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Profile Development and Soil Properties of Three Forest Reclamations of Different Ages in Sokolov Mining Basin, Czech Republic

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Abstract: Forestry reclamation practices have been very popular in the second half of the last century, and many spoil heaps have been converted into forests since. In our experiment, three forest reclamations of different ages (~90, ~50, and ~30 years) and three soil vegetation covers (I—maple and cherry, II—maple, and III—alder) from Sokolov, Czech Republic, were investigated. In each of the three stands, two soil profiles have been dug, and both disturbed and undisturbed soil samples were taken from all recognized horizons. Samples were tested for bulk and particle density, porosity, water retention capacity, pH (H_2O, KCl), cation exchange capacity, oxidizable carbon content, organic matter quality, plant available nutrients, and risk elements. A comparison of these properties throughout the profile, as well as between the stands, was presented. A significant role of stand age in soil profile development and soil quality was observed, as well as the tendency of the anthropogenic mine Technosol to evolve into a forest Cambisol in this climate region and parent material. Influence of forest vegetation cover was observed to ameliorate soil properties by accumulating organic matter, thus reducing compaction and increasing CEC and nutrient availability.

Keywords: soil development; forest reclamation; post-mining; pedogenesis; soil depth; soil properties; soil nutrient balance; ecosystem restoration

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1. Introduction

Open-cast coal mining significantly changes the landscape and destroys soil functions, making these vast sites practically desolate, thus positioning itself among the most disputed industries in the world [1–4]. Besides disturbing landscape and soil, it also affects the integrity of the habitat, environmental flows and ecosystem functions, as well as water and air quality, thus often leading to human health problems [5]. Many countries have developed legislations about the ways these sites need to be treated after the excavation process is completed [3,6–9], and our knowledge expands every year with various research results conducted in these localities. Some of the trends and progress in post-mining sites research were summarized by Shao et al. [10] and Spasić et al. [11].

Many studies have shown that technical reclamation, a process widely used in the 20th century, may have its flaws, and that there are other, in many cases more feasible and effective solutions, such as natural succession [8,12]. However, the fact that many of these sites have been reclaimed, either for environmental, scientific (experimental), or legislative purposes, remains. The full effects of the forest reclamation process can be visible only after some time has passed, usually ranging from several decades to the scales of centuries. Compared to natural, undisturbed forest soils, which take thousands of years to develop, this is a very short time indeed. However, observing the development of soils in these initial phases is very important [13,14] and allows us to evaluate pedogenetic processes difficult to see in mature soils [15]. Studies which show that the soil formation process on post-mining sites can be observed within a shorter time period compared to natural sites have also been conducted [16]. Karan et al. [17] stated that the continuous monitoring of the reclamation sites should be given emphasis in order to devise a feasible and effective policy for degraded land reclamation and restoration.

In post-mining reclamation research, a chronosequence approach is often used. Simply defined, a chronosequence is "A set of sites formed from the same parent material or substrate that differs in the time since they were formed" [18]. According to Hugget [19], they are excellent indicators of the rate and direction of pedogenic change, and they provide invaluable information for testing theories of pedogenesis. One of the major limitations of the chronosequence approach is the heterogeneity of the initial conditions. In post-mining sites, however, this problem is not such a limiting factor, since it usually encompasses the same parent material and the same extraction techniques used over a longer period of time, constantly creating new sites. Due to this, the chronosequence approach is very often used in post-mining reclamation research [20].

The Sokolov mining basin, in northwestern Bohemia, Czech Republic, is one of the largest and most extensively exploited coal deposits in central Europe. In the Czech Republic, technical reclamation practice became compulsory in 1957, when a "Mining Act" was issued [21], and it was extensively used throughout the second half of the 20th century, mainly focusing on forest and agricultural reclamations, and sometimes the creation of artificial lakes—methods still widely used today [22]. A significant number of research experiments took place on both the reclaimed spoil heaps of the Sokolov mining region and the ones left to natural succession, many of them observed as chronosequences [20,23–29]. It should be noted that, due to the previously described reclamation expansion in the late 20th century, most of the oldest reclaimed sites in the Czech Republic are still younger than 60 years. On some of them, however, depending on the other pedogenetic factors of influence, complex horizon differentiation (not only development of organic and organo-mineral layers on technogenic parent material, but also formation of secondary minerals) has been observed [9]. With time and continuous monitoring, these sites can provide valuable information on soil formation processes.

Pedological soil development is usually observed through the weathering of parent material and the development of soil diagnostic horizons, a process that can take hundreds or thousands of years in nature. Biological soil development, on the other hand, can be observed in much shorter time periods, and usually includes the accumulation of soil organic matter and nitrogen and the re-establishment of nutrient cycling processes, and it can be observed in a matter of decades [9,30]. Although vast research has been conducted on both actively and passively revegetated post-mining sites, the rates of soil formation (from a pedological point of view) on post-mining sites still present an imponderable. This is mostly due to the short time intervals elapsed from the reclamation and revegetation, which, in most cases, became a practice in the second part of the 20th century, after large-scale surface mining started being utilized. Thus, there is an emerging need to observe the soil formation process through the formation of diagnostic soil horizons in the future, or at reclamation sites of suitable age and the level of effectiveness of the reclamation process, which already offer the opportunity to do so.

2. Materials and Methods

The study area is located in the Sokolov mining basin, in the northwestern part of the Czech Republic. Within it, 3 forest reclamation localities of different ages were isolated for the purpose of this research. Bohemia I, approximately 90 years old, is a heap created by spoil material from and old, deep mining site, that was afforested with sycamore (*Acer pseudoplatanus*) and cherry (*Prunus avium*) as the main dominant species. Currently, there is a second-generation forest stand. The second locality is a homogenous sycamore (*Acer* *pseudoplatanus*) stand within the Antonín forest arboretum (created on spoil material from open-cast mining), afforested approximately 50 years ago. The third locality is the Loketská spoil heap formed after open-cast mining, afforested by black alder (*Alnus glutinosa*) around 30 years ago. In all localities, target trees were planted directly into the technogenic parent material. At Bohemia and Antonín, rows of alders were planted together with the target tree species, and cut after a period of 10 years, leaving the formed biomass on site [14]. At all three localities, reclamation was conducted without the application of topsoil. The localities are presented on a map in Figure 1. Parent material of all three spoil heaps primarily consists of cypress clays, which have been known for their soil improvement properties and pH increase [31]. Detailed descriptions of the cypress (or cypris) clay properties of Sokolov region were previously described by Buryan et al. [31], Kříbek et al. [32,33] and Jačka et al. [34].

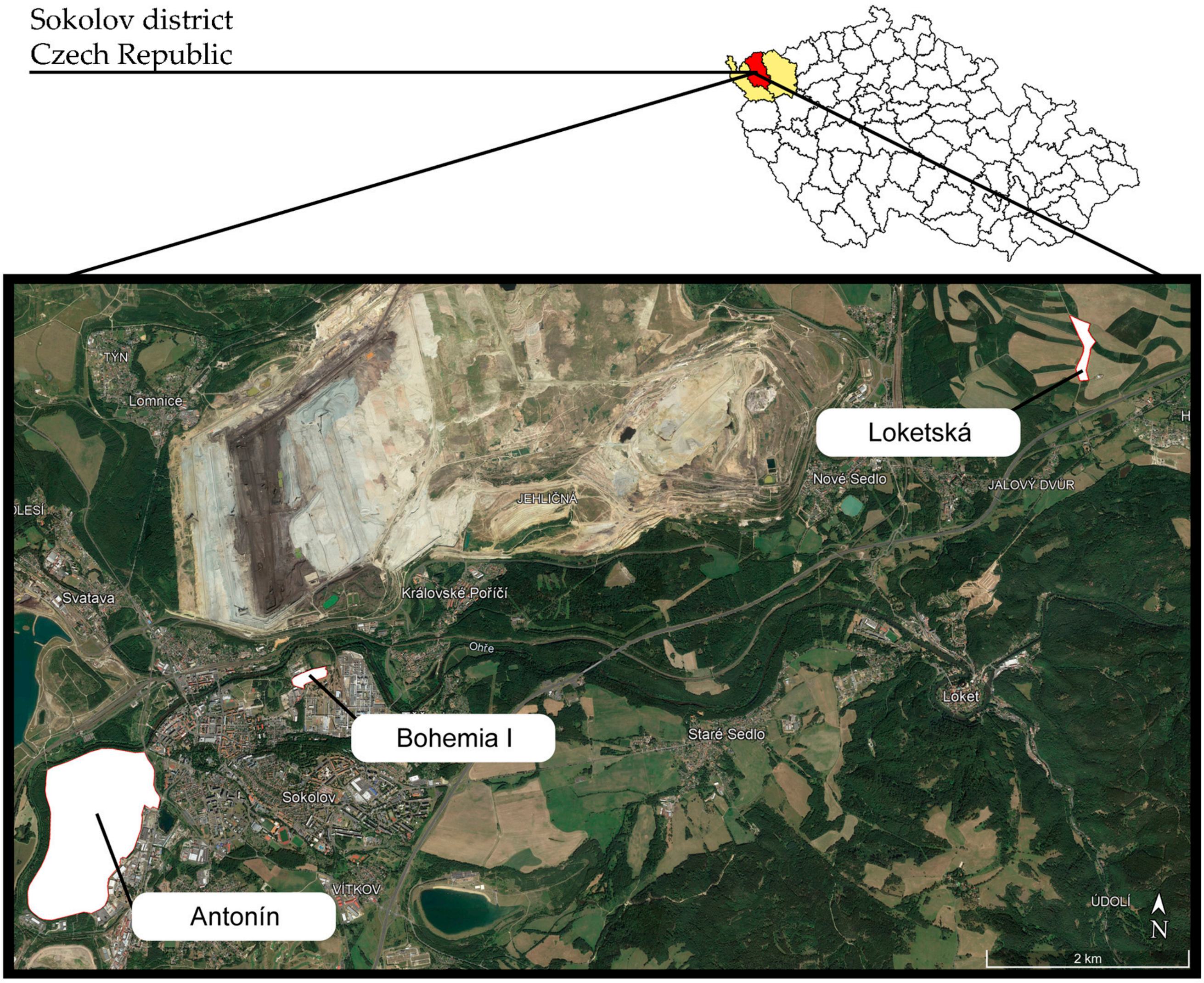

Figure 1. Study area (Sokolov mining region) with sampling locations—Bohemia I, Antonín and a part of Loketská spoil heap (source: Google Earth).

In all three localities, soil profiles were dug and thoroughly described. Two profiles were dug at each location, one on level terrain and one on a slope, making a total of six soil profiles. The thickness of all the formed horizons was measured using measuring tape. Undisturbed soil samples (5 Kopecký 100 cm^3 cylinders from each recognized horizon) were collected for physical analyses. Disturbed soil samples were taken from all recognized soil horizons (and at two depths at the deepest recognized horizon, in order to see whether the chemical properties of the parent material differed in depth). The undisturbed samples were used for the determination of bulk and particle density, porosity, and water retention, following the Novák methodology [35]. Disturbed soil samples were used for chemical analyses—replicated homogenized samples from each horizon of each profile were used for each measurement. pH (H_2O and KCl, WTW pH7110 pH meter) was measured using the standards from ÚKZÚZ [36]. Cation exchange capacity (CEC) was measured by inductively coupled plasma optical emission spectrometer (ICP-OES) iCAP 7000 by Thermo Scientific™, Waltham, MA, USA, following the standards from ICP Forest's Sampling and Analysis of Soil Manual [37]. Plant available nutrients (Mehlich III extraction method, ICP-OES iCAP 7000, Thermo Scientific™, Waltham, MA, USA) were determined according to the 30068.1 standard from ÚKZÚZ [36]. Oxidizable carbon content (Cox) was determined by modified Tyurin's method [38] by wet combustion (sulfuric acid and potassium dichromate, potentiometric titration). Quality of organic matter (A_{400}/A_{600}) was determined by soil extract (in sodium pyrophosphate) absorbance ratio for 400 and 600 nm (HP/Agilent 8453 UV/VIS Spectrophotometer, Santa Clara, CA, USA), according to the standards from Pospíšil [39].

Due to the complexity of statistically comparing the differences between individual formed horizons, as well as between the stands, which have a hierarchical structure and relatively low number of samples, which originated from the same pits/horizons used for chemical analyses, data were presented as average values with standard deviations.

The results of the physical and chemical properties of the studied localities may help us compare the similarities and differences of the parent material, and show us the trends of soil profile evolution in a chronosequence approach in three broadleaved stands of different ages. We hypothesized the following:

1. Considering the alkaline clayey parent material and broadleaved vegetation cover in all locations, the soil type may tend to evolve from an anthropogenic mine Technosol to a forest Cambisol in this climate region;
2. Reclamation time may strongly affect the development and thickness of formed horizons, as well as soil quality;
3. The profiles positioned on the slopes may manifest somewhat poorer physical and chemical properties compared to their level terrain counterparts, due to the effects of surface runoff, surface and internal erosion processes, and lack of water logging.

3. Results

In all three studied localities from which the soil profiles were made (Bohemia I, Antonín, and Loketská), the sites showed a similar profile evolution—evolving from a mine Technosol to a forest Cambisol, or its initial stages. In all three locations, horizon differentiation (A-Bv-C) was visible, although cambic (Bv) horizon characteristics were only faintly indicated in the youngest stand on level terrain. All Bohemia I and Antonín profiles fulfilled the WRB [40] criteria to be classified as Cambisols. In the youngest, Loketská stand, the depth of the observed Bv horizons was $\leq$15 cm thick, which is one of the five diagnostic criteria for the cambic horizon and, furthermore, Cambisol classification. Horizon transitions and their color differences were clearer in the older sites. Organomineral (A) horizon thickness ranged between 2 cm and 19.5 cm, whereas the cambic (Bv) ranged between 10 and 50.5 cm, depending on the site. Soil horizon A thickness was 2 cm in the Loketská stand on level terrain, whereas it was 4 cm in the same stand on the slope. The 50-year-old Antonín stand had the same A horizon thickness (5 cm) in both level and slope terrain. In Bohemia I, the thickness of A horizon on level terrain was greater than that on slope terrain (19.5 and 11 cm, respectively). Cambic (Bv) horizon thickness followed similar patterns to A horizon across stands, with the profile on level terrain being less thick in Loketská than its slope counterpart (10 and 15 cm, respectively), Antonín ones being almost the same depth (31 and 30 cm), and somewhat greater Bv horizon thickness was noticed on level terrain in Bohemia I (50.5 and 44 cm for level vs. slope). Within all sites, in the deeper layers, coal residues and cypress claystones in various stages of weathering were found.

The development of the soil horizons is graphically presented in Figure 2, and their detailed descriptions can be found in Table 1.

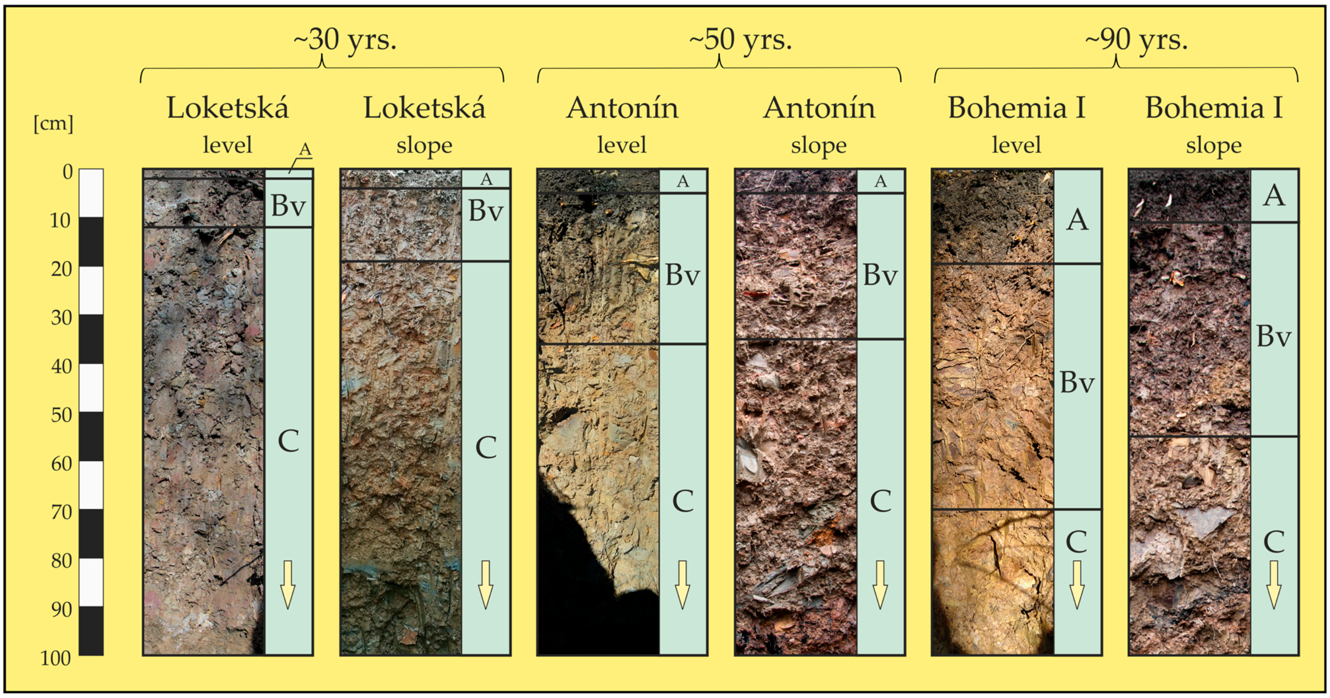

Figure 2. Representation of the profile development of soil pits from 3 forest reclamation sites.

Bulk density analysis has shown that the bulk density varied, on average, between 0.79 and 1.39 g/cm^3. The clearest distinction could be noticed between horizons—all of the A horizon samples had lower values (0.75–1.03 g/cm^3) than the Bv and C horizons (1.08–1.39 g/cm^3), and the A horizon values of pairs on level and slope terrain on the same locality always had the closest values. In all profiles, the bulk density values were A < Bv < C. On average, the bulk density values were generally the highest in Loketská stands, and the narrowest range (the least difference in values between the horizons) was noticed in the youngest site (Loketská) on flat terrain. The values and their distribution can be seen in Figure 3.

Table 1. Profile details and individual horizon descriptions from 3 forest reclamation sites.

Location		Loketská		Antonín		Bohemia I	
Terrain configuration		Level	Slope	Level	Slope	Level	Slope
Coordinates (WGS84)	N	50.218117	50.222160	50.173460	50.173756	50.185560	50.185383
	E	12.772825	12.772984	12.631110	12.631248	12.657514	12.656961
Elevation [m a.s.l.]		550	532	496	496	466	457
Slope [°]		2.0	8.6	2.3	8.3	1.6	25–30
Mineral horizon thickness [cm]	A	2	4	5	5	19.5	11
	Bv	10	15	31	30	50.5	44
	C	>12	>19	>36	>35	>70	>55

Table 1. *Cont.*

	Humus type	Moder to mull	Moder to mull	Mull	Mull	Moder to mull	Moder to mull
	L	Last year's dead grasses, in places individual fallen alder leaves	Last year's dead grasses, in places individual fallen alder leaves	Continuous layer of last season's litter	Layer of irregularly deposited last season's litter (up to 1 cm), horizon A visible on the surface	1 cm of last year's litter with significant decomposition (due to maple leaves)	Approximately 60% of the area without overlying organic horizons, horizon A visible on the surface. Mixed L and F horizons. Indistinctive H horizon.
	F	Residues of decomposed alder leaves	Residues of decomposed alder leaves	Imperceptible	Barely present (mixed with upper A horizon)	Up to 1 cm, dark brown, transfers directly to A horizon	
	H	Not present - soil surface generally covered with grassland under trees, locally disturbed by animals (wild pigs)	Not present - soil surface generally covered with grassland under trees. Approximately 50 % of the surface is not covered by vegetation or litter	Transfers to A horizon	Imperceptible	Indistinctive, surface of A horizon covered with a large number of hawthorn seeds	
Horizon description	A	Brown-black, crumbly and loose in the upper part, slightly moist, finely polyhedral in the lower part, compact, moist, clay loamy, weakly plastic. Densely rooted with roots up to 5 mm diameter. Grass roots, and roots of trees up to 1 cm diameter in some places. The horizon contains a skeleton of up to 20% composed of decomposed cypress clay up to 2 cm in size. The transition is sharp and slightly undulating. Edaphon was not observed.	Brown-black, crumbly and loose in the upper part, slightly moist and polyhedral in the lower part, compact, moist, clay loamy, weakly plastic. Densely rooted with roots up to 5 mm diameter. Grass roots, and roots of trees up to 1 cm diameter in some places. The horizon contains a skeleton of up to 20% composed of decomposed cypress clay up to 2 cm in size. The transition is distinct (2–5 cm) and slightly undulating. Edaphon was not observed.	Brown-black, crumbly in the upper part, loose, compacted in the lower part, moist, clay-loamy, weakly plastic, densely rooted with roots up to 1 cm in diameter. Earthworms are seldom present in the horizon. No skeletal particles. It transitions clearly to the next horizon (2 cm). The transition is straight to slightly wavy.	Dark brown, loose, crumbly in the upper part, compacted in deeper layers, densely rooted, with an admixture of earthworm excrement, and earthworms. No skeletal particles. The transition to the next horizon is distinctly straight to slightly wavy.	Brown-black, crumbly to finely polyhedral, moist, loamy, weakly plastic, loose on the surface. The horizon is densely rooted, even with strong roots, with high biological activity (active earthworms were found). No skeletal particles. The transition to the Bv horizon is straight, distinctive, with vertical intrusions of organic matter to the upper part of Bv horizon.	Brown-black, crumbly on the surface, finely polyhedral to polyhedral within the horizon, clay loamy, moist, weakly plastic, loose on the surface, firmer deeper. The horizon is densely rooted with fine roots. Roots up to 5 cm in diameter are also common. Earthworms are seldom present. Without the presence of skeleton. It transitions clearly to the next horizon (up to 2 cm). The transition is straight to slightly wavy.

Table 1. *Cont.*

Horizon description	Bv	The horizon is only faintly indicated at a depth of 2 to 12 cm, grey-brown, moist, clay loam, weakly plastic to plastic, coarse polyhedral structure indicated. Fine grass root content decreases rapidly with depth, sparse tree roots to 1 cm diameter. Skeleton is composed of residual weathering of cypress clays up to 25% in the whole volume of the horizon. The transition to the C horizon is distinct (2–5 cm), wavy.	Brownish rusty, moist, weakly plastic, without distinct structure. The skeleton is composed of weathered cypress wet clays with a volume of up to 25 %. The horizon is densely rooted with tree roots up to 5 mm in diameter, in some places up to 1 cm. The transition to horizon C is distinct (2–5 cm), slightly wavy. Edaphon was not observed.	Grey-red-brown, with a indications of roughly polyhedral structure, moist, weakly plastic to plastic. Coatings of secondary Fe and Mn minerals are developed on deeply weathered cypress clays with a still visible layered structure. Sparse rooting, seldom with roots up to 1.5 cm. The horizon is without the presence of an edaphon, the skeleton consists of weathered cypress clays weathered throughout their entire volume, the layered structure is still clear. No resistance when breaking apart. The transition to the next horizon is clear (up to 2 cm). The transition is wavy.	The upper part is reddish-yellow-brown, the color changes to yellow-brown towards the depth. Moist, the skeleton is porous, with coatings of secondary Fe and Mn minerals. The matrix is plastic, with indications of the development of a roughly polyhedral structure in the upper parts. The entire horizon is sparsely covered with roots up to 5 mm thick. There is an admixture of porcelanite. Less noticeable coal particles. The transition to the next horizon is clear.	Red-brown color gradually changes from brown-ochre to brown-yellow color. Without distinct structure, loamy clayey, moist, weakly plastic to plastic, stiff, containing weathered cypress clays (pieces of clay are soft, ocher-rusty in the entire volume) with coatings of secondary minerals (Fe, Mn) on the surface. Remains of coal at a depth of approx. 50 cm. Skeleton content approx. 50%, transition to the next horizon diffuse. Horizon is rooted to 65 cm.	Strong reddish-brown, moist, weakly plastic to plastic, without distinct structure, rooted with roots up to 1 cm in diameter, with a high content of coal residues, compacted. Without the presence of edaphon, no skeletal particles, the cypress clays are completely weathered, the layered structure is still clear, no resistance when breaking apart. The transition to the next horizon is clear, (up to 2 cm). The transition is wavy.

Table 1. *Cont.*

Horizon description	C	The red-brown-grey matrix consists of moist, heavily weathered cypress clays of coarse consistency. The skeletal content is approximately 80 %. The skeleton is moist, soft and easy to break with a spade. The spaces between the skeleton are filled with a yellowish-brown clay loam, a plastic mass of clayey consistency. Tree roots up to 5 mm in diameter occur sporadically to a depth of 80 cm.	Brownish rusty, with a skeletal content of up to 80 %, the skeleton is composed of distinct pieces of wet soft cypress clay which are easily dislodged with a spade. The cypress clay pieces are oxidized throughout their volume to a soil horizon depth of approximately 40 cm. They are rusty-brown in color when cut. After 40 cm, the larger pieces of cypress clay are rusty brown only on the surface, inside they are grey, unoxidized. From about 70 cm downwards, there is moist, slightly weathered spoil material. Tree roots occur sporadically to a depth of 70 cm. Edaphon was not observed.	Gray-yellow-brown, formed by cypress clays on the surface with coatings of secondary Fe and Mn minerals, partially weathered (inside, their original gray color is preserved). Moist, plastic to strongly plastic. Rooting is sparse with fine roots that are visible up to a depth of 80 cm. Below 80 cm, yellow-red-brown color with surface coatings of secondary minerals, and less weathered cypress claystones. Below 100 cm, the horizon is wet and sticky, with no presence of roots. In the entire profile, coal residues can be found.	Brown-yellow-gray in color, without a distinct structure, moist, highly plastic. The skeletal particles consist of cypress clays, gray inside and yellow-gray on the surface. Intrusions of rusty sands in some places of the horizon can be found.	Brown-yellow color. In the horizon, strongly weathered cypress clays are present (brown-rusty on the surface, blue-gray inside the skeletal pieces). On the surface, coatings of secondary minerals with a high content of Fe and Mn. Coal residues are seldom mixed in the horizon. Skeletal content app. 80%. Roots are rarely present to a depth of 90 cm.	Yellow-brown. Cypress clays are no longer completely weathered, they are rusty yellow on the surface, soft, blue-gray on the inside, hard. A large amount of coal remains present in the horizon, often in layers. There is no clear structure in the profile, the soil is moist, weakly plastic to plastic. Rooting with small roots to a depth of 110 cm. After 110 cm, clays are less weathered, soil is more compacted, and greater presence of coal can be observed.

Average particle density ranged between 2.12 and 2.69 g/cm^3, and the lower values were noticed in A horizons. Location wise, the lowest overall values were noticed in the 50-year-old Antonín stand on flat terrain. Porosity values mostly corresponded to bulk density values, as can be seen in Figure 4. The average values ranged between 47 and 68%. The average porosity of the A horizon in Antonín and Bohemia I ranged between 64 and 68%, whereas the Loketská values ranged between 57 and 61%.

Average values of maximum capillary capacity (MCC) ranged from 45.41% to 56.87%, belonging to classes of soil with strong and very strong water retention [35]. At most of the locations, the water retention values dropped with horizon depth (A > Bv > C), except in the case of the 50-year-old Antonín stand on level terrain, where the MCC values were greater in C than in Bv horizon. Highest average water retention values were noticed in the Antonín stand on the slope (52.95%–56.87%). The greatest ranges in average values were noticed in Bohemia I on level terrain and Antonín on level terrain (6.93% and 6.63%, respectively), although Antonín exhibited greater variations between all samples, and bigger overall standard deviations. On the other side, both localities on the youngest site (Loketská) showed rather narrow MCC ranges (2%–3%). MCC values can be seen in Figure 5.

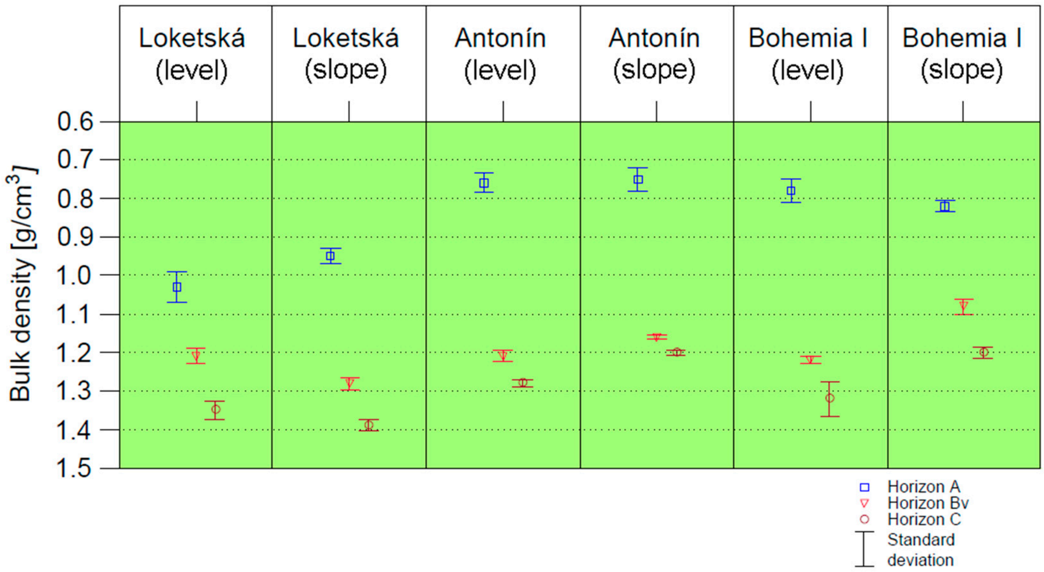

Figure 3. Bulk density values on Loketská, Antonín, and Bohemia I sites on level and slope terrain.

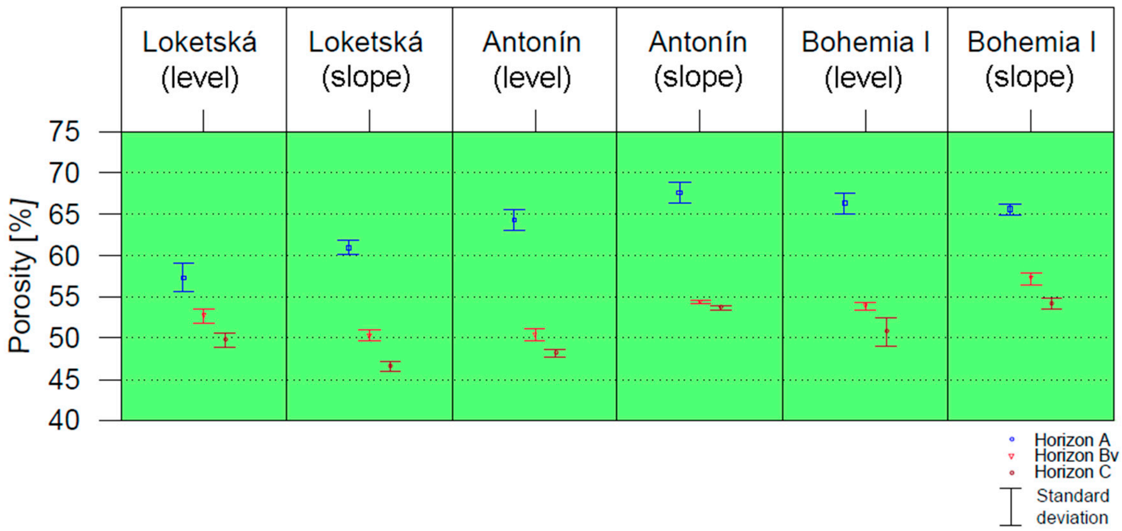

Figure 4. Porosity values on Loketská, Antonín, and Bohemia I sites on level and slope terrain.

Chemical analyses showed that the pH (H_2O, KCl) increased with depth in all sites and that the parent material was alkaline (7.72–8.30 on average, measured in water). Average CEC values ranged from 9.05 to 36.3 cmol(+)/kg. In all stands, CEC was the greatest in the A horizon samples. In the two older stands (Bohemia I and Antonín), the values were higher than in the 30-year-old one (Loketská). Oxidizable carbon content (Cox) was the greatest in the A horizons (7.1%–10.5%) of all stands, and usually dropped with depth, except in the Antonín and Loketská pits, where the levels were higher in the deepest horizon, probably caused by high amount of coal that was present in the profile. Organic matter quality analysis (A_{400}/A_{600}) was performed only on A horizon samples, due to the high clay dispersion in sodium pyrophosphate occurring in the samples from the mineral horizons, thus skewing results. The results have, nonetheless, shown the greater quality of humic and fulvic substances (lower A_{400}/A_{600} ratio) in the oldest stand (Bohemia I

3.83–4.17, Antonín 5.99–6.03, Loketská 5.34–5.38). In terms of plant available nutrients, P levels are, according to the forest soil standards that apply in the Czech Republic [41], insufficient or low, whereas K, Ca, and Mg levels are very high. Although insufficient, the concentrations of P were much greater in the A horizon than in all of the underlying ones, which were, in most cases, under the detection limit (1.35 mg/kg). Some of the measured chemical properties are given in Table 2.

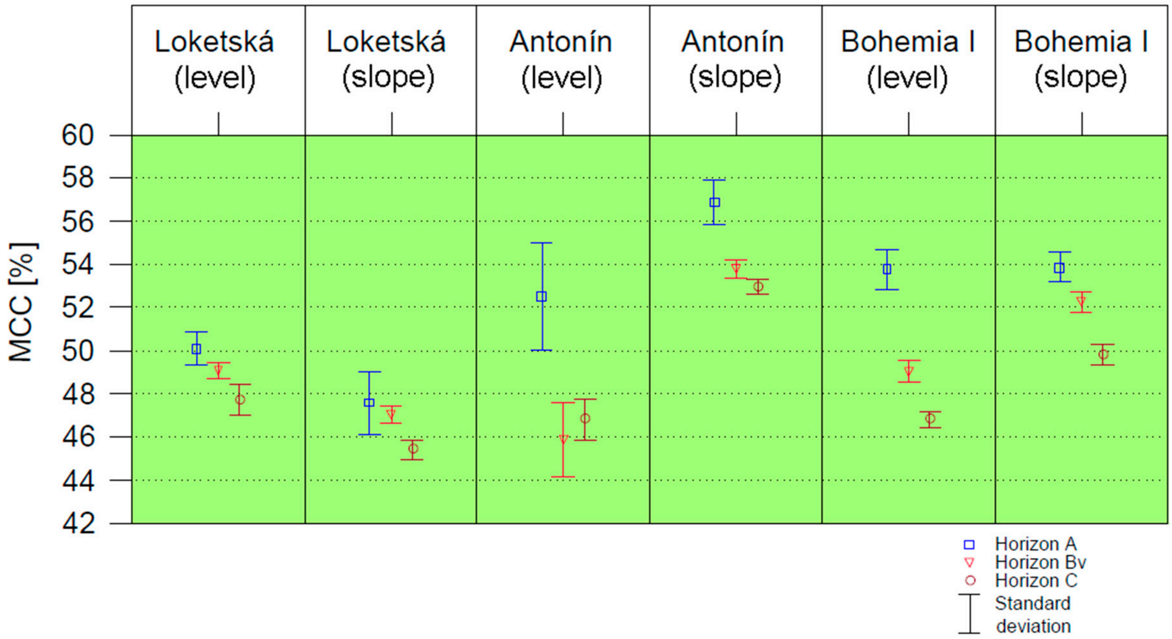

Figure 5. Maximum capillary capacity (MCC) values on Loketská, Antonín, and Bohemia I sites on level and slope terrain.

Table 2. Average values of chemical soil properties from samples from all 6 soil profiles (with standard deviations).

Analysis	Horizon	Loketská Level	SD	Loketská Slope	SD	Antonín Level	SD	Antonín Slope	SD	Bohemia I Level	SD	Bohemia I Slope	SD
pH [H_2O]	A	6.57	0.02	7.67	0.03	7.13	0.02	6.95	0.00	6.12	0.04	6.84	0.04
	B_v	7.25	0.00	7.93	0.03	8.13	0.03	7.94	0.01	6.60	0.04	7.64	0.03
	C	7.61	0.06	8.22	0.07	8.47	0.05	7.96	0.03	7.48	0.02	7.96	0.06
	>1 m	7.72	0.01	8.30	0.02	8.26	0.07	7.81	0.04	8.10	0.02	8.20	0.00
pH [KCl]	A	6.12	0.02	6.88	0.02	6.52	0.00	6.51	0.00	5.80	0.04	6.53	0.02
	B_v	6.81	0.02	7.59	0.01	7.70	0.03	7.58	0.01	6.12	0.00	7.15	0.02
	C	7.19	0.02	7.94	0.03	7.98	0.04	7.85	0.02	7.16	0.06	7.79	0.07
	>1 m	7.63	0.01	8.03	0.03	7.87	0.02	7.36	0.02	7.87	0.02	8.05	0.03
CEC [cmol(+)/kg]	A	26.58	0.22	22.82	0.01	36.32	1.97	33.61	0.13	29.69	0.32	35.29	0.03
	B_v	19.99	1.22	10.92	0.11	18.79	0.34	18.15	0.28	15.05	0.15	24.10	0.33
	C	14.62	0.02	9.05	0.06	15.80	0.29	17.36	0.21	15.01	0.28	17.69	0.28
	>1 m	15.90	1.26	10.47	0.63	21.29	3.46	26.32	0.61	18.29	2.39	17.01	0.50
C_{ox} [%]	A	8.49	0.32	7.11	0.08	9.87	0.10	8.72	0.04	10.47	0.18	9.81	0.02
	B_v	2.06	0.00	2.81	0.13	2.43	0.20	3.11	0.15	3.96	0.04	5.97	0.07
	C	1.25	0.07	2.19	0.04	2.50	0.12	2.78	0.09	3.50	0.03	4.15	0.59
	>1 m	4.16	0.20	2.11	0.03	2.90	0.07	6.00	0.18	2.96	0.06	4.01	0.10
A_{400}/A_{600}	A	5.38	0.25	5.34	0.26	5.99	0.06	6.03	0.34	4.17	0.11	3.83	0.15
$P_{available}$ [mg/kg]	A	15.00	1.03	6.66	0.08	14.13	0.09	16.45	0.45	14.50	0.63	14.69	0.52
	B_v	6.31	0.05	ND	/	ND	/	ND	/	1.51	0.84	ND	/
	C	4.70	1.11	ND	/	ND	/	ND	/	ND	/	ND	/
	>1 m	ND	/	ND	/	ND	/	ND	/	ND	/	ND	/

Table 2. *Cont.*

Analysis	Horizon	Loketská Level	SD	Loketská Slope	SD	Antonín Level	SD	Antonín Slope	SD	Bohemia I Level	SD	Bohemia I Slope	SD
$K_{available}$ [mg/kg]	A	442	14.45	435	3.34	490	7.82	416	7.34	481	2.63	754	9.88
	B_v	284	12.09	243	8.83	286	5.74	308	12.33	404	102.2	459	2.12
	C	227	11.60	226	2.43	256	3.10	334	18.91	209	1.76	327	1.83
	>1 m	310	5.89	236	4.74	301	39.86	270	1.74	285	2.16	318	3.49
$Ca_{available}$ [mg/kg]	A	2651	119.9	5386	72.9	4292	77.6	3209	116.3	3661	52.9	4221	47.6
	B_v	1960	27.3	8498	397.6	7389	263.9	5612	172.5	2937	903.1	4883	81.0
	C	1781	101.3	8386	401.7	5172	16.7	5499	383.2	2481	112.3	5797	119.1
	>1 m	6678	26.2	17,587	1277	2650	337.0	1449	1.0	2716	3.2	2935	17.4
$Mg_{available}$ [mg/kg]	A	1043	54.8	1059	8.2	1884	8.4	1317	53.9	1064	10.2	1460	17.3
	B_v	981	1.8	813	0.9	1393	22.0	990	35.4	1175	349.0	996	8.2
	C	858	46.4	1082	18.2	1389	48.5	1515	126.3	1420	10.5	1599	3.9
	>1 m	1170	7.7	1369	23.7	1461	163.3	1885	57.5	1892	17.5	2145	14.9
$Al_{available}$ [mg/kg]	A	392.60	7.96	301.70	8.46	366.81	19.49	285.79	0.49	580.80	9.36	445.00	16.86
	B_v	334.92	2.65	50.78	6.46	102.76	13.38	73.16	2.69	394.60	120.99	278.96	8.62
	C	324.27	12.74	30.00	2.90	62.98	0.80	93.77	2.44	236.79	6.50	210.98	4.70
	>1 m	72.05	32.49	31.93	21.04	223.99	43.30	250.72	50.10	215.48	23.05	193.43	16.31
$Fe_{available}$ [mg/kg]	A	258	10.93	346	3.49	519	16.81	432	1.07	410	3.64	443	8.80
	B_v	122	0.97	228	13.34	314	27.20	234	6.92	420	134.3	336	5.85
	C	142	7.83	193	14.35	225	3.95	242	2.67	336	4.90	270	6.79
	>1 m	268	11.98	251	2.69	310	4.90	324	18.04	322	11.43	310	7.10
$Mn_{available}$ [mg/kg]	A	57.82	4.02	118.03	0.95	108.43	4.62	87.31	1.50	81.04	1.03	86.55	0.45
	B_v	60.23	0.36	153.18	5.41	126.94	3.24	105.63	2.55	209.74	62.53	118.60	6.51
	C	51.90	5.46	128.21	5.95	78.80	1.97	82.43	6.22	103.58	2.61	132.65	3.15
	>1 m	97.92	1.29	174.97	0.35	47.29	4.06	55.00	2.47	83.20	1.94	68.98	0.26

Analysis of plant available potentially toxic elements (Al, Fe, and Mn) showed that Al and Fe concentrations, according to the Central Institute for Supervising and Testing in Agriculture of the Czech Republic [41], were very low, and Mn levels were very low or low. The assessment of elemental concentrations for PTE was made by comparing the values obtained by Mehlich III extraction to the classification criteria prepared for 2 mol/L HNO_3 extractable elements, which extracts more from the same sample (and gives greater values), and are often used as "the worst case scenario" availability values. Having done this, it is safe to assume that all of the tested PTEs were far below the limit wherein they would pose a threat. The classification criteria for macronutrients (P, Ca, K, Mg) and PTE (Al, Fe, Mn) according to Fiala et al. [41] and ÚKZÚZ (Central Institute for Supervising and Testing in Agriculture of the Czech Republic) are given in Tables 3 and 4. Other elements (Cd, Pb, Ni, Cu, and Zn) were found in ranges of 0.03–0.16, 0.58–2.97, 0.64–3.47, 1.46–16.88, and 0.95–23.37 mg/kg, respectively.

Table 3. Classification criteria of available elements extractable by Mehlich III method for the forest soils of the Czech Republic (under broadleaved vegetation), compiled from Fiala et al. [41].

Element [mg/kg]	Horizon	1 Insufficient	2 Low	3 Sufficient	4 High	5 Very High
P	Organo-mineral	≤8	9–17	18–30	31–50	>50
	Mineral	≤7	8–19	20–40	41–70	>70
K	Organo-mineral	≤70	71–110	111–150	151–190	>190
	Mineral	≤40	41–60	61–90	91–120	>120
Ca	Organo-mineral	≤310	311–630	631–1200	1201–1870	>1870
	Mineral	≤190	191–500	501–950	951–1530	>1530
Mg	Organo-mineral	≤45	46–90	91–160	161–250	>250
	Mineral	≤25	26–50	51–90	91–150	>150

Table 4. Classification criteria of potentially toxic elements extractable in 2 mol/L HNO_3 for the forest soils of the Czech Republic (under broadleaved vegetation), compiled from Fiala et al. [41].

Element [mg/kg]	Horizon	1 Very Low	2 Low	3 Medium	4 High	5 Very High
Al	Organo-mineral	≤1830	1831–3000	3001–4200	4201–5800	>5800
	Mineral	≤2100	2101–3600	3601–5500	5501–8000	>8000
Fe	Organo-mineral	≤2400	2401–4300	4301–6400	6401–9100	>9100
	Mineral	≤2800	2801–5100	5101–7900	7901–11,700	>11,700
Mn	Organo-mineral	≤200	201–600	601–1000	1001–1400	>1400
	Mineral	≤120	121–310	311–500	501–690	>690

4. Discussion

In all three investigated stands, horizon differentiation was observed, with organo-mineral and cambic horizons development (even if they cannot be officially classified as cambic due to depth, "cambic-like" changes of the parent material were evident, as was explained in the Results Section). This is in accordance with the statements that A horizon can develop within less than 20 years from reclamation, and that formation of secondary minerals can be observed after around 40 years [9]. The formation of "cambic-like" horizons in 50-year-old mine soils has been described by Feng et al. [42], along with various depths of A and B horizons. Having in mind that the clayey parent material of the Sokolov region is not too severe for establishing vegetation, and the high quality litter that the broadleaved vegetation cover provides [26], these results are not surprising. Frouz et al. [15,28] found that, in reclaimed sites in Sokolov under broadleaves (stands with low C/N ratio), a thin organic and a thick organo-mineral (A) horizon usually forms. On the contrary, under conifers (high C/N ratio), a thick organic and a thin organo-mineral horizons were present. Spasić et al. [14] have found that, in most cases (with some exceptions), similarly aged (~50 years old) conifers within the Antonín forest arboretum in Sokolov formed A horizons thinner than 3 cm, whereas most broadleaves formed 4–6 cm thick A horizons. On a 28-year-old site reclaimed by alders in Sokolov, 9.8 cm thick organo-mineral horizons were recorded [28]. Frouz et al. [27] have recorded A horizon depths of up to 6 cm in 41-year-old spontaneous succession sites.

Coal mine sites reclaimed before World War II are rarely found, and Bohemia I, although belonging to somewhat different excavation and overburden deposition methods from the other two localities, has shown itself to be a valuable site for observation as a 90-year-old reclaimed forest. Hüttl and Weber [43] have highlighted the problem of finding reclamation plots older than 40 years. The development of A and Bv soil horizons which were, in the case of level terrain, noticed to be almost around 20 and 50 cm deep, respectively, proved to be deeper than what we initially expected, and this definitely highlighted the effect of time on the soil formation process. It can even be argued that the thickness of the formed A and Bv horizons is greater on these reclaimed mine sites than in many natural forests under similar vegetation. This can be due to the fact that old natural forest soils are usually formed by vegetation colonizing hard parent rocks, whereas the deposited clayey material of the Sokolov area is already partly broken down even during the deposition process and has proven suitable for vegetation development. The process of soil forming faster on Technosols than in natural soils due to various factors has been thoroughly described by Huot et al. [44]. Disequilibria between parent material and natural environmental conditions, high pH promoting the dissolution of silicates, good soil saturation properties, and the presence of salts or sulphates accelerating weathering are just some of the causes mentioned. Greater horizon depths formed on mine Technosols compared to those found in natural forests were also noted by Thomas et al. [45].

Our presumption about soil formation depth on level vs. slope terrain proved to be correct in case of the oldest (Bohemia I) stand. In Antonín, the horizon thickness did not vary significantly. In Loketská, our presumption proved to be wrong, and greater horizon formation was noticed in sloped terrain. This can potentially be explained by the following reasons: firstly, the elapsed period of 30 years may be too short for observing the soil formation process through horizon formation with great certainty; secondly, local site variations, like the pH of parent material that was presumed to be more homogenous within the stand, was noticed to be different (7.6–7.7 for level vs. 8.2–8.3 for slope), as well as the differences in slope steepness (the slope at Bohemia I was much steeper than slopes at Antonín and Loketská).

When looking at the bulk density, porosity, and water retention values and distributions, it can be noticed that, with time, the distinctions between horizons tend to be more clear. Such were, also, the horizon boundaries during the sampling. Although noticeable in all horizons (and following similar patterns), the differences in physical soil properties were, in particular, more pronounced between organo-mineral A and the underlying mineral horizons. Although high in all samples, which can be explained by the clayey parent material, MCC values have shown much broader ranges in the two older stands than in the 30-year-old one. It is also worth noting that the physical properties from Loketská samples have such values because the soil cylinders used have a height of 5 cm, so in the Loketská samples they encompass not only A, but the underlying Bv horizon as well. Roberts et al. [46] have found that water retention increased over time in surface soil horizons (0–5 cm) at all spoil types except pure sandstone. Apart from Loketská, where the development of the horizons was also greater in the profile located on the slope, wider ranges in the soil physical properties' values were noticed in the two older stands on level terrains compared to the ones on slopes, which further proves our hypothesis.

In most cases, pH decreased as new horizons formed (the highest pH values were mostly noticed in the deeper layers that presented the parent material), and the changes were not so drastic with age. In Sokolov, Bartuska and Frouz [20] also found a pH decrease in high pH parent material, and stated that it was significant at both 0–5 and 5–10 cm depths, but more pronounced in the upper layer. They also stated that the changes from alkaline to acidic and vice versa (depending on the parent material) reflect the establishment of an active buffering system based on the balance between basic cations and organic matter. A similar trend was also noticed in studies by various other authors [23,24,26,27], where they found that pH decreased with plot age.

Carbon and nitrogen accumulation in the upper layers of reclaimed and successional forests on mining sites was expected and well documented in the scientific literature [20,24,26,27,47,48]. The reported carbon levels varied between 1.35 and 9.5%. In our study, carbon accumulation was also the most pronounced in A horizon (usually between 2 to 3-fold greater in A than in the underlying horizons).

Due to the high levels of fossil carbon (kerogen of algal origin type I and II) in the parent material of many post-mining sites in Sokolov, certain corrections, like subtracting the carbon values of parent material (deeper layers) from the upper layers, are sometimes used to assess recently formed carbon [48]. Fossil C correction methods have also been well described [47]. In some instances, it has been shown that no significant increase in C content was found in layers below the A horizon [23,28].

According to Mládková et al. [49], the A_{400}/A_{600} ratio shows the level of polymerization and stability of the extracted organic substances. The lower the value, the more polymerized and stable the substances are. Pospíšilová et al. [50] have compared various methods for the assessment of organic substance quality, and have shown that various soil types in Czech Republic have shown different OM quality levels. Chernozem was found to have the highest quality, whereas Eutric Cambisol was on the other end of the spectrum. In Sokolov, the oldest Bohemia I stand had the lowest A_{400}/A_{600} ratio values in the A horizon, followed by the youngest Loketská, whereas the middle-aged, 50-year-old Antonín stand had the highest values, although we have hypothesized that quality may increase with the age of the stands. The Bohemia I and Antonín stands have maple as the dominant vegetation type in common, whereas the Loketská stand, although younger, could have shown better OM quality results based on the fact that it is the only stand afforested by alders, widely known for their litter quality. Apart from the effect of age between Bohemia I and Antonín, the mixed dominant tree species (maple and cherry) in Bohemia I could have resulted in greater humus quality, as Godefroid et al. [51] have found to be the case in beech and oak forests in Belgium. The effect of slope on organic matter quality was noticeably different only in the Bohemia I stand (where the difference in slopes was the greatest), but OM quality was, surprisingly, greater on slope than on level terrain. Due to the high dispersion of clays in sodium pyrophosphate, using some other method (like FTIR spectroscopy) may be advisable when dealing with OM quality analyses of clayey soils.

Available phosphorus was found to be insufficient or low for forest growth, and the values are comparable to the results obtained by other authors on reclaimed mine sites [14,52,53]. Bartuska and Frouz [20] have found that total P levels decreased in reclaimed alder forests in Sokolov with reclamation age (unlike C and N), and explained this by leaching, plant uptake, and phosphorus being of mineral origin. In our research, although not largely differing from each other based on site age (comparable to the findings of Bartuska and Frouz [20]), the available P levels (although low) were found to be much greater in the organo-mineral than in the mineral horizons (which should also be a representation of the initial parent material and, further, representation of younger sites). This may be explained by root exudation, mycorrhizal or microbial activity and higher organic matter input, as well as its decomposition and mineralization, which are all important factors known to increase P availability in soil. Soil pH of 6–7.5 is generally known to be a good range for phosphorus availability for plants, whereas anything below or above this range limits P availability due to its fixation to Al, Fe, or Ca [54]. Only one of the six samples from A horizon had an average pH value over 7.5, and it was the one where the lowest P level in all A horizon samples was noticed, further substantiating this theory. High amounts of aluminum and iron oxides and weathered clays (especially kaolinite) are known to increase P sorption, thus limiting its availability, which explains the very low or undetectable values of available P in all the mineral horizons. Šourková et al. [55] have found higher P in the microbial biomass of reclaimed mining sites in Lusatia, Germany, than in Sokolov, although the total P content was far greater in Sokolov parent material, and showed low phosphorus availability in clays due to their high pH. Frouz et al. [27] have found water-soluble P to increase, especially in late successional stages in Sokolov.

Other major macronutrients (Ca, K, Mg) have shown to be very high, which corresponds to other findings from the Sokolov region [14,53]. The tested plant available and potentially toxic elements had very low or low values, which are in accordance to the values obtained by Spasić et al. [14] and Frouz et al. [56]. Only zinc values in A and Bv horizon in Loketská on level terrain (14.0 and 24.74 mg/kg on average, respectively) have somewhat surpassed the previously mentioned values. These values are not alarming, since such soil plant available zinc concentrations (extracted by DTPA) are considered to be safe even for the growth of some edible plants [57]. The Mehlich III method was found to extract higher amounts of Cu, Fe, Mn, and Zn, especially in high pH [58], so the obtained values are even less concerning. Most available elements were, much like phosphorus, higher in the A horizon, presumably due to the lower pH. Frouz et al. [56] have shown that a low pH was the most important factor for the toxicity of soil material from post-mining sites, and for this reason, alkaline tertiary clays usually do not show signs of toxicity.

5. Conclusions

By observing the differences in six soil profiles from three differently aged, broadleaved forest reclamation stands that are in close proximity to each other and established on similar parent material type, the effect of time as one of the most influential factors of soil formation was found to be undisputable. The development of formed diagnostic soil horizons showed the evolution of soil type to progress from an anthropogenic mine Technosol to a forest

Cambisol in all three investigated localities. Soil in the two older stands (Bohemia I and Antonín) can be classified as Cambisols according to WRB. In the youngest, 30-year-old (Loketská) stand, an initial development of the cambic (Bv) horizon was observed, but has not fully met the diagnostic criteria, due to the limitation in its thickness. However, it can be stated with certainty that, with time, further development of these soils will result in Cambisol. The level of development (and thickness) of the soil horizons increased with age, and the differences in physical and chemical soil properties relative to the parent material characteristics were noticed to be greater as time passed. Physical properties have mostly shown wider ranges in pits located on level terrain compared to the ones on slopes, further complementing our initial presumptions. Accumulation of pedogenic organic matter led to an increase in porosity and water retention, and greater cation exchange capacity of the A horizon. Organic matter incorporated into the organo-mineral horizon led to a decrease in pH, making most nutrients more available for plants. No significant elemental toxicity levels were found in any of the samples tested. The quality of the organic substances was noticeably higher in the oldest stand. In order to better understand soil development on reclaimed post-mining sites, further observations of soils formed under different conditions (parent material, climate, vegetation, and topography) is advised, together with their additional monitoring in the future. The effect of soil pH and slope on soil development was observed. However, in the future, more comprehensive research needs to be carried out.

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