and the value of clay content in Soils B which was insufficient to build stable aggregates (less than 40 percent). In the case of Soils A, we based our conclusions on previous studies that pointed to the high dispersion role of free  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions [74–76]. The negative effect of low clay content (sandy loam) on aggregate stability also was observed by some authors in soils with similar soil texture [77,78]. Despite the small area (about 25 percent of the total area), occupied by Eutric Regosol (Protocalcic) and Haplic Luvisol (Protocalcic) in the research plot, these soils can be a main source of runoff because of their low resistance to water impact. Based on the data of the study, we presume that hummocky landscape soils with average clay content (15–25%) have lower water stability, especially in combination with an SOC deficiency. An increase in SOC content led to a rise in the soil's water stability. However, to achieve good or very good water stability, the amount of soil carbon should be very high for mineral soils (more than 4%). The above data were consistent with the data presented by Rzaša and Owczarzak [60] for Albic Luvisols and Phaeozems in a post-glacial landscape in Poland. The authors argue that high SOC content increases the water stability of dry aggregates in all size categories. Moreover, the data confirmed previous Polish research [58] with regard to the high dependence of water stability on SOC content, especially in colluvial soils. The aggregate stability of the soils under study was strongly related to the fact that shoulder slope complexes lose humus material by erosion and footslope complexes gain more colluvial material that is relatively rich in organic C under long-term cultivation [79,80].

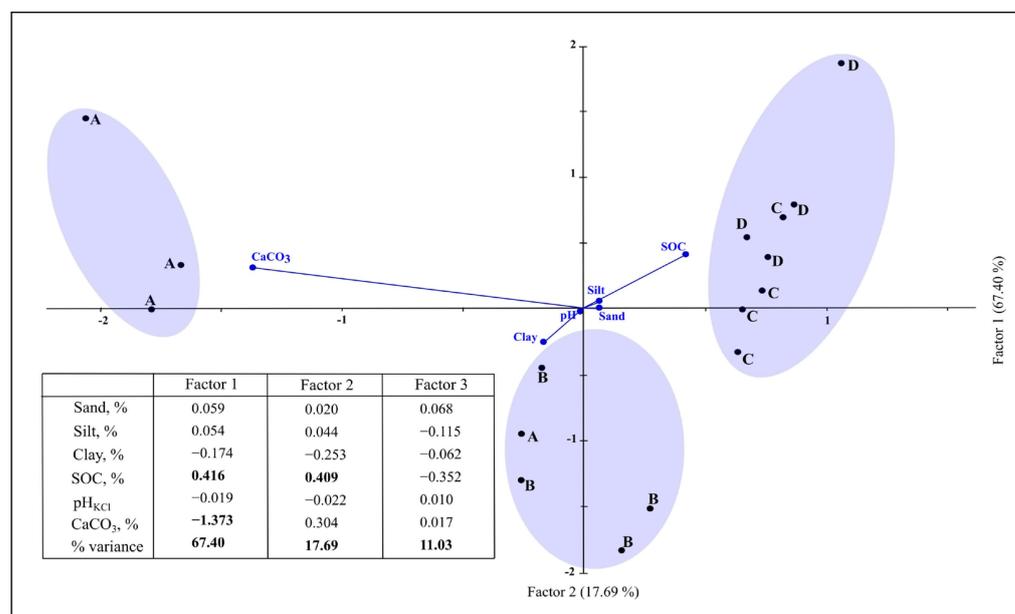
To find some regularity in data, we assessed the distribution of  $\text{WSA} > 1$  values depending on clay and soil organic carbon content (Figure 6).



**Figure 6.** Assessment of aggregate stability in different soils depending on clay and soil organic carbon content.

The data shows that an increase in clay content with a corresponding low SOC value has a direct negative impact on aggregate stability in the soils under study. These data were confirmed by the correlation. Thus, the most obvious way to increase aggregate stability is by increasing soil organic carbon content. As Figure 5 presents, subsoils with very low organic carbon content and relatively high (compared with other soils in the landscape) clay were characterized as soils with very poor aggregate stability.

The correlation does not make it possible to draw an explicit conclusion regarding the role of specific soil properties in water-stable aggregates due to the complex factors that affect soils at different slope positions. To reveal hypothetical interactions between aggregate stability parameters and soil properties, we performed factor analyses operating on data representing the soil stability characteristics as group-independent variability (Figure 7).



**Figure 7.** The main factors affecting the aggregate stability of the plow horizons: A—Soils A; B—Soils B; C—Soils C; D—Soils D.

Three factors were found that explain about 96 percent of the variance. The first one has the greatest impact on the variance (67 percent) and combines the medium positive effect of SOC content and the significant negative effect of secondary carbonate content. The second factor also includes SOC content without any other additions. Clay content did not have a strong impact on soil aggregate stability.

However, the sample distribution on the plot (Figure 7) illustrates the grouping of soils, depending on soil organic carbon content (Soils C and D), secondary carbonate content (Soils A, laying oppositely of Soils C and D along the axis X), and clay content (mostly Soils B). Other properties, such as pH, silt and sand content, did not show any impact on aggregate stability.

Based on the reasoning indicated before, we were able to determine that:

- The stability—or in this case instability—of the aggregates present in soils A depends mainly on the content of secondary carbonates. This effect has a detailed explanation in several studies that point to the high dispersion role of free  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  ions [74–76]. Aggregate instability may also be connected with a small amount of dissolved organic matter in high pH conditions [81].
- The second group includes all soils C and soils D, where SOC content was the main factor of aggregate stability and was probably responsible for the formation of the soil structure in all the soils developed from colluvial material.
- The third group contains soils with equally unstable aggregates—soils B and one of soils A. Here, we were able to register some impact of clay content. Nevertheless, it was lower than in the case of other components and was therefore not reflected in the factor matrix.

Silt, sand content and acidity did not affect the water stability of the soils.

It should be noted that these groups of soils were formed as a result of soil erosion transformations—both the high content of calcium carbonate and the clay fraction in the surface horizons—and changes in the humus content in the upper part of the slopes—are related to the stages of soil erosion.

The results of the research show conclusively that in the case of highly heterogeneous soil covers, describing the properties of aggregates in the context of an entire field (agricultural plot)—even when it has been used in a uniform manner—is inappropriate. A solution for such diversified areas and soil units may be the use of aerial or satellite photos, where—based on the variability of the colors of surface horizons—the properties of aggregates can be estimated and interpolated with the help of geostatistics. These issues seem to be of particular importance as they can find practical application in precision agriculture. This approach will be developed at a later stage of the authors' research.

## 6. Conclusions

Our research proved the existence of a diversity of soil aggregate stability in a hummocky landscape, reflecting the high variability of the soil cover in undulating and hilly moraine uplands. Both the differentiation of the soils themselves and the stability of the aggregates were very strongly linked to erosive transformations:

- (1) The tops of the hills and the upper parts of the slopes are covered with completely (Regosols) or strongly eroded (Luvisols) soils in which the aggregates have the least favorable characteristics. Due to the smallest amount of humus and the highest clay content, the soils have the largest share of soil clods, which are aggregates larger than 7 mm which may have formed in dry conditions (soil drought). At the same time, the lack of organic matter makes these aggregates the most unstable when exposed to water.
- (2) A factor influencing the low stability of the aggregates in completely eroded soils located on the tops of the hills may be the erosive exposure of carbonate material—Ck horizons. In strongly eroded Luvisols located in the upper sections of the slopes—it is a significant content of clay in ABtp horizons which is not associated with humus.
- (3) As a result of further erosional denudation, the soil structure may continue to deteriorate, as evidenced by the very inconsistent values of the MWD,  $WSA > 1$  and PAD coefficients in the subsoil of Regosols and eroded Luvisols.
- (4) The low water stability of aggregates in already eroded pedons may intensify slope processes due to soil sealing during rainfall. Soils which have already been completely or strongly eroded were approximately twice more susceptible to erosion in comparison to the non-eroded state.
- (5) Colluvial soils are characterized by the most favorable soil structure—they have the highest amount of soil organic matter, and the texture is favorable to the formation of medium-sized peds.

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