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Comparison of Topsoil Organic Carbon Stocks on Slopes under Soil-Protecting Forests in Relation to the Adjacent Agricultural Slopes

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Abstract: Soil erosion is one of the major processes degrading the natural environment but also agricultural production areas. Soil erosion may lead to soil organic carbon (SOC) loss, especially from sloping agricultural terrain units. The use of phytomelioration in environmental management, particularly long-term, permanent forest vegetation, is widely recognized as a possible measure for soil erosion protection and mitigation of climate change through carbon sequestration. The aim of this study was to compare of the topsoil organic carbon stocks on the slopes under soil-protecting forests in relation to the adjacent agricultural slopes. The research was conducted in the young glacial landscape of North-Central Poland. The study indicated the significant role of forest management on the increase of soil organic matter content and SOC stock. The results show that land use and slope gradients are important factors controlling soil organic carbon pools in topsoil in young glacial areas. This topic is extremely important particularly as the effects of climate change become more and more visible, and society faces new challenges in preventing these changes.

Keywords: soil organic matter (SOM); soil organic carbon (SOC) stock; global carbon cycle; topsoil; hillslopes; erosion; soil-protecting forests

Citation: Wiśniewski, P.; Märker, M. Comparison of Topsoil Organic Carbon Stocks on Slopes under Soil-Protecting Forests in Relation to the Adjacent Agricultural Slopes. *Forests* **2021**, *12*, 390. https://doi.org/10.3390/f12040390

Academic Editors: Cezary Kabała, Jarosław Lasota and Ewa Blonska

Received: 12 February 2021
Accepted: 23 March 2021
Published: 26 March 2021

1. Introduction

In the course of the ongoing civilization processes that lead to rapid changes of the natural environment, the carbon balance is increasingly important not only for a proper functioning of ecosystems but also for the socio-economic development of many regions of the world [1]. Soil organic carbon (SOC) in the form of soil organic matter (SOM) plays an important role in the soil nutrient cycles and soil biodiversity. Benefits of soil organic matter include improvement of soil quality through increased retention of water and nutrients, resulting in greater productivity of plants in natural environments and agricultural settings. SOM improves soil structure and reduces erosion, leading to improved water quality in groundwater and surface waters, and ultimately to increased food security and decreased negative impacts to ecosystems [2]. It is a natural resource for the sustainable development of human society and a key foundation for sustainable forestry development [3]. SOC is also the most important indicator of soil fertility, and monitoring its space-time changes is a prerequisite to establish strategies to reduce soil loss and to preserve soil quality [4].

Soil organic matter is an important sink for atmospheric carbon dioxide, thus influencing the global carbon cycle directly. Hence, SOC plays an important role in governing the dynamics of greenhouse gases (GHG), as its pools and its transformations in the terrestrial ecosystems may influence the concentrations of carbon dioxide, as well as those of other greenhouse gases in the atmosphere [5–8]. In the global carbon cycle, soils constitute the third largest reservoir. It is estimated that carbon contained in soil accumulate 75% of the total organic carbon pool, exceeding twice the resources of carbon in the atmosphere [9–11]. Globally, the soil contains a carbon pool estimated at approximately 1500 Gt of organic carbon in the first 1 m of the soil profile [12]. Current land use changes have a net negative impact on soil carbon. Desertification and erosion associated with overgrazing and excess fuelwood harvesting, conversion of natural ecosystems into cropland and pasture land, and agricultural intensification are causing losses of soil carbon [13]. Therefore, the protection of soils against erosion and the maintenance of soil organic matter and soil structure are two pillars helping to protect soils and to enhance soil quality and soil functions [14].

An effective way to protect soils is applying phytomelioration measures. Strategic landscape-level deployment of plants through agroforestry systems may represent an efficient way to rebuild total ecosystem carbon, while also stabilizing soils and hydrologic regimes, and enhancing biodiversity [13]. In particular, the use of long-term, permanent forest vegetation (especially mixed forest) seems very promising [15–18]. These protective effects consist primarily in stabilizing the soil through a dense root system. Moreover, precipitation is intercepted and retained along the stem and in the leaf litter or organic soil layers. The forests also trigger the melting of snow cover and reduce, distribute, or facilitate infiltration of surface runoff. Finally, subforest vegetation helps to redeposit material eroded in the upper parts [19–26].

The aim of this study was to compare of the topsoil organic carbon stocks (SOCP) and correlations between SOCP and selected soil properties on the slopes under soil-protecting forests (legally recognized forests for soil-protection) in relation to the adjacent agricultural slopes. Topsoils are more sensitive to environmental conditions and changes than other parts of soil profiles [27]. Our study is focused on the moraine areas of Northern-Central Poland. In Poland, soil-protecting forests occupy an area of 323 thousand ha, which represents 8.9% of the total area of protective forests and 3.5% of all forest resources managed by the National State Forest Holding [28].

2. Materials and Methods

The research was carried out in the young glacial lake districts in Northern-Central Poland, on the slopes that are subject to plough tillage. Alongside these ploughed slopes, we identified slopes that are partially or completely covered with soil-protecting forests having the same climatic conditions and similar humidity conditions, as well as the same or similar slope gradient. The landscape morphology of these areas has been mainly formed during the last glacial (Vistulian) and postglacial period. The study area is located in the temperate warm transitional climate zone. Its territory is affected by air masses from both the Atlantic Ocean and the continental Eurasian landmass. Concerning the transfer of air masses, westerly winds are the most prevailing ones in the study area. On average, annual totals of precipitation are ca. 500–600 mm. The number of days with precipitation sum >0.1 mm ranges from 130 to about 170 a year [29]. Apart from moraines, there are kames, eskers, glacial troughs, river valleys, and glacial lakes. The soil cover is dominated by Cambisols overlaying boulder clays and loamy sands. The other important soil units are the Podzols developed on glacial outwash material, as well as Brunic Arenosols formed from glacio-fluvial and mixed cover sands. Locally, outwash sands are found [30,31]. Cambisols generally make good agricultural land and are used intensively. Parent material are mainly medium and fine textured materials derived from a wide range of rocks. They are characterized by slight or moderate weathering of parent material and by absence of appreciable quantities of illuviated clay, organic matter, Al, and Fe compounds. Podzols have an illuvial horizon with accumulation of black organic matter and reddish Fe oxides. Their parent material are mainly weathering materials of siliceous rock, including glacial till and alluvial and aeolian deposits of quartz sands. Most Podzols are under forest or shrubs [32]. Brunic Arenosols (termed rusty soils in Poland) are developed from glaciofluvial, old-alluvial, and mixed cover sands, and have a relatively low agricultural suitability. Compared to Podzols, Brunic Arenosols have a somewhat finer texture, higher pH, and higher base saturation throughout the profile. They also have a thick subsurface Bv horizon [33]. The dominant forest areas are pine forests and mixed forests, although there are also large areas of deciduous forests. The stands mainly consist of pine (over 85%). In general, forests are very homogeneous. The majority of forest area is occupied by single-storied stands [34].

According to Reference [35], we subdivided the slopes in topographic units. Along the cross sections, we selected different top-slope, mid-slope, and toe-slope positions to establish soil pits. The soil pits in the top-slope positions cover interfluve and convex slope units, whereas the mid-slope soil pits characterize straight sloping transport related land units. The toe-slope positions are described by concave colluvial slope units showing colluvial processes (Figures 1–5).

The soil profiles were described in terms of morphology in line with the 6th edition of the Polish Soil Classification [36], which adopted a new classification of soil texture and mineral materials, compatible with particle sizes and textural classes of the United States Department of Agriculture (USDA) Soil Taxonomy system [37]. On arable land and rangeland, pits were dug to a depth of 150 cm, whereas, under the soil-protecting forests—according to the Forest Management Planning Instruction [38]—we dug to a depth of 200 cm. From each pit, topsoil samples at a depth of 0–10 cm were taken for further analysis. The final sample, representative of a homogeneous topsoil unit, had a weight of 1 kg. Detailed description of the particle size distribution and selected chemical and physicochemical properties of soils along the analyzed cross sections was presented in a previous paper of the authors [39] (Table A1 in Appendix A). Based on the land unit concept, the main slope units and the respective soil forming processes, such as erosion, transport, and deposition processes related to infiltration, surface runoff, and hypodermic soil water dynamics, were characterized.

In each soil pit, topsoil samples at a depth of 0–10 cm were taken, and the pools of soil organic carbon (SOCP) were determined. For the calculation of SOCP accumulated in the topsoil, we used Equation (1), as follows:

$$\mathrm{SOCP} = \mathrm{Corg} \times \rho \times \mathrm{h}/10, \tag{1}$$

where: SOCP—pools (stocks) of SOC accumulated in the surface layers (kg m^{-2}); Corg—organic carbon content (%); ρ—soil bulk density (g cm^{-3}); h—thickness of soil layer (cm) [40].

The SOC content was analyzed using the modified Tiurin method [41] to give results practically identical with those of the dry combustion method. This method is suitable for almost all soils. Soil bulk density was assessed using the core method (volumetric cylinder method). The core sampling method is the most common method used to determine ρ in agricultural soils [42]. Rings of 100 cm^3 volume were used as the reference method because this follows International Organization for Standardization (ISO) [43] and is the common sample ring size in soil surveys. As recommended by Reference [44], all samples were dried at 105 °C to constant weight, and the total dry mass was divided by the sampled volume to obtain the soil bulk density value. Gravel and other particles >2 mm were previously removed from all soil samples.

The topsoil organic carbon stocks were subjected to statistical and comparative analysis. Subsequently, all relationships between soil variables were evaluated using Pearson's correlation tests. In order to calculate the Pearson correlation coefficients, the relationship between the SOC stocks and the variables, such as of soil texture, concentration of available forms (P, K, Mg), soil organic carbon content, and soil bulk density, were assessed.

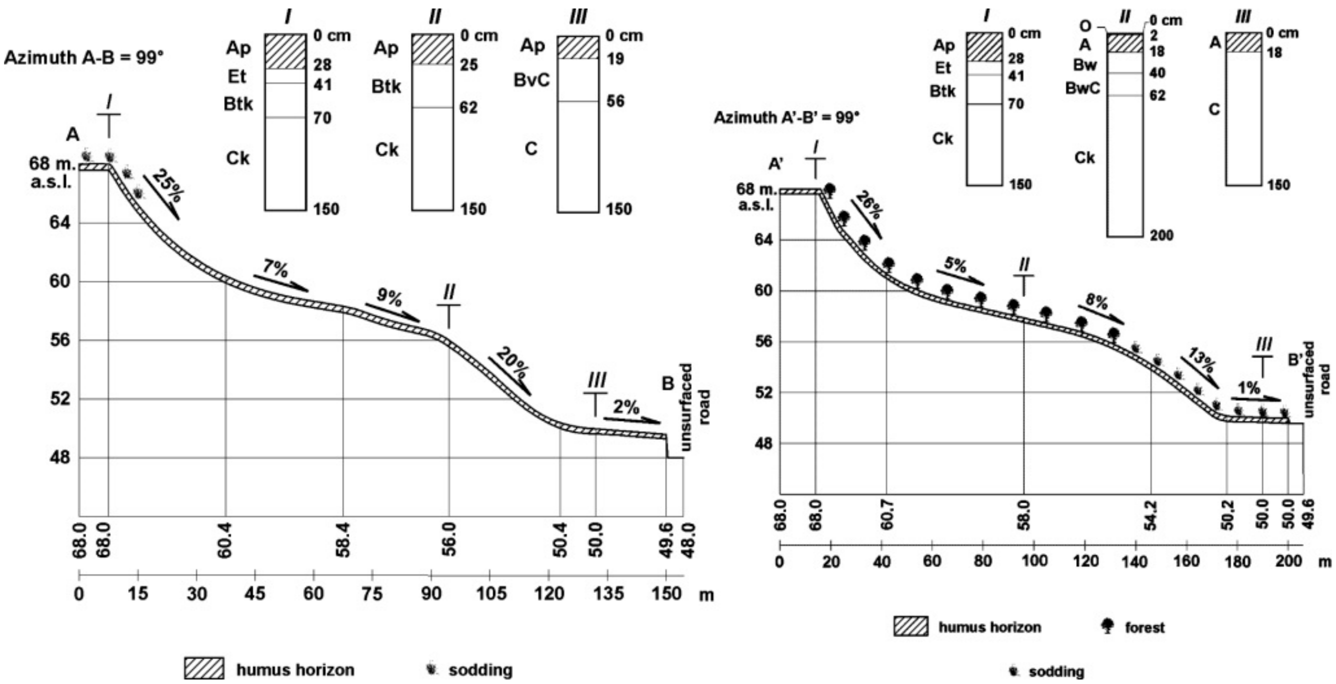

Figure 1. The soil cross sections A-B and A′-B′. Slope gradient in %; A: humus horizon; E: eluvial horizon; B: enrichment horizon; C: parent material (substratum); O: organic horizon; *p*: plow layer; t (for E horizons): leaching of clay fraction; t (for B horizons): illuvial accumulation of clay; k: accumulation of pedogenic carbonates; v: occurrence of plinthite; w: development of color or structure in a horizon but with little or no apparent illuvial accumulation of materials [39].

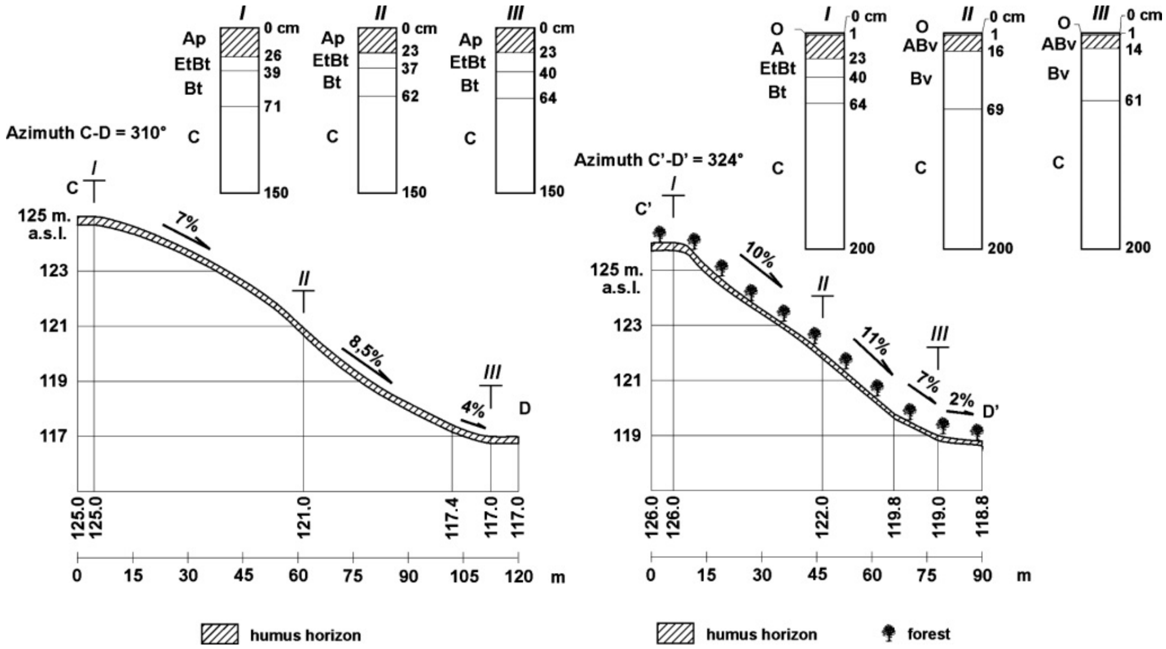

Figure 2. The soil cross sections C-D and C′-D′. Slope gradient in %; A: humus horizon; E: eluvial horizon; B: enrichment horizon; C: parent material (substratum); O: organic horizon; *p*: plow layer; t (for E horizons): leaching of clay fraction; t (for B horizons): illuvial accumulation of clay; v: occurrence of plinthite [39].

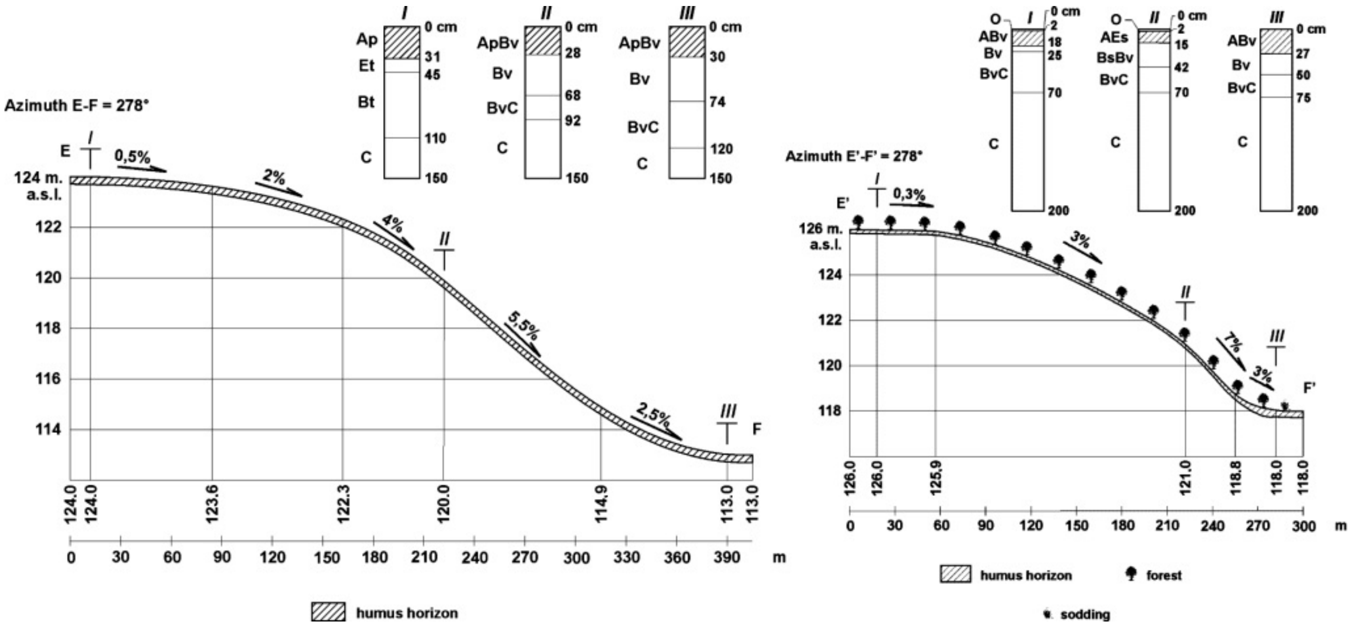

Figure 3. The soil cross sections E-F and E′-F′. Slope gradient in %; A: humus horizon; E: eluvial horizon; B: enrichment horizon; C: parent material (substratum); O: organic horizon; *p*: plow layer; t (for E horizons): leaching of clay fraction; t (for B horizons): illuvial accumulation of clay; v: occurrence of plinthite; s: iron and aluminium leaching [39].

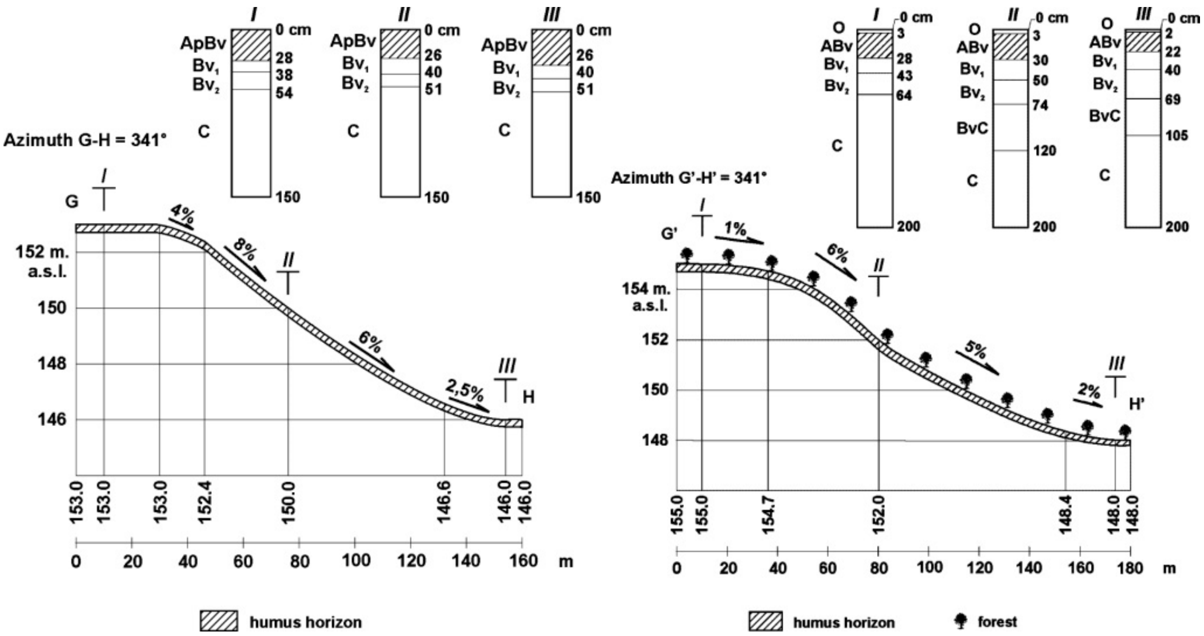

Figure 4. The soil cross sections G-H and G′-H′. Slope gradient in %; A: humus horizon; B: enrichment horizon; C: parent material (substratum); O: organic horizon; *p*: plow layer; v: occurrence of plinthite [39].

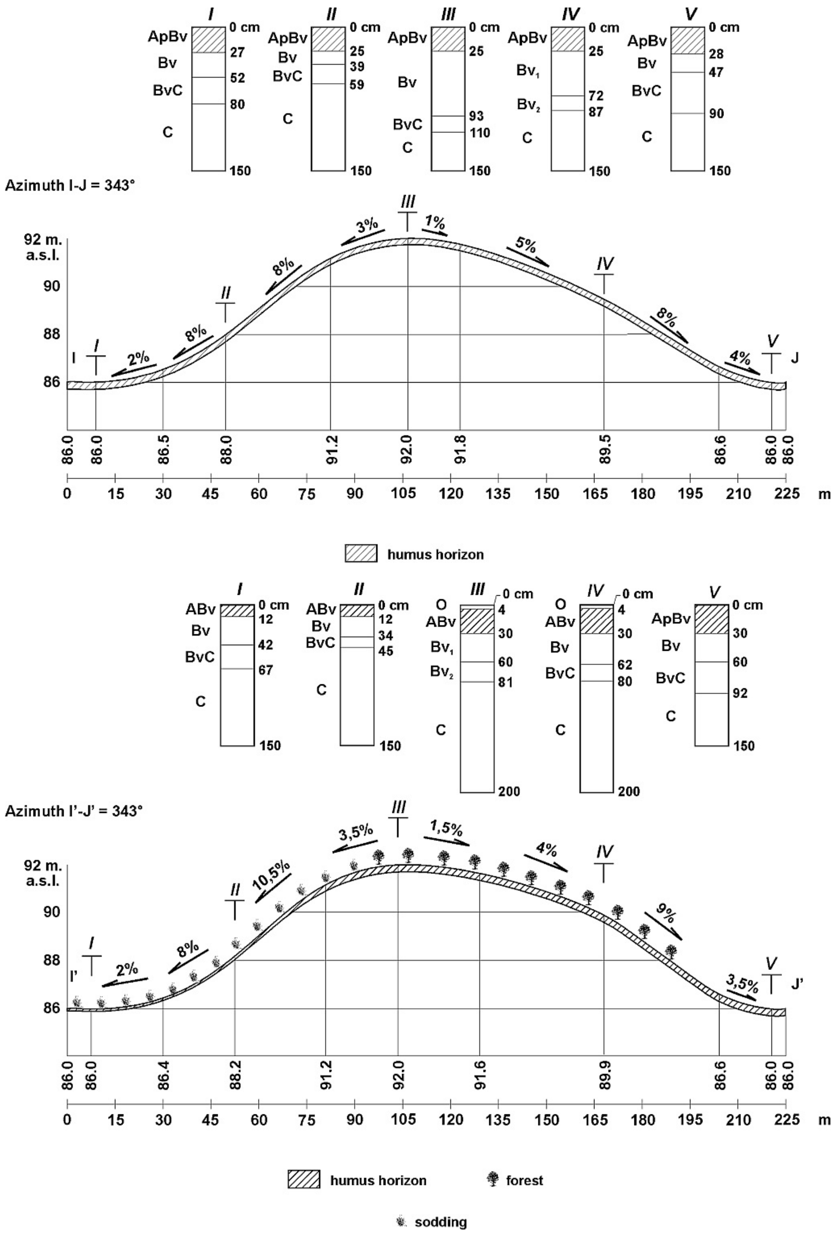

Figure 5. The soil cross sections I-J and I′-J′. Slope gradient in%; A: humus horizon; B: enrichment horizon; C: parent material (substratum); O: organic horizon; *p*: plow layer; v: occurrence of plinthite [39].

3. Results and Discussion

Soil cross sections, as well as the analysis of material collected from the soil pits, reveal the spatial variability of soil morphology, as well as the physical and chemical properties of the soil within the topsoil layer, consequently, up to a depth of ca. 10 cm. Generally, the soil properties of the areas under the soil-protecting forests show different characteristics than the soils under cultivation or not used for agriculture [39]. The soil profiles along the cross sections illustrate that, on slopes, that are agriculturally used, eroded soils with capped natural profiles are found. Especially, the Luvisols (cross sections A-B, C-D) show erosion of the humus rich A-horizons, as well as reduced eluvial and illuvial horizons. Soils on the slopes covered by the soil-protecting forests are not subject to these visible transformations by erosion processes. For example, in the case of cross section G′-H′, characterized by the presence of iron oxides over the entire soil profile, no reduction of horizons in any soil profile location along the cross section was found. Moreover, on the cross section

C′-D′, characterized by a higher variability of soil types, no soil thickness reduction was observed on the slopes or on the plateau nor in the lower parts of the slope. Differences in the composition of soil pedons were also noticed comparing soils under soil-protecting forests and on rangeland. On the cross section I′-J′ in soil pit No. II, located on a concave side covered with grassland and exposed towards the South, we clearly observe a marked reduction of a Brunic Arenosol profile. In contrast, no profile reduction is documented for soil pit No. IV, which is located on the convex slope, exposed towards the North and covered by soil-protecting forest. The greatest diversity of soils occurs along cross sections A-B and A′-B′. The diversity may be related to the location of the cross section on the slopes of an erosional-denudational valley that, in turn, enriches the mosaic landscape due to different substrates [45]. In the soil pit at the bottom of the slope A-B, we identified a Brunic Arenosol with fluvioglacial sands, while, in the soil pit, located at the bottom of the valley, at the foot of slope A′-B′, we found a Haplic Phaeozems (Arenosols).

The cross sections are characterized by loamy sand, sand, and sandy loam texture (Table A1). On the slopes used for agricultural purposes, the average sand content is 78.7%, and the silt content is 19.5%, while the clay fraction is 1.8%. The slopes covered with soil-protecting forests show an average sand fraction of 83.9%, a silt fraction of 15.2%, and a clay content of 0.9%. In most cases, the soils on the agriculturally used plateau/top slope position have lower sand content, and a higher percentage of silt and clay fractions in relation to the top slopes covered with soil-protecting forests. The same relationship exists for the respective slope sections. At the bottom of the not forested slopes, however, we can observe higher average contents of sand and clay, with smaller silt fractions, in comparison the bottom of the forested slopes. The upper soil layers in the studied cross sections are characterized by a great diversity of pH values. The pH of soils used for agricultural purposes and those covered with grassland vary from extremely acid to slightly alkaline, whereas the pH of those soils under soil-protecting forests are mostly lower and range from ultra-acid to neutral. Significantly higher contents of phosphorus and potassium was found in soils of arable land than in the protective forest stands. This is mostly due to the effect of phosphorus and potassium fertilization. The presence of calcium carbonate in the humus horizons was observed in most soil pits located on the slopes under ploughing and tillage action, mainly on the slopes and at the foot slope positions (Table A1).

Soil bulk density determines the infiltration, available water capacity, soil porosity, rooting depth/restrictions, soil microorganism activity, root proliferation, and nutrient availability [46]. Changes of bulk density are different in various parts of the slopes. Most often, the highest bulk density occurs along the top-slope [47,48]. Our research also confirms this characteristic (Tables 1 and 2). In addition, the research of Duan et al. [49] showed that soil bulk density in the 0–10 cm soil layer is influenced by stand planting density.

Table 1. Soil organic matter content, soil organic carbon content, soil bulk density, and pools (stocks) of soil organic carbon accumulated in the surface layers (topsoil) along the analyzed cross sections.

Research Cross Section	Soil Pit Number	Position of the Soil Pit *	Land Use **	SOM (%)	Corg (%)	ρ (g cm^{-3})	SOCP (kg m^{-2})
A-B	I	p	r	0.94	0.55	1.610	2.46
	II	s	a	0.72	0.42	1.593	1.66
	III	f	a	0.90	0.52	1.272	1.26
A′-B′	I	p	f	0.94	0.55	1.610	2.46
	II	s	f	1.85	1.07	1.624	3.14
	III	f	r	0.76	0.44	1.606	1.27
C-D	I	p	a	0.72	0.42	1.617	1.76
	II	s	a	1.35	0.78	1.600	2.88
	III	f	a	0.36	0.21	1.610	0.77

Table 1. *Cont.*

Research Cross Section	Soil Pit Number	Position of the Soil Pit *	Land Use **	SOM (%)	Corg (%)	ρ (g cm^{-3})	SOCP (kg m^{-2})
C′-D′	I	p	f	0.79	0.46	1.593	1.68
	II	s	f	1.48	0.86	1.477	2.03
	III	f	f	1.84	1.07	1.485	2.22
E-F	I	p	a	0.53	0.31	1.611	1.54
	II	s	a	0.48	0.28	1.560	1.22
	III	f	a	0.51	0.30	1.502	1.33
E′-F′	I	p	f	0.49	0.28	1.322	0.68
	II	s	f	0.78	0.45	1.299	0.88
	III	f	f	0.18	0.10	1.272	0.36
G-H	I	p	a	1.16	0.67	1.187	2.24
	II	s	a	0.91	0.53	1.388	1.90
	III	f	a	1.01	0.59	1.424	2.17
G′-H′	I	p	f	1.60	0.93	1.187	3.08
	II	s	f	0.77	0.45	1.176	1.58
	III	f	f	0.74	0.43	1.557	1.47
I-J	I	f	a	0.49	0.28	1.643	1.26
	II	s	a	0.53	0.31	1.544	1.19
	III	p	a	0.32	0.19	1.608	0.75
	IV	s	a	0.54	0.31	1.490	1.17
	V	f	a	0.53	0.31	1.502	1.29
I′-J′	I	f	r	1.74	1.01	1.611	1.95
	II	s	r	0.92	0.53	1.598	1.02
	III	p	f	1.32	0.77	1.603	3.68
	IV	s	f	2.05	1.19	1.432	5.11
	V	f	a	0.48	0.28	1.606	1.34

* p—plateau, s—slope, f—foot of the slope; ** a—arable lands, f—soil-protecting forests, r—rangelands; SOM—soil organic matter content; Corg—soil organic carbon content; ρ—soil bulk density; SOCP—pools (stocks) of soil organic carbon accumulated in the surface layers.

Table 2. Descriptive statistics of the soil organic carbon content, soil bulk density, and pools (stocks) of soil organic carbon accumulated in the surface layers (topsoil) along the analyzed cross sections.

Position of the Soil Pit *	Corg (%)			ρ (g cm^{-3})			SOCP (kg m^{-2})		
	Min	Max	Average	Min	Max	Average	Min	Max	Average
Research cross sections: A-B, C-D, E-F, G-H, I-J									
p	0.19	0.67	0.43	1.19	1.62	1.53	0.75	2.46	1.75
s	0.28	0.78	0.44	1.39	1.60	1.53	1.17	2.88	1.67
f	0.21	0.59	0.37	1.27	1.64	1.49	0.77	2.17	1.35
Research cross sections: A′-B′, C′-D′, E′-F′, G′-H′, I′-J′									
p	0.28	0.93	0.60	1.19	1.61	1.46	0.68	3.68	2.32
s	0.45	1.19	0.76	1.18	1.62	1.43	0.88	5.11	2.29
f	0.10	1.07	0.55	1.27	1.61	1.52	0.36	2.22	1.44

* p—plateau, s—slope, f—foot of the slope; Corg—soil organic carbon content; ρ—soil bulk density; SOCP—pools (stocks) of soil organic carbon accumulated in the surface layers.

The thickness of the humus horizon along the studied slopes used for agricultural purposes depends mainly on the plowing depth, that normally ranges from 19 to 31 cm, on average reaching to a depth of 26 cm. On almost all cross sections, the Ap-horizon (with the exception of I-J) reaches its maximum thickness in the apical part of the slopes. On the slopes, it is on average ca. 3 cm shallower, while, at the foot slopes, ca. 2 cm. In case of sodded and afforested slopes, the thickness of the humus horizon is smaller and ranges from 12 to 30 cm (average 22 cm). The spatial variability of the A-horizon depth shows some deviations from the regularities observed on the slopes used for agricultural purposes. For example, the concave Northern exposed slopes, that are covered with 57-year-old soil-protection forest with a fresh mixed forest habitat type (cross section G′-H′) show the maximum thickness of humus horizons on the slopes, while the minimum depth was registered on the foot slopes. However, on the convex Northern exposed slope of cross section I′-J′, covered with a 45-year-old protective forest, the thickness of the humus horizon does not change throughout the cross section.

The content of organic matter in the upper layers of the agriculturally used soils of the cross sections amounts to an average of 0.41% ranging from 0.19 to 0.78% (Table 1). Higher SOC content can be found in soils covered with grassland and under the soil-protecting forests (average 0.64%), reaching a maximum value of 1.19%. In cross sections A-B, E-F, and G-H, we observed the depletion of SOC on the slopes according to the erosion dynamics, with an average of 0.17%. However, in case of most of the afforested slopes (cross sections A′-B′, C′-D′, E′-F′, I′-J′), the SOC content on the slope is from 0.29 to 0.91% higher than on the plateau areas. Obviously, the fact that, in some soils, there is an organic horizon, some SOC values for the tested surface layer are strongly influenced by the thickness of the O horizon in this pedon and spatial heterogeneity, and not by specific processes in a given landscape.

Our study shows a high variability of topsoil organic carbon stocks on the slopes, in relation to the land use (Table 1). In the surface layers of soils used for agricultural purposes, SOC stock was much lower (varies from 0.75 to 2.88 kg m^{-2} with an average of 1.58 kg m^{-2}) than in forest soils that were not subject to agriculture where it varies from 0.36 to 5.11 kg m^{-2} with an average of 2.00 kg m^{-2} (Table 2). The pool of SOC reaches its maximum value of 5.11 kg m^{-2} on the slope transect I′–J′, which is covered with 45-year-old protective forest of fresh mixed forest habitat type. These values are slightly lower, e.g., in relation to the mean pools of SOC accumulated in surface layers (0–10 cm) of forest soils in the Karkonosze Mountains in Poland, calculated by Szopka et al. [5]. These authors, referring to References [50,51], note, however, that the comparison of carbon pools accumulated in soils, reported by various authors, faces problems due to the different profile depths. In the cited studies, the depth varies from 20 cm, over 30–50 cm, up to 100 cm, and is including or excluding the forest litter. Moreover, the determination of soil bulk density, particularly in organic horizons, also varies since, in some studies, it is estimated in others measured.

Our research has shown that the average SOC stocks on afforested slopes are higher compared to the adjacent agricultural slopes, regardless of the position of the soil pits (Table 2). These values are higher by about 33% in the case of the plateau position, by 37% on the slopes, and by 7% at the foot slope positions under forests in relation to the adjacent agricultural slopes. These results confirm the conclusions from our earlier work that soil-protecting forests provide an effective protection from the washing out and blowing away of soil particles, unwanted surface transformations of genetic horizons, and organic matter decline due to erosion processes. This is very important in the context of climate change mitigation through carbon sequestration. Indeed, soil management strategies targeting towards a carbon sequestration will be most effective when accompanied by measures that reduce soil erosion due to the fact that erosion loss can balance potential carbon uptake, particularly in sloping areas [52].

The results of the Pearson's correlation analyses of the topsoil organic carbon stocks and nine soil properties analyzed are given in Table 3. Pearson's correlation analysis revealed that there were no significant correlations between the SOC stocks and most of the soil physico-chemical properties, and that the correlation between soil physico-chemical properties was not consistent across the slope positions. As expected, significant positive, very high correlation was found between Corg and SOCP both on agricultural slopes and slopes under soil-protecting forests (r = 0.737 and 0.843, respectively; p = 0.001). In the case of agricultural slopes, significant positive correlations between SOCP and the content of clay and potassium were also found. In turn, in the case of slopes under soil-protecting forests, significant positive correlation between SOCP and the content of potassium and magnesium were found. The negative correlation between soil organic carbon stocks and sand content is in agreement with many studies [53,54]. As indicated by Conforti et al. [55], generally, soils with a high content of sand are well aerated and tend to have low soil moisture content, which is due to a rapid decomposition and a low stabilization of the organic carbon. As in some studies [56–58], we also found weak correlations between soil organic carbon stocks and clay content (mostly on agricultural slopes). As pointed out by Reference [59], though many studies have established a strong relationship between SOC and clay contents due to the key role of clays in soil physiochemical processes, there is no clear-cut evidence on the role of clays stabilizing SOC. Significant differences, depending on the use of the slopes, were noted for the correlation between SOCP and pH and bulk density. In the case of agricultural slopes, the correlations were negative, and, in the case of slopes under forests, they were positive. In contrast, P content positively correlated with the SOCP on the agricultural slopes, but not on slopes under soil-protecting forests.

Table 3. Pearson's correlations among the topsoil organic carbon stock (SOCP) and selected soil properties analyzed in the study area.

Variable	**Correlation Coefficient**	
	Agricultural Slopes	**Slopes under Soil-Protecting Forests**
Sand (2.0–0.05 mm)	−0.350 *	−0.153 *
Silt (0.05–0.002 mm)	0.347 *	0.154 *
Clay (<0.002 mm)	**0.365** *	0.140 *
P	0.262 *	−0.149 *
K	**0.447** **	**0.544** **
Mg	0.415 **	**0.470** *
pH	−0.213 *	0.108 *
Corg	**0.737** ***	**0.843** ***
ρ	−0.201 *	0.336 *

*—significance level p = 0.1; **—significance level p = 0.05; ***—significance level p = 0.001; bold—statistically significant correlations.

4. Conclusions

Soil-protecting forests provide an effective protection from the washing out and blowing away of soil particles, unwanted surface transformations of genetic horizons, and organic matter decline due to erosion processes. The surface layers of the soils on the slopes under the protective forest stands, in relation to the neighboring arable soils, tend to have a higher content of SOM and higher pool of SOC. The highest pool of SOC (5.11 kg m^{-2}) was observed in the surface layers of Brunic Arenosols on the slope transect I′–J′, which is covered with a 45-year-old protective forest of fresh mixed forest habitat type. In agricultural soils, the stock of organic carbon was much lower, with an average SOC stock of 1.58 kg m^{-2}, than in forest soils, that show on average 2.00 kg m^{-2}.

Pearson's correlation analysis revealed that there were no significant correlations between the organic carbon stocks in topsoil and most of the soil physico-chemical properties, and that the correlation between soil physico-chemical properties was not consistent across the slope positions. As expected, significant positive, very high correlation was found between Corg and SOCP and a negative correlation between the soil organic carbon stock and sand content both on agricultural slopes and slopes under soil-protecting forests. In the case of agricultural slopes, significant positive correlations between SOCP and the content of clay and potassium were also found. In turn, in the case of slopes under soil-protecting forests, significant positive correlation between SOCP and the content of potassium and magnesium were found. Significant differences, depending on the use of the slopes, were noted for the correlation between SOCP and pH and bulk density. These results show that land use and slope gradients are important factors controlling soil organic carbon pools in topsoil in young glacial landscapes.

Our study confirms other investigations that indicated the significant role of forest management on the increase of soil organic carbon stock. This is very important in the context of climate change mitigation through carbon sequestration. Soil management strategies targeting carbon sequestration will be most effective when accompanied by measures that reduce soil erosion.

Author Contributions: Conceptualization, P.W.; methodology, P.W. and M.M.; formal analysis, P.W. and M.M.; investigation, P.W. and M.M.; resources, P.W.; data curation, P.W.; writing—original draft preparation, P.W. and M.M.; writing—review and editing, P.W. and M.M.; visualization, P.W. All authors have read and agreed to the published version of the manuscript.

Funding: The APC was funded by Department of Landscape Research and Environmental Management, University of Gdansk.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Particle size distribution and selected chemical and physico-chemical properties of soils along the analyzed cross sections, at a depth of 0–10 cm [39].

Research cross Section	Soil Pit Number	Position of the Soil Pit *	Land Use **	Percentage of Particle Size Fractions (mm)			Texture Class ***	Concentration of Available Forms(mg $100g^{-1}$)			$CaCO_3$ (%)	pH KCl
				2.0–0.05	0.05–0.002	<0.002		P	K	Mg		
A-B	I	p	r	55.4	40.8	3.8	SL	10.4	12.0	7.5	-	6.9
	II	s	a	53.9	42.1	3.9	SL	18.7	12.5	6.0	0.85	7.3
	III	f	a	98.1	1.9	0.0	S	11.2	2.0	0.8	0.30	4.7
A′-B′	I	p	f	55.4	40.8	3.8	SL	10.4	12.0	7.5	-	6.9
	II	s	f	57.3	39.2	3.5	SL	3.4	8.5	13.1	0.15	7.1
	III	f	r	75.2	23.1	1.7	LS	2.8	20.0	5.2	-	5.4
C-D	I	p	a	72.1	25.3	2.6	SL	19.9	18.0	6.0	-	5.0
	II	s	a	66.4	30.4	3.2	SL	18.3	31.0	6.2	0.35	5.6
	III	f	a	81.0	17.4	1.6	LS	11.0	15.5	3.0	traces	5.5

Table A1. *Cont.*

Research cross Section	Soil Pit Number	Position of the Soil Pit *	Land Use **	Percentage of Particle Size Fractions (mm)			Texture Class ***	Concentration of Available Forms(mg 100g^{-1})			$CaCO_3$ (%)	pH KCl
				2.0–0.05	0.05–0.002	<0.002		P	K	Mg		
C′-D′	I	p	f	74.9	23.2	1.9	LS	4.5	5.5	1.8	-	3.8
	II	s	f	81.0	17.9	1.1	LS	1.8	4.5	0.9	-	3.5
	III	f	f	79.7	19.5	0.8	LS	2.8	8.5	2.9	-	3.2
E-F	I	p	a	78.2	19.6	2.2	LS	53.0	7.5	4.4	2.46	7.4
	II	s	a	86.7	12.1	1.2	S	24.6	7.0	3.3	0.70	7.2
	III	f	a	84.0	14.6	1.4	LS	36.0	9.0	4.1	0.75	7.4
E′-F′	I	p	f	81.9	17.0	1.1	LS	6.2	2.5	1.3	-	4.1
	II	s	f	90.4	9.6	0.0	S	2.7	1.0	0.9	-	3.7
	III	f	f	90.2	9.4	0.4	S	5.9	1.5	1.6	-	4.3
G-H	I	p	a	92.1	7.5	0.4	S	23.9	5.5	2.2	traces	5.8
	II	s	a	87.8	11.5	0.7	S	22.9	6.0	2.0	traces	4.4
	III	f	a	81.2	17.3	1.5	LS	20.3	10.0	3.4	-	4.6
G′-H′	I	p	f	93.8	6.2	0.0	S	13.0	1.5	0.5	-	3.6
	II	s	f	95.2	4.6	0.2	S	15.9	1.5	0.5	-	4.2
	III	f	f	89.4	10.0	0.6	S	9.5	2.0	1.0	-	4.0
I-J	I	f	a	68.2	29.2	2.6	SL	18.2	9.8	3.3	0.20	7.2
	II	s	a	83.8	14.9	1.3	LS	9.7	5.0	2.0	2.54	7.7
	III	p	a	77.1	21.0	1.9	LS	3.8	4.0	1.8	-	4.8
	IV	s	a	74.7	23.3	2.0	LS	13.2	9.0	4.2	0.55	7.3
	V	f	a	74.6	23.5	1.9	LS	19.0	9.0	3.6	0.93	7.3
I′-J′	I	f	r	62.6	35.0	2.4	SL	31.0	35.0	15.1	traces	6.5
	II	s	r	87.1	12.0	0.9	S	7.3	9.0	3.4	2.56	7.4
	III	p	f	82.5	16.3	1.2	LS	5.4	10.5	3.4	-	4.1
	IV	s	f	90.2	9.6	0.2	S	2.0	6.0	5.1	-	3.6
	V	f	a	77.4	21.1	1.5	LS	18.2	13.0	3.2	0.35	7.2

* p—plateau, s—slope, f—foot of the slope; ** a—arable lands, f—soil-protecting forests, r—rangelands; *** Soil texture is defined according to the USDA textural classification [37]: S—sand, LS—loamy sand, SL—sandy loam.

References

1. Degórski, M. Influence of forest management into the carbon storage in soil. *Monit. Sr. Przyr.* **2005**, *6*, 75–83.
2. Ontl, T.A.; Schulte, L.A. Soil Carbon Storage. *Nat. Educ. Knowl.* **2012**, *3*, 35.
3. Lei, Z.; Yu, D.; Zhou, F.; Zhang, Y.; Yu, D.; Zhou, Y.; Han, Y. Changes in soil organic carbon and its influencing factors in the growth of Pinus sylvestris var. mongolica plantation in Horqin Sandy Land, Northeast China. *Sci. Rep.* **2019**, *9*, 16453. [CrossRef] [PubMed]
4. Schillaci, C.; Acutis, M.; Lombardo, L.; Lipani, A.; Fantappiè, M.; Märker, M.; Saia, S. Spatio-temporal topsoil organic carbon mapping of a semi-arid Mediterranean region: The role of land use, soil texture, topographic indices and the influence of remote sensing data to modelling. *Sci. Total. Environ.* **2017**, *601–602*, 821–832. [CrossRef] [PubMed]

5. Szopka, K.; Kabała, C.; Karczewska, A.; Jezierski, P.; Bogacz, A.; Waroszewski, J. The pools of soil organic carbon accumulated in the surface layers of forest soils in the Karkonosze Mountains, SW Poland. *Soil Sci. Ann.* **2016**, *67*, 46–56. [CrossRef]
6. Lal, R. Forest soils and carbon sequestration. *For. Ecol. Manag.* **2005**, *220*, 242–258. [CrossRef]
7. Martin, D.; Tarsem, L.; Sachdev, C.B.; Sharma, J.P. Soil organic carbon storage changes with climate change, landform and land use conditions in Garwal hills of the Indian Himalayan mountains. *Agric. Ecosyst. Environ.* **2010**, *138*, 64–73. [CrossRef]
8. Sinoga, J.D.R.; Pariente, S.; Diaz, A.R.; Murillo, J.F.M. Variability of relationship between soil organic carbon and some soil properties in Mediterranean rangelands under different climatic conditio (South of Spain). *Catena* **2012**, *94*, 17–25. [CrossRef]
9. Farquhar, G.D.; Fasham, M.J.R.; Goulden, M.L.; Heimann, M.; Jaramillo, V.J.; Kheshgi, H.S.; Le Quere, C.; Scholes, R.J.; Wallace, D.W.R. Climate change. The Scientific Basis IPCC. Chapter 3. In *The Carbon Cycle and Atmospheric Carbon Dioxide*; Cambridge University Press: Cambridge, UK, 2001; pp. 183–237.
10. Błońska, E.; Lasota, J. Soil Organic Matter Accumulation and Carbon Fractions along a Moisture Gradient of Forest Soils. *Forests* **2017**, *8*, 448. [CrossRef]
11. Zwydak, M.; Błońska, E.; Lasota, J. Organic carbon accumulation in soil of different forest site types. *Sylwan* **2017**, *161*, 62–70.
12. Abdullahi, A.C.; Siwar, C.; Shaharudin, M.I.; Anizan, I. Carbon Sequestration in Soils: The Opportunities and Challenges. In *Carbon Capture, Utilization and Sequestration*; Agarwal, R.K., Ed.; IntechOpen: Rijeka, Croatia, 2018; pp. 3–15.
13. Hendrickson, O. Influences of global change on carbon sequestration by agricultural and forest soils. *Environ. Rev.* **2003**, *11*, 161–192. [CrossRef]
14. Borrelli, P.; Paustian, K.; Panagos, P.; Jones, A.; Schütt, B.; Lugato, E. Effect of Good Agricultural and Environmental Conditions on erosion and soil organic carbon balance: A national case study. *Land Use Policy* **2016**, *50*, 408–421. [CrossRef]
15. Dvorak, J.; Novak, L. *Soil Conservation and Silviculture*, 1st ed.; Elsevier: Amsterdam, The Netherlands; London, UK; New York, NY, USA; Tokyo, Japan, 1994; p. 396.
16. Gray, D.H.; Sotir, R.B. *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*; John Wiley & Sons: New York, NY, USA, 1996; p. 194.
17. Silva, G.L.; Lima, H.V.; Campanha, M.M.; Gilkes, R.J.; Oliveira, T.S. Soil physical quality of Luvisols under agroforestry, natural vegetation and conventional crop management systems in the Brazilian semi-arid region. *Geoderma* **2011**, *167–168*, 61–70. [CrossRef]
18. Panagos, P.; Borrelli, P.; Meusburger, K.; Alewell, C.; Lugato, E.; Montanarella, L. Estimating the soil erosion cover-management factor at the European scale. *Land Use Policy* **2015**, *48*, 38–50. [CrossRef]
19. Gray, D.H.; Leiser, A.T. *Biotechnical Slope Protection and Erosion Control*; Krieger Publishing Company: Malabar, FL, USA, 1982; p. 271.
20. Lal, R. Water management in various crop production systems related to soil tillage. *Soil Tillage Res.* **1994**, *30*, 169–185. [CrossRef]
21. Morgan, R.P.C. *Soil Erosion and Conservation*, 3rd ed.; Blackwell Publishing: Oxford, MI, USA, 2005; p. 304.
22. Davie, T. Forests for soil and water conservation—What does the science say? *N. Z. J. For.* **2006**, *51*, 8–9.
23. Brang, P.; Schönenberger, W.; Ott, E.; Gardner, R.H. Forests as protection from natural hazards. In *The Forests Handbook*; Evans, J., Ed.; Blackwell Science Ltd.: Oxford, MI, USA, 2008; Volume 2, pp. 53–81.
24. Germer, S.; Neill, C.; Krusche, A.V.; Elsenbeer, H. Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. *J. Hydrol.* **2010**, *380*, 473–480. [CrossRef]
25. Galatsidas, S.; Amanatidou, D.; Soutsas, K. Applying multivariate statistics into forest management planning: Potential conditions of erosion danger in the forest of Thessaloniki, Greece. *J. Environ. Prot. Ecol.* **2015**, *16*, 233–242.
26. Miura, S.; Amacher, M.; Hofer, T.; San-Miguel-Ayanz, J.; Thackway, R. Protective functions and ecosystem services of global forests in the past quarter-century. *For. Ecol. Manag.* **2015**, *352*, 35–46. [CrossRef]
27. Gerasimova, M.; Lebedeva-Verba, M. Topsoils—Mollic, Takyric and Yermic Horizons. In *Interpretation of Micromorphological Features of Soils and Regoliths*; Stoops, G., Marcelino, V., Mees, F., Eds.; Elsevier: Amsterdam, The Netherlands, 2010; pp. 351–368.
28. Wiśniewski, P.; Kistowski, M. Structure and importance of soil-protecting forests in the areas administered by the RDSF Toruń. *Bull. Geogr. Phys. Geogr. Ser.* **2015**, *8*, 123–132. [CrossRef]
29. Błażejczyk, K. Climate and bioclimate of Poland. In *Natural and Human Environment of Poland. A Geographical Overview*; Degórski, M., Ed.; Polish Academy of Sciences; Institute of Geography and Spatial Organization Polish Geographical Society: Warsaw, Poland, 2006; pp. 31–48.
30. Kondracki, J. *Regional Geography of Poland*; Polish Scientific Publishers: Warsaw, Poland, 2002; p. 441.
31. Jankowski, M.; Przewoźna, B.; Bednarek, R. Topographical inversion of sandy soils due to local conditions in Northern Poland. *Geomorphology* **2011**, *135*, 277–283. [CrossRef]
32. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015; p. 192.
33. Kabała, C. (Ed.) *Soils of Lower Silesia: Origins, Diversity and Protection*; Polish Society of Soil Science Wrocław Branch, Polish Humic Substances Society: Wrocław, Poland, 2015; p. 258.
34. Gruszka, W. The concept of lichen refugia classification. A proposal based on the case study of Krajeńskie Lakeland, Poland. *Ecol. Quest.* **2017**, *27*, 65–75. [CrossRef]
35. Conacher, A.J.; Dalrymple, J.B. The nine unit landsurface model and pedogeomorphic research. *Geoderma* **1977**, *18*, 127–144.

36. Kabała, C.; Charzyński, P.; Chodorowski, J.; Drewnik, M.; Glina, B.; Greinert, A.; Hulisz, P.; Jankowski, M.; Jonczak, J.; Łabaz, B.; et al. Polish Soil Classification, 6th edition—principles, classification scheme and correlations. *Soil Sci. Annu.* **2019**, *70*, 71–97. [CrossRef]
37. Ditzler, C.; Scheffe, K.; Monger, H.C. *Soil Science Division Staff. Soil Survey Manual. USDA Handbook 18*; Government Printing Office: Washington, DC, USA, 2017; p. 603.
38. SFIC. *Forest Management Planning Instruction. Part II*; State Forest Information Center: Warsaw, Poland, 2012; p. 160.
39. Wiśniewski, P.; Märker, M. The role of soil-protecting forests in reducing soil erosion in young glacial landscapes of Northern-Central Poland. *Geoderma* **2019**, *337*, 1227–1235. [CrossRef]
40. Zhang, Z.; Zhou, Y.; Wang, S.; Huang, X. Estimation of soil organic carbon storage and its fractions in a small karst watershed. *Acta Geochim.* **2018**, *37*, 113–124. [CrossRef]
41. Mebius, L.J. A rapid method for the determination of organic carbon in soil. *Anal. Chim. Acta* **1960**, *22*, 120–124. [CrossRef]
42. Al-Shammary, A.A.G.; Kouzani, A.Z.; Kaynak, A.; Khoo, S.Y.; Norton, M.; Gates, W. Soil bulk density estimation methods: A review. *Pedosphere* **2018**, *28*, 581–596. [CrossRef]
43. International Organization for Standardization (ISO). *ISO 11272-2017. Soil Quality—Determination of Dry Bulk Density*; International Organization for Standardization: Geneva, Switzerland, 2017.
44. Walter, K.; Don, A.; Tiemeyer, B.; Freibauer, A. Determining Soil Bulk Density for Carbon Stock Calculations: A Systematic Method Comparison. *Soil Sci. Soc. Am. J.* **2016**, *80*, 579–591. [CrossRef]
45. Jonczak, J. Influence of litho-morphogenetic, hydrologic and anthropogenic factors on sorptive and buffer properties of soils of erosional-denudational valleys: Case study from Sławieńska Plain. *Pol. J. Soil Sci.* **2012**, *45*, 205–220.
46. Indoria, A.K.; Sharma, K.L.; Reddy, K.S. Chapter 18—Hydraulic properties of soil under warming climate. In *Climate Change and Soil Interactions*; Prasad, M.N.V., Pietrzykowski, M., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 473–508.
47. Przewoźna, B. Changes of bulk density, air-water properties and morphology of soils in basins without outlets as an effect of erosion and anthropogenic denudation (a study from northwestern Poland). *Soil Sci. Plant Nutr.* **2014**, *60*, 30–37. [CrossRef]
48. Kobierski, M. *Morphology, Properties and Mineralogical Composition of Eroded Luvisols in Selected Morainic Areas of the Kuyavian and Pomeranian Province*; University of Science and Technology: Bydgoszcz, Poland, 2013; p. 121.
49. Duan, A.; Lei, J.; Hu, X.; Zhang, J.; Du, H.; Zhang, X.; Guo, W.; Sun, J. Effects of Planting Density on Soil Bulk Density, pH and Nutrients of Unthinned Chinese Fir Mature Stands in South Subtropical Region of China. *Forests* **2019**, *10*, 351. [CrossRef]
50. Gałka, B.; Łabaz, B.; Bogacz, A.; Bojko, O.; Kabała, C. Conversion of Norway spruce forests will reduce organic carbon pools in the mountain soils of SW Poland. *Geoderma* **2014**, *213*, 287–295. [CrossRef]
51. Prietzel, J.; Christophel, D. Organic carbon stocks in forest soils of the German Alps. *Geoderma* **2014**, *221–222*, 27–39. [CrossRef]
52. Nadeu, E.; Gobin, A.; Fiener, P.; van Wesemael, B.; van Oost, K. Modelling the impact of agricultural management on soil carbon stocks at the regional scale: The role of lateral fluxes. *Glob. Chang. Biol.* **2015**, *21*, 3181–3192. [CrossRef] [PubMed]
53. Konen, M.; Burras, C.; Sandor, J. Organic carbon, texture, and quantitative color measurement relationships for cultivated soils in north central Iowa. *Soil Sci. Soc. Am. J.* **2003**, *67*, 1823–1830. [CrossRef]
54. Lopes, M.I.M.S.; Ribeiro Dos Santos, A.; Zuliani Sandrin Camargo, C.; Bulbovas, P.; Giampaoli, P.; Domingos, M. Soil chemical and physical status in semideciduous Atlantic Forest fragments affected by atmospheric deposition in central-eastern São Paulo State, Brazil. *iForest* **2015**, *8*, 798–808. [CrossRef]
55. Conforti, M.; Matteucci, G.; Buttafuoco, G. Organic carbon and total nitrogen topsoil stocks, biogenetic natural reserve 'Marchesale' (Calabria region, southern Italy). *J. Maps* **2016**, *13*, 91–99. [CrossRef]
56. Percival, H.J.; Parfitt, R.L.; Scott, N.A. Factors controlling soil carbon levels in New Zealand grasslands: Is clay content important? *Soil Sci. Soc. Am. J.* **2000**, *64*, 1623–1630. [CrossRef]
57. Silver, W.L.; Neff, J.; McGroddy, M.; Veldkamp, E.; Keller, M.; Cosme, R. Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems* **2000**, *3*, 193–209. [CrossRef]
58. Bricklemyer, R.S.; Miller, P.R.; Turk, P.J.; Paustian, K.; Keck, T.; Nielsen, G.A. Sensitivity of the century model to scale-related soil texture variability. *Soil Sci. Soc. Am. J.* **2007**, *71*, 784–792. [CrossRef]
59. Logah, V.; Tetteh, E.; Adegah, E.; Mawunyefia, J.; Ofosu, E.; Asante, D. Soil carbon stock and nutrient characteristics of Senna siamea grove in the semi-deciduous forest zone of Ghana. *Open Geosci.* **2020**, *12*, 443–451. [CrossRef]