CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Agrobiology, Food and Natural Resources

Department of Soil Science and Soil Protection

THE INFLUENCE OF VARIOUS TREE SPECIES ON INITIAL SOIL FORMING PROCESSES ON RECLAIMED DUMPSITES

Doctoral Thesis

Faculty of Agrobiology, Food and Natural Resources

Author: Ing. Marko Spasić

Supervisor: doc. Ing. Ondřej Drábek, Ph.D.

Co-supervisor: RNDr. Václav Tejnecký, Ph.D.

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Declaration

I declare that the doctoral thesis "The influence of various tree species on initial soil forming processes on reclaimed dumpsites" is my own work that I have conducted under the supervision of my supervisor doc. Ing. Ondřej Drábek, Ph.D., and my co-supervisor, RNDr. Václav Tejnecký, Ph.D. All literature sources cited in this doctoral thesis are listed in the References.

In Prague on 25. 02. 2024.

Ing. Marko Spasić

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1. Introduction

The topic of this doctoral thesis deals with the soil formation processes on forest reclaimed mine sites after the process of brown coal mining and the influence of tree species used in the reclamation process on the development and quality of the soil formed underneath them. The layout of this doctoral thesis consists of a compilation of published scientific publications related to the mentioned topic and the results obtained through them. Since a lot of theoretical parts related to the topic that would be a suitable introduction to the subject matter were covered in the two review papers published as a part of this thesis, combined with the introductions and discussions of the other publications also used, without the need to fully repeat what is stated there, this introduction is kept to a minimum, and covers only the most important definitions and information a potential reader needs to get familiarized with the problem matter.

Mining is defined as „the extraction of valuable minerals or other geological materials from the earth from an orebody, lode, vein, seam or reef“ and is a process required for obtaining materials that cannot be grown through agriculture or artificially created in a laboratory or factories (Schulte, n.d.). Techniques used for mining are usually divided into two categories: sub-surface (also known as underground) and surface mining. Surface mining can further be open pit mining, strip mining and mountaintop removal (Schulte, n.d.). Surface mining is commercially more viable, and safer for workers than underground mining. According to Ramani (2012), surface mining methods, on a global scale, are used for obtaining more than 95% of non-metallic minerals, more than 90% of metallic minerals and more than 60% of coal. This accounts to around 80% (25 out of 30 billion metric tonnes) of mine and waste material. According to a recent research from a large-scale satellite imagery survey, around 101600 square kilometres were recognized to be directly visually affected (open cuts, tailings dams, waste rock dumps, water ponds and processing infrastructure) by the mining industry (Maus et al., 2020, 2022). According to these sources, the largest number of recognized commodities from active mines included coal, gold, silver, copper, zinc and iron. Overburden (also commonly referred to as waste or spoil) is the material lying above the economically viable coal seam or ore body (Ministry of Coal, n.d.). It usually consists of sedimentary rocks which compress and consolidate the material below them (Magoon, 2004). During the process of surface coal mining, overburden can be moved from the premises of the mining site and deposited as an external spoil heap, or deposited inside the mining area in places where the coal seam has already been mined, creating an internal spoil heap.

Surface mining alters landscape, natural ecosystems, microclimate conditions, environmental flows, ecosystem functions, water and air quality, also often leading to human health problems, and is often referred to as one of the most disputed industries in the world (Hendrychová & Kabrna, 2016; Hilson, 2002; Kuter, 2013; Spasić et al., 2021; Spasić et al., 2023a; Svobodova et al., 2019; Wang et al., 2021). Due to the vastness of operations and the heavy machinery used, post-mining landscapes are susceptible to further land subsidence, various forms of erosion, and degradation of these fragile ecosystems (Spasić et al., 2021; Wang et al., 2021). One of the greatest problems it causes is the uttermost destruction of fertile topsoil which is rich in organic matter and nutrients, and essential for the growth of vegetation and other ecosystem functions. Deposited overburden material can often be very harsh in its physico-chemical properties, which can affect natural colonization processes and lead to further land degradation of these vast areas.

Due to the abovementioned, legislation of many countries around the world requires the mined sites to be returned to functional or economically usable state after the mining activities have ceased. This process is often called mine reclamation – making severely degraded land suitable for cultivation (Bradshaw, 1997) or some human use (Gerwing et al., 2022). The often interchangeable and sometimes confusing „R4“ terms – reclamation, restoration, rehabilitation and remediation have been re-addressed and more clearly defined by Lima et al. (2016) (summarized in Spasić et al. (2021)) and Gerwing et al. (2022), also introducing two more terms – ecological reclamation and ecological restoration.

Soil formation, or pedogenesis, is a natural process which was defined by Jenny (1941) as transformation of parent material into soil. The process undergoes its evolution from the parent material to a mature soil with distinguished diagnostic horizons under the influence of 5 soil forming factors: parent material, time, climate, relief (topography), and biota (living organisms).

Post-mining sites are often considered large-scale laboratories where the process of soil formation can be observed through the comparison of physical, chemical, microbiological and other soil, water and litter properties, because they offer the rare opportunity of seeing and monitoring the soil formation process starting from „point zero“, which is rarely possible in natural conditions (Frouz et al., 2013; Spasić„et al., 2023a; Spasić et al., 2023c; Treschevskaya et al., 2019).

In research performed on post-mining sites, chronosequences are often used. Chronosequence is “a set of sites formed from the same parent material or substrate that differs in the time since they were formed” (Walker et al., 2010). Apart from certain downsides associated with them, like the heterogeneity of parent material and initial conditions (Bartuška & Frouz, 2015), they can be excellent indicators of rates and directions of pedogenic changes, and for testing pedogenesis theories (Huggett, 1998; Spasić et al., n.d.).

Pedological soil development is usually observed through weathering of parent material and 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 accumulation of soil organic matter and nitrogen and re-establishment of nutrient cycling processes, and it can be observed in a matter of decades (Bradshaw, 1997; Spasić et al., 2021).

Excavation of overburden (spoil) material and the process of its deposition in spoil heaps on the Earth's surface exposes it to a completely new set of conditions, such as air and oxygen, daily and seasonal temperature changes, precipitation, water fluctuation etc. It's presumed that because the overburden material of many mining sites is usually already partly weathered, depending on its initial stage (parent rock type, its chemistry and level of weathering) and the climate conditions, transformations of the overburden material can occur, thus leading to a somewhat faster process of soil formation (Huot et al., 2013; Santini & Fey, 2016; Spasić et al., 2021).

Post-reclamation land use can be very versatile, and reclaimed landscapes can be returned to their pre-mining land use type, or converted to various other land use types (forests, agricultural land, wetlands, water bodies, wildlife habitats, conservation, recreational, urban or industrial centres, or waste storages). In the last two decades, due to land degradation, many experts are endorsing ecological restoration and ecological reclamation practices over conversion practices, and are trying to prioritize recovery of natural ecosystems over human needs (Gerwing et al., 2022). One of the best way to achieve this is through revegetation practices (Bradshaw, 1997). Revegetation practices can be divided into active (introduction of plant species through sowing and planting) or passive (spontaneous succession) (Navarro-Ramos et al., 2022). Passive revegetation practices can be very useful due to their much lower cost and providing a more natural ecosystem recovery without human interference, and increasing biodiversity (Navarro-Ramos et al., 2022; Spasić et al., 2021). However, certain extreme soil conditions, lack of organic matter and nutrients, the presence of risk elements or toxic chemical species, accumulation of soluble salts, and seed dispersal issues (availability of seed sources, site isolation, etc.) will slow this process down. Thus, human intervention is often required, especially in the initial phases of vegetation establishment (Bradshaw, 1997; Navarro-Ramos et al., 2022; Vachová et al., 2022). Afforestation is the most common method used for post-mining reclamation (Rawlik et al., 2019), and it was shown that tree plantations can have an ameliorative effect (restoring site conditions and arrival of forest biota) (Rawlik et al., 2018, 2019). Some of the first forest reclamations on anthropogenic spoil heaps in literature sources can be dated back to 1916 around Leipzig, Germany (Kubát, 2010).

Due to the large amounts of topsoil being irreversibly lost during the process of mining, and since topsoil is a very scarce resource (because importing it from somewhere else would degrade that ecosystem), re-creation of topsoil is usually required in order to reach any ecosystem recovery or production potential. This is, as stated earlier, best achieved by re-establishment of vegetation cover. Some treatments that are often used for more successful vegetation establishment on post-mining sites and their effectiveness were assessed by Navarro-Ramos et al. (2022). Most experts agree that natural vegetation of the area should be allowed to develop (Navarro-Ramos et al., 2022; Spasić et al., 2021). Pioneer herb and tree species of the area are important due to their nativeness, seed propagation and regeneration, fast growth, low demands in terms of soil substrate quality, and being able to tolerate sunlight well. In most European conditions, tree species like aspen (*Populus tremula*), silver birch (*Betula pendula*) and various willows (*Salix* sp.) usually come to mind when the word „pioneer“ is mentioned. Colonization strategies of these very species on post-mining sites were recently explained by Reitschmiedová et al. (2022). Species selection for use on post-mining sites depends on many important factors, like planned goals of the revegetation project, specific site conditions and socio-economic reasons (Navarro-Ramos et al., 2022). Organic matter and nutrient input rates through litter are very important for re-creation of topsoil, and positive effects of broadleaved trees like alders (*Alnus* sp.), birches (*Betula* sp.), lindens (*Tilia* sp.), maples (*Acer* sp.), hornbeam (*Carpinus* sp.) and elms (*Ulmus* sp.) have been known (Spasić et al., 2021). Nitrogen fixing species are considered particularly beneficial, due to their high litter input and faster decomposition (Rawlik et al., 2019). Some introduced species can also be used for these purposes (black locust – *Robinia pseudoaccacia*, and northern read oak – *Quercus rubra*, for example), but their status and wide-scale application is often questioned, and in some countries even illegal, due to their potential invasiveness (Chmura, 2020; Májeková et al., 2023; Novotný et al., 2023; Spasić et al., 2021; Spasić et al., 2023a; Stanek et al., 2020; Vítková et al., 2017; Woś et al., 2020).

Although vast research has been performed on both actively and passively revegetated post-mining sites, the rate of soil formation (from a pedological point of view) on post-mining sites still presents somewhat of 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 20th century, after large-scale surface mining started being utilized.

The effect of different tree species on rates of soil formation presents another conundrum. This is mostly because plots of more than just a few often used species are rarely found in a close proximity to each other, which usually leads to a high variability of other soil forming factors.

2. Hypotheses and aims

2.1. Hypotheses

(I) The current literature related to the effect of vegetation on soil formation processes on actively and passively revegetated post-mining sites is sufficient and thorough enough for understanding the mechanisms, problems and trends present at these sites.

(II) Type and rate of soil forming processes is strongly influenced by soil vegetation cover. Broadleaved species have a tendency to speed up these processes more in comparison to coniferous species (given that the soil formation time, parent material, topography and climatic conditions are the same).

(III) Soil forming (pedogenetic) processes start unexpectedly soon at reclaimed sites and they follow the trends corresponding to climatic and site conditions.

2.2. Aims

(I) Comparing the stage of soil development and the indices of soil forming processes among stands with different vegetation, particularly with different tree species;

(II) Assessing the rate and type of soil forming processes in a chronosequence of reclaimed sites (humification and soil organic matter (SOM) accumulation, weathering, soil structure formation and stabilization, braunification, clay formation, podzolization, illimerization); Identification of newly formed soil horizons;

(III) Comparing the rate of soil development between stands of various age and assessing the speed of soil forming processes;

(IV) Assessing the effect of relief (slope) on the process of soil formation on reclaimed post-mining sites of the same age;

(V) Defining the premises for further research based on the knowledge gained through literature sources and research activity;

3. Methodology

3.1. Literature overview and experiment setup

In order to gain deeper knowledge about the process of coal mining and its subsequent restoration, terminology used in practice and research, the processes and problems occurring on post-mining sites, and the current scientific knowledge of post-mining sites restoration, a wide variety of scientific publications related to the topic of reclamation/restoration/rehabilitation/remediation was read and addressed, and summarized into two planned scientific publications (review papers). Some of the main goals were trying to assess the current knowledge on the effect of different tree species used in forest reclamations (especially in Europe), but also the mechanisms and challenges of establishing vegetation on these severely altered landscapes. Current global trends and directions of research performed on post mining sites were also addressed. The knowledge obtained through this literature overview would substantiate hypothesis (I).

The study area is located in Sokolov mining basin, in the north-western part of the Czech Republic. Sokolov basin is the largest brown coal excavation site in the Czech Republic, and one of the biggest in central Europe. Within it, four forest reclamation localities of different ages were isolated for the purpose of this research. Bohemia I is a spoil heap created by spoil material from an old underground coal mining site, that was afforested in 1934 with alders (*Alnus glutinosa*, *Alnus incana*), small-leaved linden (*Tilia cordata*), European ash (*Fraxinus excelsior*), wych elm (*Ulmus glabra*), English oak (*Quercus robur*), sycamore (*Acer pseudoplatanus*) and cherry (*Prunus avium*) (Kubát, 2010). Currently, there is a second generation forest stand growing there, mainly consisting of sycamore, cherry and elm. Second locality is the Antonín forest arboretum, internal spoil heap afforested with 220 different species, ecotypes and phenotypes of trees and shrubs that have gradually been planted on the area of 165 ha, and more than 30 tree species planted there have been introduced species (Vacek et al., 2018), whereas 16% of the area was left to spontaneous succession. All afforestation works have been finished by 1974. Within the forest arboretum, 23 homogenous (10 native broadleaved, 3 native and 9 introduced coniferous species) forest stands have been chosen for this research (*Acer platanoides*, *Acer pseudoplatanus*, *Alnus glutinosa*, *Betula pendula*, *Carpinus betulus*, *Fagus sylvatica*, *Pyrus communis*, *Quercus robur*, *Tilia cordata* 1 & 2, *Ulmus glabra*, *Picea abies*, *Pinus sylvestris*, *Larix decidua*, *Picea mariana*, *Picea omorika*, *Picea pungens*, *Pinus contorta*, *Pinus nigra*, *Pinus ponderosa*, *Pinus strobus*, *Pinus uncinata* subsp. *uliginosa* aka. *Pinus rotundata* and *Pseudotsuga mensiesii*). The third locality is part of Loketská spoil heap, formed after surface mining, afforested by black alder (*Alnus glutinosa*) in 1995. Fourth locality is Lítov spoil heap, created as an external spoil heap of overburden originating from mines Medard, Libík and Boden. Deposition of overburden material was finished in 1997; parts of the spoil heap were turned into agricultural (with topsoil addition) and forestry (without topsoil addition) reclamation sites, and parts of it were turned into water bodies. Afforested segments were afforested mainly by pines (*Pinus sp.*) and alders (*Alnus sp.*), but also spruces (*Picea sp.*), oaks (*Quercus sp.*) and ash (*Fraxinus excelsior*).

The localities are presented on a map in Figure 1. Parent material of all three spoil heaps is consisted primarily of cypress clays, which have been known for their soil improvement properties and alkaline pH (Buryan et al., 2014). Only on certain spoil heaps of the area, like Lítov, acid mine drainage problems and extremely low pH were noted (Bořůvka et al., 1999; Bořůvka & Kozák, 2001).

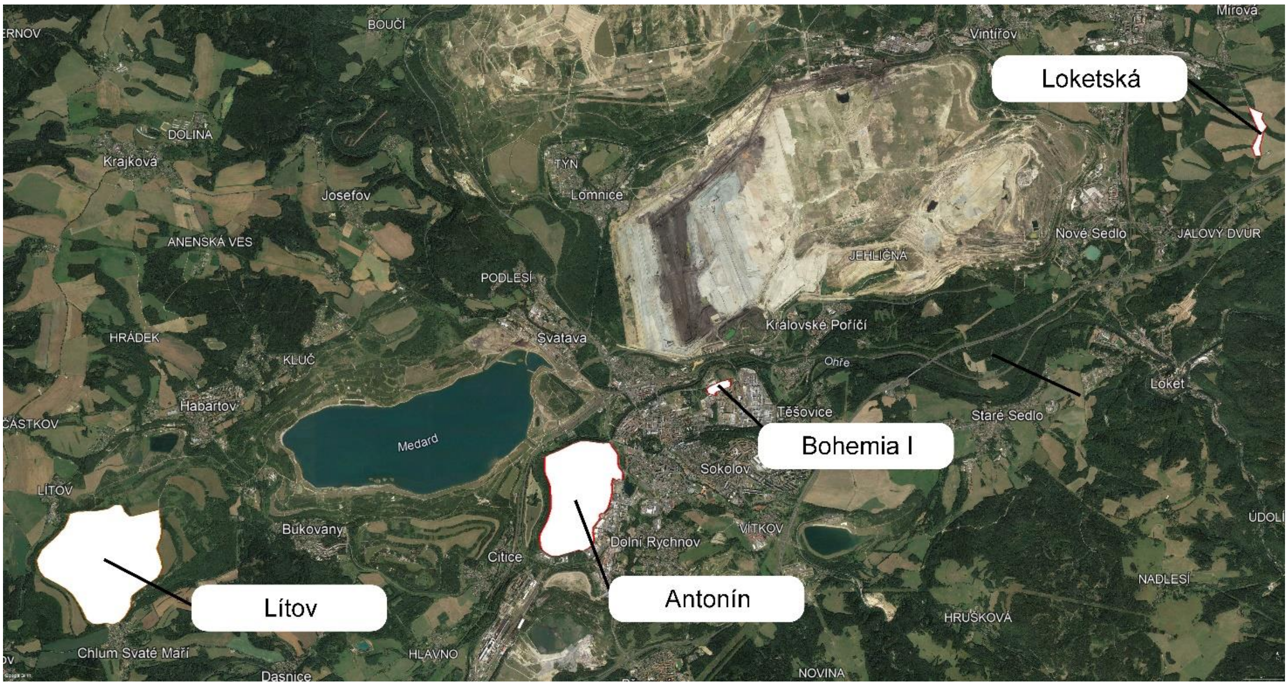

Figure 1 - Study area with sampling locations - Bohemia I, Antonín and a part of Loketská spoil heap (source: Google Earth)

3.2. Chronosequence experiment - 6 soil profiles development (Bohemia I, Antonín, Loketská)

In three of the four mentioned localities (Bohemia I, Antonín, and Loketská), soil profiles have been dug (2 profiles each location, one on flat terrain, one on a slope) and thoroughly described. Within Antonín, a sycamore (*Acer pseudoplatanus*) stand was chosen for this purpose. Undisturbed (5 Kopecký 100 cm^3 cylinders from each horizon) and disturbed samples were taken from all recognized soil horizons. The samples were tested for bulk and particle density, porosity and water holding capacity according to Novák (Spasić et al., 2023b). pH (H_2O and KCl, WTW pH7110 pH meter) was determined using the standards from ÚKZÚZ (2016). Cation exchange capacity (CEC) was measured by inductively coupled plasma optical emission spectrometer (ICP-OES) iCAP 7000 by Thermo Scientific™, USA, following the standards from ICP Forest's Sampling and Analysis of Soil Manual (Cools & De Vos, 2010). Plant available nutrients (Mehlich III extraction method, ICP-OES iCAP 7000, Thermo Scientific™, USA) was determined by the standard 30068.1 from ÚKZÚZ (2016). Oxidizable carbon content (C_{ox}) was determined by modified Tyurin method (wet combustion using potassium dichromate) (Pospíšil, 1964), and quality of organic matter ($A_{400/600}$) was determined according to the standards from Pospíšil (1981). The results of physical and chemical properties of the studied localities could 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 3 broadleaved stands of different age, substantiating hypothesis (III) and aims (II), (III) and (IV).

3.3. Antonín 23 stands experiment – physical and (bio)chemical properties under different tree species

Within Antonín forest arboretum, shallow soil profiles (<50 cm) were dug in the centre of each stand and described. 5 undisturbed soil samples (Kopecký steel cylinders, Eijkelkamp, Ø53 mm, L50 mm, V100 cm^3) were taken from the uppermost 5 cm, encompassing the organo-mineral and mineral layers. Additional, disturbed (carefully sampled, in order not to destroy the aggregates and stored into rigid containers) organo-mineral samples were taken for chemical and aggregate stability analyses. The samples were tested for bulk and particle density, porosity, water retention using the methodology according to Novák (Spasić et al., 2023b). pH ($CaCl_2$, WTW pH7110 pH meter (WTW, Germany) was determined following the standards by Murray (2011), oxidizable carbon content (C_{ox}) was determined by modified Tyurin method (wet combustion using potassium dichromate) (Pospíšil, 1964). Total carbon and nitrogen content were determined using Thermo Scientific Flash 2000 NCS Analyzer. Available nutrients (Mehlich III extraction method, ICP-OES iCAP 7000, Thermo Scientific™, USA). All results from both physical and chemical analyses from Kopecký cylinders have been analyzed by ANOVA (StatSoft, TIBCO) with repeated measurements variance analysis and Post-hoc Tukey HSD test. Due to the large amount of determined soil properties, principal component analysis was also performed. The aim of this part of our study is to directly compare different physical and chemical properties of 50-year old forest reclamation site under 23 homogenous tree stands, located on the same spoil heap, and in close proximity to each other, and observe their differences, assuming that all soil forming factors (parent material, time, climate and relief) except organisms (which are controlled mainly by the vegetation type) are more or less the same between the stands. Hypothesis (II) and aims (I) and (IV) would be encompassed and answered in this part of the research.

Additional samples from Antonín forest arboretum, not included in this doctoral thesis, and planned for further publications not encompassed here, were collected and analysed. Analysis of structural aggregates was performed according to the standards described by Nimmo & Perkins (2018). Distribution of soil structural aggregates was done by dry sieving according to the method described by Iticha & Debele (2017). Fourier-transform infrared spectroscopy (FTIR) analyses were performed on ground soil samples from disturbed A horizon (mixed sample), as well as all the undisturbed samples. FTIR spectroscopy was also performed on humic and fulvic acids isolated from the disturbed A horizon samples according to Piccolo et al. (2002). These analyses are supposed to provide more information about the formation of structural aggregates and their relationship with humic substances and their quality. Frozen soil samples from the organo-mineral horizon of all 23 stands were collected for enzymatic activity (EA) analyses, in 2 periods of the year (summer and winter). Results obtained from these analyses could, together with the results from a small-scale litter decomposition experiment (described later) and findings from the previously explained analyses, give more detailed information for choosing the most suitable tree species for reclamation of post-mining sites. Also within Antonín forest arboretum, 4 stands (sycamore, beech, small-leaved linden and spruce) were selected for a litterbag decomposition experiment. 20 PET litterbags (20x20 cm, mesh sizes 1600 μm on the upper side and 99 μm on the lower side) with 5±0.1g of air-dried litter collected in the autumn of previous year from these very stands were positioned within each stand (Figure 2), making a total of 80 litterbags, and all were collected over 4 periods (1, 3, 6 and 12 months after installation), using a portable freezer, and stored in a laboratory freezer at -80℃. The samples were later freeze-dried, and decomposition rates were calculated. Litter samples were analysed for enzymatic activity (EA) and low molecular mass organic acids (LMMOA) in order to assess their changes throughout the decomposition process, and to compare them between the chosen tree species that are native and relatively frequent in the Czech Republic and central Europe.

Figure 2 - Litter decomposition experiment setup in Tilia cordata stand on Antonín spoil heap

3.4. Temporal changes of soil properties after 20 years on Lítov spoil heap

This part of our study aimed to assess the effect of time and reclamation practices on chemical properties of Lítov spoil heap, by comparing the values obtained from the soil sampling that was performed in 2018 to the values obtained by the sampling from 1998, published in Borůvka et al. (1999) and Borůvka & Kozák (2001). The same sampling method (0-20 cm soil auger) and analyses were used in both sampling periods in order to make the results comparable. Exchangeable soil pH (in 1M KCl solution, 1:2.5 weight to volume ratio), exchangeable acidity (E_a), quality of humic substances ($A_{400/600}$), oxidizable carbon content (Cox), and contents of two aluminium forms (I -labile exchangeable (Al_{lab}), and II - mainly organically bound (Al_{org})) were determined according to Borůvka et al. (1999) and Borůvka & Kozák (2001). The effect of time as a soil forming factor, as well as the success of reclamation techniques used (including afforestation with different tree species) should be assessed. Hypotheses (II) and (III), and aims (I), (II), and (III) should be, partially, further substantiated by this research.

4. Discussion

A vast number of literature sources mentioned in Publications 7.1.1. and 7.1.2, as well as Chapter 1 of this doctoral thesis successfully partially substantiated hypothesis (I), showing that the currently available scientific literature on the subject matter of reclamation/restoration of post-mining sites is a very broad area with many sub-branches and topics of interest, ranging from purely mining and geotechnical engineering related topics, over used terminology debates and problems post-mining sites are known for, to very specific sub-branches of biology, ecology, agriculture and forestry, landscape architecture and civil engineering, and implementations of many new methods and technologies that are constantly being developed.

As presented in Publication 7.1.2., vast amount of research activities related to post-mining coal sites comes from USA, China and India, which are some of the countries with the highest energy demand and countries with some of the highest coal reserves). The results obtained in this publication were, to a significant extent, comparable to the results of Shao et al. (2023), who have done a similar research on a larger temporal scale. Maus et al. (2022) stated that 52% of the globally recognized mining areas is concentrated in only six countries: Russian Federation, China, Australia, USA, Indonesia and Brazil. Interesting fact pointed out in their research was that the number of mines and their surface can vastly differ in these countries, and that China, for example, prioritizes small-scale mining industry, whereas Australia is known for a several times smaller number of mega-mines that cover a similar overall surface. It is worth mentioning that Poland and Czech Republic, which are listed only as 31st and 50th in terms of global surface area affected by mining activities, respectively, have had a very high score in terms of visible publications related to post-mining reclamation research, which highlights this central European region as very important for post-mining sites research, especially when the addressed visible publications are written in English, a language native to the other leading countries, except for China. Similarly, the abundance of research related to post-mining sites can, arguably, also be related to the proportion of mining-affected area to the total country area, as well as the location of the mines and their proximity to human settlements, and other socio-economic factors. Publication 7.1.2. has shown an increasing trend in research dealing with carbon pooling and nutrient cycling, which is, after some consideration, not surprising considering the still relatively young reclamation site ages and biological soil development assessment covered in Chapter 1 of this thesis, combined with a general global trend of trying to sequester as much carbon as possible in land ecosystems.

In Publication 7.1.1., terminology issues already mentioned in Chapter 1, and problems and mechanisms that are common on post-mining sites were discussed. These included general problems of mining and soil destruction also referred to in Chapter 1, and physical, chemical and biological problems mainly responsible for difficulties related to establishment of vegetation, were also addressed. The influence of soil organic matter accumulation (either through amendments, initially, or through vegetation input after the vegetation establishment) was recognized as a very important tool for remediation of most issues related to physical, chemical and biological nature of post-mining landscapes. Effectiveness of various techniques used for establishment of initial vegetation was also investigated by Navarro-Ramos et al. (2022), and in their research, it was shown that the addition of organic amendments and organic fertilizers were some of the most commonly used and proven methods to ensure successful vegetation cover on post-mining sites. They noticed that, when establishing woody vegetation, organic amendments (such as waste compost, manure, peat, cellulose fibres and wood debris) have shown better results compared to inorganic (mineral) fertilizers in terms of woody vegetation survival rates, and that both inorganic fertilizers and organic amendments have shown a positive effect on the growth of woody species. According to Dožić & Lujić (2005), trying to speed up the recultivation process by simple addition of large amounts of mineral fertilizers or watering has not, historically, shown very good results. Woody vegetation is usually planted, because sowing woody species has been documented to result in low establishment rates on severely degraded areas (Macdonald et al., 2015; Muñoz-Cerro et al., 2023; Navarro-Ramos et al., 2022). In order to achieve favourable site conditions, use of nurse plants (both herbaceous and woody) has also been reported (Filazzola & Lortie, 2014; Navarro-Cano et al., 2018; Padilla & Pugnaire, 2006; Smolen et al., 1988; Vítková et al., 2017; Zedler & Lindig-Cisneros, 2013). Alder trees (*Alnus* sp.) were often used in European region on post-mining sites (sand extraction, oil shales and sand mining, lignite mining, lignite combustion wastes) (Chodak et al., 2019; Dožić & Lujić, 2005) for this purpose. This use can also be clearly seen in the presentation of localities in Chapter 3 of this thesis (where all four mentioned localities were, at some point, planted with alders). As mentioned by Chodak et al. (2019), alders usually die out in post-industrial ecosystems, but are often introduced with the target species to improve soil properties and growth of the target species. Pietrzykowski et al. (2018) and Chodak et al. (2019) concluded that, although all 3 commonly used alder species have proven to be useful on post-mining sites, the effectiveness of black alder (*A. glutinosa*) was somewhat greater than gray (*A. incana*) and green alder (*A. viridis*).

Publication 7.1.1. also addressed certain problems of pedological approach to post-mining sites, partially explained in Chapter 1. Some of the highlights included the rate of weathering of parent material, the age of the reclaimed plots, and the lack of addressing soil formation process through the formation of diagnostic horizons. A likely model of profile differentiation and potential future soil types was given for a specific set of conditions related to the climate and parent material. The issue of afforestation usually combined with technical reclamation practices (also known as active revegetation) versus allowing natural flora (passive revegetation) and fauna of the area to colonize the affected landscape was also discussed. Although ecological restoration under natural succession processes has been proven beneficial for preservation of biodiversity, as well as for its lower cost, the effect of reclamation process through afforestation cannot be diminished. From an aesthetical standpoint, as well as from the point of biomass production (which also directly refers to litter and biomass inputs and higher soil formation rates), afforestation usually gives very satisfying results. According to Sklenička & Kašparová (2008), consultations with a well-informed local community and their input, as well as creating a broader consensus on the needed changes are vital for an effective solution to the problem of restoration of visual values in post-mining landscapes. Kohlová et al. (2021a; 2021b) have investigated the attractiveness of post-mining forests for recreational purposes and stated that most questioned people preferred planted coniferous (pine) forests to successional or planted alder forests, but that all of them were not able to compare to commercial spruce timber forests. They highlighted the important effect of forest stand age, as well as silvicultural stewardship practices (the more, the better) on the perceived attractiveness of these sites. It was also noted that creation of terrains with heterogeneous relief (crests and valleys) was not perceived as attractive, especially in the early stages, although they have been known to facilitate greater biodiversity, and that their attractiveness becomes greater with time. Vacek et al. (2018) have shown that afforested stands at Antonín spoil heap have shown higher stand volumes and quality production than the stands that were left to spontaneous succession, but they had lower biodiversity levels. Vachová et al. (2022) have found that alders (*Alnus* sp.), long-life deciduous (*Tilia* sp. and *Quercus* sp.), and larch (*Larix decidua*) stands were the monocultures that were more suitable for afforestation of Velká Podkrušnohorská spoil heap in Sokolov, than pines (*Pinus* sp.) or spruces (*Picea* sp.)

In Publications 7.1.3. and 7.1.4., the effect of different afforested tree species (broadleaved and coniferous) on soil's physical and chemical properties, as well as a comparison of production potential, biodiversity, and soil properties of various coniferous (both native and introduced) species growing on Antonín forest arboretum in Sokolov were presented. Publication 7.1.4. compared multiple factors and suitability of certain tree species for afforestation of post-mining sites of Sokolov region (through biomass production, wood quality parameters, stand diversity, biodiversity, stand health status, soil properties, etc…). In publication 7.1.3, soils under different tree species (both broadleaved and coniferous) were observed from a purely pedological point of view (horizon development and soil properties that are generally considered beneficial), overlapping with the title of this doctoral thesis. The obtained results from these two publications have shown that some quite contrasting findings would have been reported (for the conifers included in both papers) if only one approach was taken. Publication 7.1.4. has shown that Scots and black pine (*Pinus sylvestris*, *Pinus nigra*), Douglas-fir (*Pseudotsuga menziesii*) and European larch (*Larix decidua*) were the most suitable coniferous species growing at the locality. On the contrary, Weymouth pine (*Pinus strobus*), Ponderosa pine (*Pinus ponderosa*), mountain pine (*Pinus rotundata*), Norway spruce (*Picea abies*) and blue spruce (*Picea pungens*) have not shown adequate suitability due to their sensitivity to drought and pathogens, and some of them are slowly dying out in this locality. Some of these, less suitable species, have shown better overall soil properties in publication 7.1.3, than the ones mentioned as suitable in publication 7.1.4. (*Picea pungens* compared to *Pinus sylvestris* or *Larix decidua*, for example). These differences have shown that the choice of species for post-mining afforestation should be approached with care, and that observing it from a sole perspective (only soil properties or development) can lead to flaws, and that's the reason these two publications complement each other. Publication 7.1.3. has confirmed hypothesis (II) to a great extent, since there was almost a clear distinction in organo-mineral horizon depth development between the coniferous and the broadleaved species. Most conifers (apart from *Pinus nigra* and *Picea pungens*) have formed A horizon 3 cm or thinner, whereas all broadleaves (except *Betula pendula* and *Carpinus betulus*) have formed A horizon thicker than 3 cm (with *Alnus glutinosa* and *Fagus sylvatica* forming a record 6 cm). Good properties of black alder (*Alnus glutinosa*) were highlighted once again. Horizion thickness results were in accordance with the results obtained by Vachová et al. (2022), who've also found the greatest A horizon development under alders, oaks and linden on Velká Podkrušnohorská spoil heap in Sokolov. Presumed effect of slope on soil forming potential was addressed through 2 linden (*Tilia cordata*) stands, but still requires further looking into. As seen from multiple literature sources cited in this doctoral thesis, as well as review and research articles included in it, choosing the suitable tree species for post-mining land use is a complicated matter that depends on many factors. If restoration of soil is the primary concern, using alders in combination with long-lasting target species such as lindens, beech, and maples would mostly prove to be the right choice. Although, in most cases, it achieves the formed soil horizon depth (and stand growth) more slowly, spontaneous succession can often prove to be both a rather inexpensive, and from the biodiversity standpoint - the best option (Spasić et al., 2021; Vacek et al., 2018; Vachová et al., 2022). Directed (or managed) succession is also a very suitable alternative, especially on sites which cover larger areas, and where propagation of the surrounding colonizing species can be an issue. On the other hand, some rarely used introduced coniferous species which have shown good soil and growth parameters, like *Pinus nigra*, *Pseudotsuga menziesii* or *Picea omorika*, could show great potential for afforestation of post-mining sites of central European region, provided that they are properly cared for in forestry management practices. Black pine (*Pinus nigra*) is a known and extensively used tree species for afforestation of difficult terrains in the Balkans, and its native area is not too far from the Czech Republic. Serbian spruce (*Picea omorika*) is an endemic relict species of spruce whose areal got significantly reduced to small parts of west and southwest Serbia and east Bosnia and Herzegovina, and is considered endangered according to IUCN. In recent years it is facing dieback due to droughts (presumably because of extreme weather events), and is likely to face difficulties in adapting to climate change in its natural areal (Rivers, 2019). On the other hand, its growth parameters on Antonín spoil heap presented in publication 7.1.4. have shown that it's one of the best growing species there, and one of the best in its resistance to climate extremes. Furthermore, according to a recent research from Antonín forest arboretum by Zeidler et al. (2024), the wood quality of Serbian spruce growing there surpassed that of Norway spruce (*Picea abies*), and was far more superior to the two American spruce species tested (*Picea mariana*, *Picea pungens*). They've pointed out that it showed great potential for use in forest management and being a suitable replacement for Norway spruce (to whom it is taxonomically very close), which is massively dying out in the Czech Republic and central Europe due to droughts and bark beetle outbreaks. All of the above, combined with the mentioned difficulties in its native area, suggests that it should be strongly considered as a potential afforestation species of post-mining sites in the Czech Republic and, by doing this, a contribution to its potential saving from extinction can be made.

Publication 7.1.5. addressed soil formation rates and soil physical and chemical properties on three differently aged forest reclamation sites with broadleaved vegetation. Within it, hypothesis (III) was proven to a great extent, showing that development of soil horizons can occur in relatively short intervals, contrary to some common beliefs, and even surpass average horizon thicknesses of similar, non-disturbed soils belonging to the same soil type. With increasing reclamation age, the observed soil profiles have shown greater horizon thickness, and distinctively clearer horizon boundaries. Even if not improved by directly comparing them to each other across the stands, broader ranges in soil properties were found with increasing age, further indicating horizon differentiation and development, substantiating aims (II) and (III) of this thesis. Important effects of organic matter accumulation and mineralization on soil quality improvement have been pointed out. The effect of slope (aim IV) has proven to be noticeable and that soil formation and horizon development is generally quicker in flat terrains (as hypothesized in publication 7.1.5.). However, some site related conditions like heterogeneity of the parent material (mainly influenced by pH), slope steepness differences across the sites, and the lack of significant differences noticed in horizon depths and soil properties, have led to the inability of substantiating this statement with certainty. Having mentioned this, and combining it with the results obtained in publication 7.1.3, aim (IV) needs further investigation, although the presumed differences were also more visible with increasing site age. Apart from the presumed processes more likely to occur on sloped terrain (surface runoff, internal erosion processes, etc.), slope exposure can also lead to significant changes. Rawlik et al. (2019) have observed faster litter decomposition rates on northern slopes of a reclaimed spoil heap in Góra Kamieńska (Bełchatów, Poland), so that is an another variable that needs to be taken into consideration when assessing the effect of slope.

Publication 7.1.6. presented the changes on Lítov spoil heap over a time period of 20 years after reclamation. Although the conditions of this spoil heap are some of the most severe in this region, a noticeable improvement of some chemical soil propterties, mainly average pH increase, carbon accumulation and quality of humic substances were found. These changes were particularly evident under broadleaved vegetation, and in the areas where topsoil application was performed. This research partially supported hypotheses (II) and (III), as well as aims (I), (II) and (III) of this thesis.

Further analyses of the results from the experiments explained in Chapter 3 of this thesis, but not included in the list of published works (litter decomposition, stability of structural aggregates, enzymatic activity, low molecular mass organic acids, etc.) are planned, and the information gained would help to futher deepen the obtained knowledge of the effect of mentioned soil forming factors on soil formation and quality on reclaimed mine soils.

5. Conclusions

Through the work on the 6 papers presented in this doctoral thesis, significant knowledge of the processes occurring on post-mining sites was gained. Trends of research occurring on these sites were more clearly understood, as well as the mechanisms of the main causes of problems that are related to reclamation/restoration process, vegetation establishment on these sites, and mining in general.

The presumptions stated in the three hypotheses of this thesis were largely confirmed, and partial aims of the thesis were fulfilled to a significant extent.

The available literature dealing with research on post-mining sites (mainly focused on sites after coal mining) is very broad, and covers a multitude of different topics related to the matter. Accumulation of organic matter and cycling of nutrients was proven to be one of the essential parts of many research activities lately.

The effect of time on soil formation process on reclamation sites was assessed based on a chronosequence experiment performed on three variously aged forest reclamation plots from Sokolov mining region, Czech Republic. All of the tested soils have exhibited the presumed profile evolution from a mine Technosol to a forest Cambisol. When other soil forming factors are the same (or similar enough), the effect of time on the formation and differentiation of soil horizons was clearly visible. The effect of time was also assessed through the comparison of the changes in chemical properties of soil samples collected in 1998 and 2018 at Lítov spoil heap. Accumulation of organic matter played a very important role in changing the soil properties in both experiments.

Assessment of the influence of various tree species was performed on 23 monocultures growing in Antonín forest arboretum near Sokolov in the Czech Republic. From the standpoint of soil formation and soil quality, black alder (*Alnus glutinosa*) has once again shown a strong ameliorative effect recognized in many previous studies. Long-lasting native broadleaved species such as beech (*Fagus sylvatica*), linden (*Tilia cordata*), maples (*Acer pseudoplatanus*, *Acer platanoides*) and pear (*Pyrus communis*) are also recommended. Certain coniferous species, although not as good from a purely pedological point of view, but overall, have proven to be suitable species for afforestation of post-mining sites of Sokolov region – mainly native species like Scots pine (*Pinus sylvestris*) and European larch (*Larix decidua*), but also introduced species like black pine (*Pinus nigra*), Douglas-fir (*Pseudotsuga menziesii*), and Serbian spruce (*Picea omorika*).

The presumed effect of relief on soil formation on reclaimed mine sites was noticed and addressed, but further, more comprehensive research on the subject is recommended. Some of the plans for further research were mentioned in Chapter 3 of this doctoral thesis.

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7. List of published works

7.1. Published works included in the doctoral thesis

The list of works presented in this sub-chapter represents publications (including unpublished, but submitted manuscripts that are under revision) used for the doctoral thesis, listed in logical order that reflects the order of hypotheses and aims specified in Chapter 2, and referred to in Chapter 3.

7.1.1. Pedogenesis problems on reclaimed coal mining sites

Spasić, M., Borůvka, L., Vacek, O., Drábek, O., & Tejnecký, V. (2021). Pedogenesis problems on reclaimed coal mining sites. *Soil and Water Research*, 16(3), 137–150. https://doi.org/10.17221/163/2020-SWR

7.1.2. Trends of global scientific research on reclaimed coal mine sites between 2015 and 2020

Spasić, M., Drábek, O., Borůvka, L., & Tejnecký, V. (2023). Trends of Global Scientific Research on Reclaimed Coal Mine Sites between 2015 and 2020. *Applied Sciences*, 13(14), 8412. https://doi.org/10.3390/app13148412

7.1.3. Which trees form the best soil? Reclaimed mine soil properties under 22 tree species: 50 years later—assessment of physical and chemical properties

Spasić, M., Vacek, O., Vejvodová, K., Tejnecký, V., Vokurková, P., Křižová, P., Polák, F., Vašát, R., Borůvka, L., & Drábek, O. (2023). Which trees form the best soil? Reclaimed mine soil properties under 22 tree species: 50 years later—assessment of physical and chemical properties. *European Journal of Forest Research*. https://doi.org/10.1007/s10342-023-01637-x

7.1.4. Production potential, biodiversity and soil properties of forest reclamations: Opportunities or risk of introduced coniferous tree species under climate change?

Vacek, Z., Cukor, J., Vacek, S., Linda, R., Prokůpková, A., Podrázský, V., Gallo, J., Vacek, O., Šimůnek, V., Drábek, O., Hájek, V., Spasić, M., & Brichta, J. (2021). Production potential, biodiversity and soil properties of forest reclamations: Opportunities or risk of introduced coniferous tree species under climate change? *European Journal of Forest Research* 140, 1243–1266 (2021). https://doi.org/10.1007/s10342-021-01392-x

7.1.5. Profile development and soil properties of 3 forest reclamation chronosequences in Sokolov mining basin, Czech Republic

Spasić, M., Vacek, O., Vejvodová, K., Borůvka, L., Tejnecký, V., & Drábek, O. (n.d.). Profile development and soil properties of 3 forest reclamation chronosequences in Sokolov mining basin, Czech Republic. *(Submitted for review in Forests)*.

7.1.6. Temporal changes of soil characteristics on Lítov spoil heap, Czech Republic

Enkhtaivan, E., Vacek, O., Vokurková, P., Spasić, M., Vašát, R., & Drábek, O. (n.d.). Temporal changes of soil characteristics on Lítov spoil heap, Czech Republic. *(Submitted for review in Soil and Water Research)*.

7.1.1. Pedogenesis problems on reclaimed coal mining sites

Spasić, M., Borůvka, L., Vacek, O., Drábek, O., & Tejnecký, V. (2021). Pedogenesis problems on reclaimed coal mining sites. *Soil and Water Research,* 16(3), 137–150. https://doi.org/10.17221/163/2020-SWR

Pedogenesis problems on reclaimed coal mining sites

Marko Spasić [1]*, *Luboš Borůvka* [1], *Oldřich Vacek* [1,2], *Ondřej Drábek* [1], *Václav Tejnecký* [1]

[1]*Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic*
[2]*Department of Landscape Architecture, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic*

**Corresponding author: spasic@af.czu.cz*

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Abstract: Open-cast coal mining presents a big global issue because of the large areas the mines occupy, which get entirely changed. Their ecosystems lose most of their functions, and a huge amount of fertile soil gets utterly destroyed. Reclamation is a process of returning the functions of the soil after the excavation is finished, most commonly achieved by establishing vegetation, which can sometimes be very difficult. This happens due to the physical, chemical and biological changes that occur on these sites, which are described in this paper. Also, some directions for mitigating these problems are given. Once the vegetation is successfully introduced, natural cycles that were compromised by the mining are established once again, and the process of soil formation begins. Some trends and problems related to pedogenesis research on reclaimed mine sites are presented and discussed, along with presumptions of how the process of soil formation evolves on afforested clayey Technosols of central Europe. The potential future research which would confirm these presumptions is discussed, with the emphasis on the need of research performed on older reclamation sites, as well as sites with similar ecological conditions and different tree species cover.

Keywords: biodiversity; coal; mining; natural succession; pedogenesis; reclamation

Open-cast coal mining is a process in which a huge amount of fertile soil is lost, and which causes a massive disturbance or, sometimes, the complete destruction of ecosystems. During this exploitation, a large amount of spoil material is excavated and deposited in vast spoil heaps (Helingerová et al. 2010; Kuter 2013). One of the most crucial environmental impacts of these activities is the uttermost soil destruction (Kuter 2013). Since soil was proclaimed a non-renewable resource (FAO 2015), the more drastic this problem is. Erosion, nutrient losses, microbial ecosystem disturbances, habitat destruction, potentially hazardous substances (chemical and biological), and various threats to human health (contamination of air, water and food) are just some of the negative effects that coal mining comprises (Kuter 2013). Since this process usually encompasses large areas, significant changes in the climatic and hydrological regimes of the area occur (Brom et al. 2012).

When the coal extraction is over, the area that was affected has to be reclaimed (or restored) in order to relieve the damaging effects of the process (Kuter

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2013), although reclamation methods can vary due to various reasons and trends. Bradshaw (1997) explained the differences between three terms often used in science and practice: reclamation, rehabilitation and restoration, where the first two can be considered less strict than the last one, which stands for returning the soil to its initial, pre-mining conditions. Remediation is yet another term often used in practice, and more recent definitions of all of these terms, sometimes referred to as the R4, as well as the issues associated with them, were described in a publication by Lima et al. (2016). A short explanation of these terms is given in Table 1.

Post reclamation land use can vary from returning the soil to its initial purpose, to the conversion of these surfaces to various other land uses such as forests, agricultural objects, wetlands, hydrological objects, fishing ponds, special reserves, wildlife habitats and conservation areas, recreational, urban or industrial centres, or waste storages (Kuter 2013). However, the two most commonly used post-mining techniques are technical reclamation and spontaneous succession, whereas directed succession, which can be considered an intermediary solution between the two mentioned, is still rarely used (Tropek et al. 2012). The term technical reclamation usually refers to stabilising and levelling the mining affected area by heavy machinery and the creation of large, homogenous surfaces, which are then covered by organic material on which vegetation (planted or sown) is established (Řehounková et al. 2011). The majority of the technically reclaimed mine spoils are converted to either forests or agricultural land. An example of the evolution of forest and agricultural reclamation is presented in Figure 1.

During the second half of the 20th century, the emphasis of reclamation was put on soil productivity and achieving a "steady state" as fast as possible (Doll et al. 1984; Bradshaw 1997; Ussiri et al. 2014), most often by the means of technical reclamation comprised of using heavy machinery and seeding or afforestation. Depending on the severity of the conditions, reclamation strategies and availability of material, topsoil replacement can be undertaken or not, as well as nutrient addition. Although technical reclamation practices are often implemented in the legislations of many countries (McCormack 1984; Wali 1999; Bell 2001; Bradshaw & Hüttl 2001; Tropek et al. 2012; Kuter 2013), the results of such legislation can be considered both a good and a bad thing due to many reasons. Nowadays, the trends are more in favour of spontaneous and directed succession and biodiversity preservation (Brenner et al. 1984; Wiegleb & Felinks 2001; Hodačová & Prach 2003; Frouz & Nováková 2005; Mohr et al. 2005; Šourková et al. 2005a; Frouz et al. 2007b; Hendrychová 2008; Helingerová et al. 2010; Řehounková et al. 2011; Brom et al. 2012; Tropek et al. 2012; Chuman 2015). Many, both successful and unsuccessful mine reclamations, have been described all over the world (Bradshaw & Hüttl 2001), including USA (Brenner 1979; Zellmer & Wilkey 1979; Brenner et al. 1984; Mummey et al. 2002a, b; Lorenz & Lal 2007; Anderson et al. 2008; Shrestha & Lal 2008; Lanham et al. 2015), Australia (Bell 2001), India (Chaulya et al. 2000; Dutta & Agrawal 2003; Ghose & Majee 2007; Maiti 2007; Sinha et al. 2009; Ahirwal et al. 2018; Bandyopadhyay et al. 2018; Jambhulkar & Kumar 2019; Raj 2019), China (Kim et al. 2018; Tang et al. 2018), Brazil (Dick et al. 2006), Colombia (Domínguez-Haydar et al. 2018), Russia (Naprasnikova 2008; Bragina et al. 2014; Zharikova & Kostenkov 2014) and throughout Europe (Filcheva et al. 2000; Haigh & Gentcheva-Kostadinova 2002; Vega et al. 2004; Rincón et al. 2006; Pająk & Krza-

Table 1. The "R4" terms and their brief explanation based on the definitions given by Lima et al. (2016)

Term	Explanation
Restoration	Bringing back the pre-existing ecosystem and its functions (sometimes impossible).
Reclamation	Less strict than restoration, the final goal being a replacement ecosystem. Usually achieved by the geotechnical stabilisation of the land via a series of integrated operations, with a final step where repopulation occurs with the original species or other related ones.
Rehabilitation	A managerial wide term that measures the costs and benefits of maintaining the environmental quality and optimising the local land management capacity. It includes practices such as agriculture, forestry, urbanisation, etc.
Remediation	Contamination control – A physical, chemical or biological action to remove contaminants with the goals to reduce and manage the risks to human beings posed by contaminated sites.

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klewski 2007; Pietrzykowski & Krzaklewski 2007; Moreno-de las Heras 2009; Moreno-de las Heras et al. 2009; Chodak & Niklińska 2010; Alday et al. 2011; Ličina et al. 2017; Kalabić et al. 2019; Hamidović et al. 2020), but the most comprehensive research that has come from the European region is mainly from the Lusatian mining district in Germany (Rumpel et al. 1998, 1999, 2000; Schaaf et al. 1999; Waschkies & Hüttl 1999; Vetterlein et al. 1999; Zier et al. 1999; Schaaf 2001, 2003; Wanner & Dunger 2001; Wiegleb & Felinks 2001; Wilden et al. 2001; Schaaf & Hüttl 2006) and the Sokolov mining district in the Czech Republic (Kříbek et al. 1998; Frouz et al. 2001, 2007a, b, 2013; Frouz & Nováková 2005; Šourková et al. 2005a, b; Baldrian et al. 2008; Helingerová et al. 2010; Řehounková et al. 2011; Bodlák et al. 2012; Brom et al. 2012; Heděnec et al. 2017). In more recent years, an increasing number of publications related

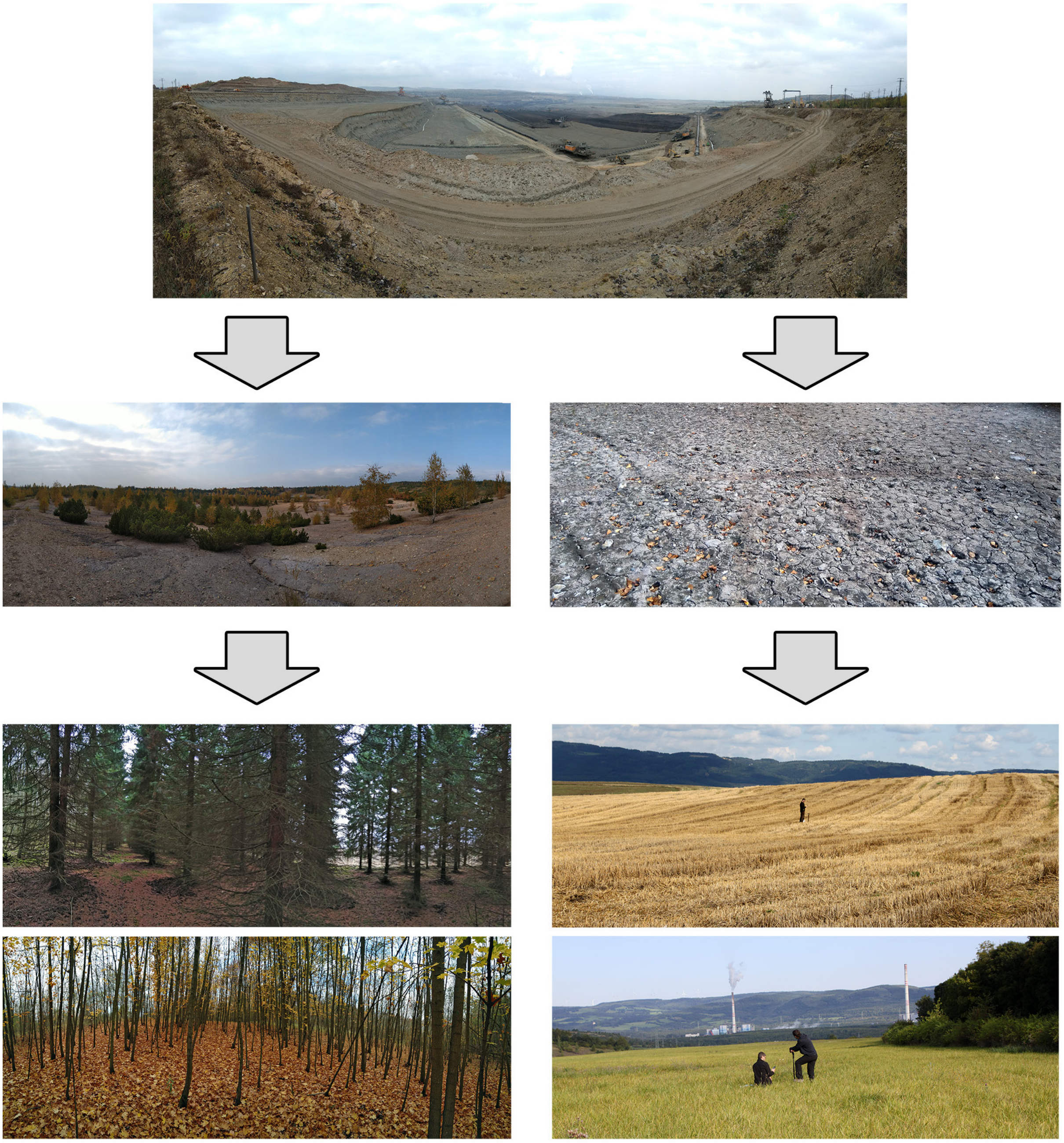

Figure 1. Evolution of forest (left) and agriculturally (right) reclaimed landscapes in the Czech Republic (source: authors, courtesy of J. Kozák)

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to reclamation sites have originated from China and, even more so, India.

When discussing the process of pedogenesis on coal mine Technosols, the five soil forming factors described by Jenny (1941), climate, organisms, parent material, relief and time still apply (Huot et al. 2013). As stated by Sixta in Bodlák et al. (2012), pedogenesis in dump areas is determined by three crucial factors: parent rock type, site conditions and land use type (agricultural, forestry use, or natural succession). Due to the extreme geochemical, mineralogical, and physical properties of the spoil materials which weather much more rapidly than natural ones, it is presumed that the process of soil formation can be observed in much shorter time periods of about 100 years (Santini & Fey 2016), where, depending on the reclamation method used, the A horizon can develop after only 20 years (Huot et al. 2013; Santini & Fey 2016), and after 40 years, the formation of secondary minerals has been observed (Hüttl & Weber 2001; Uzarowicz & Skiba 2011; Santini & Fey 2016). The undisputable and most obvious process in evolving reclaimed Technosols is the accumulation of pedogenic organic matter in the upper layers, whereas others, like mineral transformations, aggregation, decarbonation and migrations have been observed and studied (Huot et al. 2013), but could not have been well described due to the extremes related to site-specific conditions and the speed of the formation process which differs from the one in natural soils. Thus, our understanding of the vegetation type, composition and recovery time on the restoration of the biotic and abiotic soil properties, as well as our knowledge of the processes that occur during the evolution of Technosols remains incomplete (Huot et al. 2013; Echevarria & Morel 2015; Kim et al. 2018). Because no natural sites are similar to these, determination of the evolution of soils on reclaimed sites is a difficult task (Gast et al. 2001).

Although a century is a very short time from a pedological point of view, the problem is that reclaimed sites older than this can rarely be found and observed, with the majority of the surfaces being reclaimed after World War II (Bradshaw & Hüttl 2001). According to Hüttl and Weber (2001), you cannot really know whether a rehabilitation method is successful if the period over which it was undertaken is shorter than a general rotation period of a forest stand (approximately 40 years). Having this in mind, the possibilities of researching the soil formation process on reclaimed mine sites are becoming less and less limited as time passes.

Most of the research undertaken so far on reclaimed mine sites did not particularly address the pedogenesis through the formation of soil horizons, but rather described the changes and trends of the soils' physical, chemical and biological characteristics of the uppermost layer in the initial and later stages. As stated by Sheoran et al. (2010), reclamation strategies must address the soil structure, soil fertility, microbe populations, topsoil management and nutrient cycling in order to return the land as closely as possible to its pristine condition and for it to continue as a self-sustaining ecosystem. The more information about the characteristics of the soil is given during the research, the better. The aim of this paper is to present soil problems on reclaimed mine sites observed through the mentioned characteristics, as well as some significant outlines from the studies undertaken so far. However, describing these problems individually is a hard task due to the influence that these characteristics have on each other (for example, the relationships between the soil organic matter and compaction, water retention, the relationships of nutrients and texture to potentially toxic elements (PTE), vegetation and nutrients etc.), and thus, a comprehensive approach is needed.

Problems of physical and hydrological nature

Three of the greatest physical problems that occur on post mining sites are related to water retention, erosion (caused by both wind and water) and over-compaction. According to Ussiri et al. (2014), the major purpose of the reclamation process is to establish a stable landscape that is less prone to erosion and could support an adequate vegetation cover. Technical reclamation practices usually significantly reduce the effect of landslides and erosion (Hüttl & Gerwin 2005; Hendrychová 2008), but cause excessive compaction. Compaction is the increase in the bulk density of the soil which results from loads applied for short periods (Marshall et al. 1996; Paradelo & Barral 2013) and is one of the main processes of soil physical degradation (Lal 2001; Paradelo & Barral 2013). Erosion and compaction are usually opposing terms, because, in engineering practice, soil stability to erosion and landslides is usually achieved by compaction, which is, on the other hand, devastating for the soils' water holding properties and vegetation establishment. Depending on the initial spoil material and its textural composition which can often have a very wide range (from sands to clays), other

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physical phenomena, usually related to accessibility of water, occur. High infiltration rates in sandy soils, and water logging, insufficient aeration and plant inaccessible water due to the over-compaction of clays (Kaufmann et al. 2009) present some of them. Sometimes, irrigation and drainage systems are used. Increased runoff and erosion risks and high resistance to penetration due to compaction have serious negative effects on plant germination and root development (Boels & Havinga 1982; Lipiec & Hatano 2003; Paradelo & Barral 2013), also causing an unfavourable, horizontal root growth (Barry Phelps & Holland 1987). Due to these physical limitations, the aforementioned primary goal of establishing vegetation on coal mine spoils can be a very difficult task.

During the excavation and post mining operations, the loss of the soil structure and soil organic matter (SOM) is inevitable, and the former levels are very hard to achieve. The soil structure, compaction decrease and water-holding abilities of the soil significantly improve with the presence and increasing amounts of SOM content (Lavelle & Spain 2001; Frouz et al. 2007a), which is usually lost during the excavation process. The research performed by Free et al. (Free et al. 1947; Barry Phelps & Holland 1987) and Paradelo and Barral (2013) have shown that the soil is much less susceptible to compaction with an increase in the SOM content, and that these changes are greater in coarse-textured (sandy) Technosols. The accumulation of the SOM helps in reducing the negative effects of erosion processes, by cushioning the effect of raindrops (Jenny 1980; Vetterlein & Hüttl 1999), and by increasing the water retention, thus reducing the effects of the aeolian process. The increase in the SOM is also positively related to the soil aggregation process, which then correlates to better retention capacities (Wu et al. 1990; Shrestha & Lal 2008; Moreno-de las Heras 2009). As stated by Sarah (Sarah 2005; Moreno-de las Heras 2009) soil aggregation can provide important information about the soil quality. Valla et al. (2000) mentioned that the state of the soil structure influences, directly or indirectly, all the soil properties, and that the structural stability depends on the texture, SOM, vegetation and soil microorganisms, with cations and sesquioxides also being of importance. The soil texture and aggregation also control the degree of the nutrient availability to the soil, its retention and cation exchange capacity (CEC), as well as the oxygen diffusion (Lindemann et al. 1984; Sexstone et al. 1985; Bendfeldt et al. 2001; Wang et al. 2001; Moreno-de las Heras 2009; Sheoran et al. 2010). Water repellency, an issue common on coal mine sites, is also worth mentioning, and was described by Gerke et al. (2001). Since the SOM content, aggregation and water retention are inter-related to such a great extent, from a physical point of view, they might as well be observed as one. Many authors have dealt with the issues that these problems cause, and have implemented them in their research.

Problems of chemical nature

Due to physical disturbances caused by the mining process combined with the geochemical properties of the mother substrate, chemical changes also occur, and can be observed as the loss of nutrients and their cycling, as drastic pH changes, and the presence of potentially toxic elements.

Under conditions of devegetation, and due to the rapid decomposition, there is a high potential for a net loss in the soil nutrients (Vitousek & Reiners 1975; Barry Phelps & Holland 1987; Banning et al. 2008). As stated by Ghose (2001), the soil quality will continually deteriorate every year afterwards due to the loss of nutrients by leaching. Mined soils can be very rich in some elements, while poor in others (Bradshaw 1997). Nitrogen, phosphorus and potassium are generally found to be deficient in overburden dumps (Coppin & Bradshaw 1982; Sheoran et al. 2008, 2010). If conditions on the site are very severe, and there is a high chance of nutrient deficiency on coal mining sites, sometimes additional nutrients (fertilisers) have to be added in order to successfully establish vegetation (Bradshaw 1997; Hartmann et al. 1999; Sheoran et al. 2010; Ussiri et al. 2014), usually in the form of synthetic fertilisers, compost or sewage sludge, the latter two being more preferable. Several authors (Hartmann et al. 1999; Wilden et al. 1999, 2001) have investigated this matter. Hartmann et al. (1999) discovered that rock powdered N fertilisers have shown better results than water-soluble ones because there is less leaching, and also emphasised the significance of fertilisation for vegetation establishment in nutrient poor Lusatian mine sites in Germany. When recirculated through plants, the nutrients (especially P and K) get to a much more available form for microbes to use them (Bradshaw 1997). Once vegetation is successfully established, organic matter formation and litter decomposition through sufficient biological activity is provided, the

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nutrient cycling can be restored. Studies have shown that different vegetation species affect the nutrient inputs through litter differently, and that deciduous species are more preferable than coniferous ones, pointing out the positive effects of species such as the alder (*Alnus glutinosa*), birch (*Betula pendula*) and linden (*Tilia cordata*) (Bradshaw 1997; Filcheva et al. 2000; Keplin & Hüttl 2001; Šourková et al. 2005a, b; Remeš & Šíša 2007; Řehounková et al. 2011; Frouz et al. 2013). Maples (*Acer* sp.), the hornbeam (*Carpinus betulus*) and elms (*Ulmus* sp.) are also mentioned in this context (Hendrychová 2008). Alder trees have also been reported to change the quality of the humic substances of the SOM (Borůvka & Kozák 2001a). In the Czech Republic, Spasić et al. (2020) have investigated the influence of a large number of different tree species on the physical and chemical properties of mine reclaimed soil, where certain broadleaf species such as maples, the elm, the linden and the pear have proven to change the substrate properties to what is generally considered favourable. Out of the broadleaved species they have investigated, the hornbeam was considered the least favourable. Conifers that have shown significantly unfavourable conditions were the Scots pine and Weymouth pine; some of these findings are presented in Table 2.

Ghosh et al. (1983) stated that organic carbon levels above 0.75% indicate good fertility. Ussiri et al. (2014) and Rumpel et al. (1999) have dealt with the problem and methods of distinguishing between geogenic and plant derived carbon. In the studies performed by Hüttl and Weber (2001) and Fettweis et al. (2005) in Lusatia, Germany, it was concluded that although much of the carbon content on reclaimed lignite mine sites is of geogenic origin, and not recent carbon, it can compensate for the lack of SOM as storage for nutrients and water. Coal mine reclaimed sites have shown a great potential as sinks for SOC sequestration (Bodlák et al. 2012; Lorenz & Lal 2007) and it was shown that they can reach the pre-mining SOC levels in less than 20 years after the reclamation (Vindušková & Frouz 2013).

Yet another of the positive SOM effects can be observed through the storage of nutrients in humic layers and the prevention of leeching. Organic matter rich in P and N (usually the most limiting factors for vegetation establishment and growth) can be applied to these sites in order to indirectly promote the SOM accumulation through plant growth and litter formation, this being the sequence that is most similar to natural ecosystems. If the matter is not used, the leaching of nutrients and PTE accumulation may occur (Vetterlein & Hüttl 1999; Vega et al. 2004). Because the organic matter tends to form soluble or insoluble complexes with the heavy metals, they can migrate throughout the profile or be retained in the soil (Schnitzer & Khan 1975; Vega et al. 2004). Iron and manganese oxides, humified organic matter, and clay minerals are the soil components with a greater effect in the decrease in the heavy metal availability, whereas fertilisers and long-term use of animal manure increase it, as a study from Spain has shown (Vega et al. 2004). Coal can often contain potentially toxic organic compounds and trace elements. Studies of determining the levels of risk elements on coal reclamations were also performed by Tang et al. (2018), and the results have shown that the finer the texture of the soil is, the higher the heavy metal concentrations were. Other studies have dealt with risk elements all over the world, and, in some instances, elevated or high concentrations of elements such as arsenic (As), nickel (Ni),

Table 2. Tree species which have shown significant favourable or unfavourable physical and chemical soil properties (+ and – indicate significant differences in a certain category, empty fields show no significant changes)

Species	Bulk density, porosity	Water retention	pH	C	N	S
Maple (*Acer pseudoplatanus*, *A. platanoides*)		+			+	+
Scots elm (*Ulmus glabra*)		+	+		+	+
Linden (*Tilia cordata*)	+				+	
Pear (*Pyrus communis*)	+				+	
Hornbeam (*Carpinus betulus*)	–	–	–			–
Scots pine (*Pinus sylvestris*)	–		+	–	–	
Weymouth pine (*Pinus strobus*)		–	–	+	–	–

Source: Spasić et al. (2020)

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copper (Cu), lead (Pb), chromium (Cr), cobalt (Co), zinc (Zn), iron (Fe), manganese (Mn), cadmium (Cd), and mercury (Hg) were observed (Giri et al. 2013; Bragina et al. 2014; Ličina et al. 2017; Bandyopadhyay et al. 2018; Jambhulkar & Kumar 2019; Kalabić et al. 2019; Raj 2019; Hamidović et al. 2020). Štrudl et al. (2006), on the other hand, based on a research from 116 sampling locations, stated that risk elements did not present a threat in the Sokolov mining basin in the Czech Republic.

High acidity levels are a common phenomenon on reclaimed lignite mine sites, and the reason for that is usually the parent material of the spoil heap and the weathering of the reduced sulfur compounds (mainly pyrite) inside of it, which are common on lignite coal mine spoils (Hoth et al. 2005). Pyritic minerals tend to oxidise and form sulfuric acid, which drastically lowers the pH (Sheoran et al. 2010). Pyrite oxidation was thoroughly described by Rimstidt and Vaughan (2003). This leads to acid mine drainage (AMD), a significant, non-remedied environmental problem which deteriorates the surface and ground water quality (Kuter 2013). Lowering the pH value leads to the metal toxicity of elements like aluminium and manganese, which inhibits plant root growth and other metabolic processes (Sheoran et al. 2010), and makes the establishment of vegetation difficult. The most influential soil properties regarding the creation of labile aluminium forms are the pH and organic matter (Borůvka et al. 1999; Borůvka & Kozák 2001b).

These phytotoxic conditions can be mitigated in practice by adding lime or fly ash (Brenner 1979; Zellmer & Wilkey 1979; Bradshaw 1997; Hartmann et al. 1999; Waschkies & Hüttl 1999; Gast et al. 2001; Maiti 2007; Ussiri et al. 2014). The use of acid tolerant and metal tolerant plant species is often advised (Bradshaw 1997). The choice of species can vary significantly due to climatic and regional differences. Species native to the area should be preferred, since introduced species can lead to ecological problems like invasiveness or practical problems like susceptibility to diseases or having difficulties in growth.

Problems of biological nature

As stated before, the main goal of the reclamation is the successful vegetation establishment, which can be difficult due to the already mentioned physical and chemical properties of the soil. Therefore, species with a higher tolerance to these factors are preferred. The species are chosen based on their erosion and sediment control qualities, food and cover value for wildlife, and their ability to condition the area for the species native to the area (Brenner 1979). Although some non-native species like the often-used *Robinia pseudoacacia* (Bradshaw 1997; Filcheva et al. 2000) have very good overall properties like nitrogen fixation, litter quality, tolerance to various impacts and anti-erosion efficiency, their invasiveness can present a serious problem in certain areas and should be supressed where possible (Řehounková et al. 2011; Chuman 2015). The natural vegetation of the area should be allowed to develop. Native species that can be observed in the surrounding vegetation are preferable, with the already described broadleaved species taking advantage over the conifers. In the second decade of the new millennia, leading experts agree that natural or directed succession can be very useful tools in comparison to technical reclamation, unless the site conditions are extremely severe, due to the low cost, biodiversity preservation, and not as achieving different results in the long run. If a technical reclamation is inevitable, levelling is not recommended, because the formation of crests and troughs enhances the diversity of habitat structures (Frouz 1999; Topp et al. 2001; Hendrychová 2008). The organic matter that comes from litter gets decomposed by decomposer and microbial communities, and nutrient cycling becomes established. Fauna activity (especially earthworms) is a substantial mediator in the soil development process (Frouz et al. 2007a, 2013).

During the first years after the process of coal excavation is undertaken, following the devastating physical and chemical changes that occur, the soils will also microbiologically decrease to a minimum level (Ghose 2001). Although constituting only 2–4% of the SOM, microorganisms are very important due to their high turnover rate and the role in organic matter transformation (Šourková et al. 2005a). Decomposition of organic matter and nutrient cycling is largely controlled by soil microbes (Filip 2002; Moreno-de las Heras 2009; Sinha et al. 2009), and the microbial activity is influenced by various soil properties, but mainly the temperature, moisture, and the availability of organic matter (Helingerová et al. 2010). As stated by Remeš and Šíša (2007), a study of the biological activity can be an indicator of the soil revitalisation process on reclamation plots, and its levels make it possible to evaluate the success of different reclamation approaches. Nowadays, microbial activity can be measured through a range of

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different methods (Claassens et al. 2008), and can be increased through nutrient addition, agrotechnical improvements and inoculation of beneficial microorganisms (Mikanová et al. 2009). As stated by Šourková et al. (Šourková et al. 2005a; Remeš & Šíša 2007), the vegetation type and the quality of its litter are more important for the microbial activity than the substrate quality. In the research performed by Chodak and Niklinska (2010), it was shown that birch (*Betula pendula*) supports the largest and most active soil microbial communities (compared to *Larix*, *Pinus* and *Alnus* sp.).

Problems of pedological approach

Although many research studies have dealt with the pedogenesis problems on reclaimed coal mine sites, several issues related to the data processing come to mind. First of all, the site-specific nature of coal mines (parent material, temperature, annual precipitation, native vegetation and organisms, etc.) can cause problems in comparing the effectiveness of the reclamation and pedogenesis on the different sites. A vast majority of authors have usually observed the changes that occur on reclamation sites through the chronosequence approach, which was well described by Huggett (1998). Hüttl and Weber (2001) stated: "With regard to the development of ecosystems on mine sites, the major focus should be on pedogenesis, since soil is the compartment most dramatically altered by open-cast mining". The already mentioned technical reclamation vs. natural succession debate can lead to this focus being lost. From a pedogenesis point of view, only a few researchers, like Lanham et al. (2015) have described the forming of soil horizons, whilst others have usually performed their research focusing on the uppermost soil layer. One of the problems causing this is the reclamation stand age, which is usually less than 50 years old, and the assumption that there is only an organomineral A horizon developed on top of the technogenic parent material. At some of the older reclamation sites which have been afforested, horizon differentiation can already be observed. The A horizon can be presumed to form during the first 20 to 40 years from the afforestation, whilst the differentiation of the B horizon could be observed from 40–50 years onwards, reaching a steady state at around 100 years. A valuable presumption in central European regions with a clayey parent Technosol would be that the afforested reclamation sites' soil type will tend to evolve from a mine Technosol to a Cambisol. This evolution is graphically presented in Figure 2. Nevertheless, on a longer perspective, or under specific local conditions (leaching, clay swelling and shrinkage, water logging, acidification, etc.), other soil classes can develop, like Luvisols, Vertisols, Stagnosols, Gleysols, or Podzols.

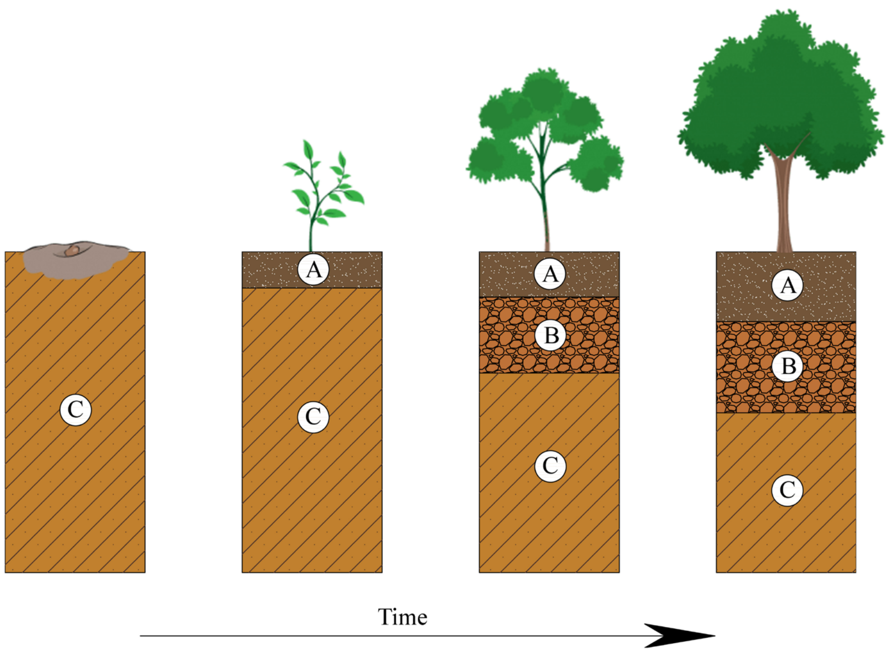

Figure 2. Presumed evolution of an afforested mine Technosol on clayey parent materials of central European region

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Different tree species have different litterfall and nutrient input rates, and are presumed to influence the formation of soil horizons in different manners, thus making this presumption more complicated. The differences should be more evident between conifers and broadleaved species.

As time goes by, the need and possibility of comprehensive research performed on older, homogenously conditioned study sites emerge. The profile characteristics should be thoroughly described, and the soil's physical, chemical and biological properties analysed, and compared to the surrounding natural forests, as well as to the initial spoil material. Also, mineralogical studies need to be performed. This way we could get some insight into the presumed pedogenetic process and changes that occur in the soil.

If this presumption is proven to be correct, research of a similar methodology of the tree species effect on the soil development is highly desirable. Instead of a chronosequence approach, different tree species stands of the same or similar age and similar ecological characteristics (area location, temperature, precipitation, etc.) would be preferable.

CONCLUSIONS

Open-cast coal mining is a process that drastically changes the landscape and its overall ecosystem functions. Soil, a part of the ecosystem, which can be considered a non-renewable resource, usually becomes utterly destroyed in mining. Negative changes that occur can be observed through the physical, chemical and biological state of the soil, and have been described in this paper. The most commonly used reclamation strategies tend to establish a successfully developed vegetation cover as their primary goal, thus restoring the natural cycles on these sites. Once vegetation is successfully established, the process of soil formation, which is slow in nature, is presumed to occur faster on reclaimed mine sites. The age and the site-specific nature of the reclaimed surfaces has been a limiting factor for pedological research and the description of the soil forming evolution. A presumption of soil evolution on reclaimed sites with a clayey parent material have been set, and guidelines for potential further research have been given, including the need for research performed on older reclaimed mine sites, as well as on mine sites with similar ecological conditions, and different tree species cover. However, with the soil being a very complex system, a comprehensive approach is needed.

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7.1.2. Trends of global scientific research on reclaimed coal mine sites between 2015 and 2020

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Review

Trends of Global Scientific Research on Reclaimed Coal Mine Sites between 2015 and 2020

Marko Spasić, Ondřej Drábek, Luboš Borůvka and Václav Tejnecký *

Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Prague, Czech Republic; spasic@af.czu.cz (M.S.); drabek@af.czu.cz (O.D.); boruvka@af.czu.cz (L.B.)
* Correspondence: tejnecky@af.czu.cz

Abstract: Open-cast coal mining is one of the most often-debated industries in the world. Due to the significant environmental and health issues it causes, many of these sites have been reclaimed over the years, and many scientific publications and research has followed. In this paper, we have tried to assess the trends in recent research performed on reclaimed coal mining sites (RMS) by analyzing the publications visible on Web of Science (WoS) between 2015 and 2020 and dividing the research into six categories. The results show that there is a trend of rapid increase in research that deals with carbon and its pooling, nutrients, vegetation, and microbiology, and a significant decline in research on RMS soil physical properties, whereas other categories have shown an increasing but relatively steady trend. The application of modern technologies is also discussed. China, the USA, and India are the countries that quantitatively take the lead in coal RMS research, with India slowly overtaking the US in more recent years.

Keywords: reclamation; coal mining; research; trends; soil; spoil heaps

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1. Introduction

Coal mining sites present a serious issue for modern society. Open-cast coal mining significantly changes the landscape and utterly destroys soil functions, making these vast sites practically desolate, thus positioning itself as probably the most disputed industry in the world [1–4]. Besides disturbing the landscape and soil, it also impacts 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 legislation about the ways that these sites need to be treated after the excavation process is done [3,6–8], and our knowledge expands every year with various research results that we obtain from these localities. Despite the fact that they have been more precisely defined in recent years, the so-called R4 terms (reclamation, rehabilitation, restoration, and remediation) are still a source of confusion for many [5,9]. Many researches have shown that technical reclamation, an approach widely used in the 20th century, might have its flaws, and there are other, in many cases, more feasible and efficient solutions, such as natural succession [8,10]. Technical reclamation is still the most common approach used on post-mining sites, and it is even a mandatory practice in some areas, due to many countries' legislation [9]. The full effects of the reclamation process can be visible only after some time has passed, usually ranging from several decades to the scale of centuries. As stated by Karan et al. [11], continuous monitoring of reclamation sites should be given emphasis in order to devise a feasible and effective policy for degraded land reclamation and restoration.

In order to observe the research trends on coal mining sites, for the purpose of this research it was decided to split the research into different categories. Although it could roughly be said that research on coal reclaimed mine sites (RMS) is most usually of a physical, chemical, or biological nature, recent technological achievements such as satellite imagery, remote sensing, the use of Unmanned Aerial Vehicles (UAVs), GIS, modelling, and various new theories and equipment which require calibration or testing often demand a section of their own [1,12]. Review papers, as well as the implementation of new technologies with data and measurements from older research, can be considered a separate, although not less important, category, since they often provide more comprehensive information and interconnect various scientific branches. Keeping in mind that soil organic matter (SOM) is one of the segments that is most drastically impacted by open-cast coal mining, and its physical, chemical, and biological properties and functions are deeply interrelated, as well as the fact that it is an unavoidable and very abundant component of much modern soil RMS research, a section of its own is called for. Soil organic carbon (SOC) research, as well as the capability of certain soils to sequester it, is becoming more and more abundant in recent years [13–20]. Since nutrients, most commonly nitrogen, are often investigated together with soil carbon, sometimes it is difficult to divide these as well. Being interested mainly in the direction that research on coal reclamation sites is going towards, the main purpose of this paper is not to compare the effectiveness of one restoration strategy or method over the other, distinguish between the terminology issues mentioned, or compare the vegetation species, age, or effectiveness, but only to point out the general trends and abundance of certain research categories over others. This paper does not provide comprehensive statistical and/or bibliometric analysis, but merely aims to reflect the trends of research performed on these sites over a specified time period, in publications visible in the Web of Science (WoS) online library.

2. Materials and Methods

The materials used were scientific publications from the Web of Science (WoS) website. In order to obtain as many publications related to coal reclamation sites as possible, the input query words were "coal AND soil AND reclama* OR reclaim*." The search filter was set to "topic," and the time span was 2015–2020. This search included journal articles and conference proceedings that appeared in the search up until 30 March 2020.

Having in mind current research activities on coal reclamation sites, they were split into 6 categories:

1. C, N, and SOM;
2. Physical;
3. Biological;
4. Chemical;
5. Technology;
6. Review and Metadata.

Each publication from the search query was analyzed, and accredited with one point in total. If the research was precisely focused on only one of the categories, that category received a full 1 point. If the research was split between two categories, each of the categories received 0.5 points if they were equally distributed throughout the research, or an uneven fraction of the point if they were not. Thus, several categories could have equally or unequally distributed points, but the sum of all fractions of all 6 categories for each single publication had to be one.

The category C, N, and SOM comprises all the research that deals with soil organic matter, soil carbon (both organic and inorganic), and macronutrients, mainly nitrogen. If the topic of the research deals with nutrients in greater detail, it can be commonly interrelated with the Chemical section. The Physical category encompasses soil physical and hydrological research, including bulk density, soil structure, soil texture, porosity, water retention and transport, compaction, etc. The Biological category deals with topics of soil micro- and macro-fauna and its activities, as well as vegetation and its establishment. The Chemical category is related to mine soil's chemical characteristics and its changes, acidification, element toxicity, etc. The category Technology has been introduced in order to fill the gap for the research that is related to the introduction and use of new technologies, models, statistical methods, and equipment, and their research, development, calibration, etc. The Review and Metadata category deals with reviews, state-of-the-art papers, and processing metadata.

The results with distributed category points are presented in a tabular form, together with references and the country a particular study originates from, as well as in the form of graphs showing the trends in the observed period.

3. Results

The Web of Science search engine, searching before the date of 30 March 2020, has given 153 search results for the parameters given in the query. Out of those, eight publications needed to be removed from the analysis for not complying with the topic (different type of mining, oriented solely to mining engineering, its process and techniques, etc.), for being an administrative mistake such as multiple appearances of the same publication, or, in two cases, for being a reprint of an older publication.

The list of publications processed, with the points accredited to them, as well as research locations (countries of origin), can be seen in Table 1:

Table 1. Distribution of points across categories.

No.	Author and Reference Number	Year	Category						Location
			C, N and SOM	Physical	Biological	Chemical	Technology	Review & Metadata	
1	Guan et al. [21]	2020	0.80	0.00	0.10	0.10	0.00	0.00	China
2	Feng et al. [22]	2020	0.00	0.50	0.00	0.00	0.50	0.00	China
3	Ezeokoli et al. [23]	2020	0.00	0.17	0.67	0.17	0.00	0.00	South Africa
4	Yan et al. [24]	2020	0.67	0.00	0.33	0.00	0.00	0.00	China
5	López-Marcos et al. [25]	2020	0.17	0.17	0.50	0.00	0.17	0.00	Spain
6	Block et al. [26]	2020	0.00	0.00	1.00	0.00	0.00	0.00	USA
7	Jambhulkar & Kumar [27]	2019	0.25	0.25	0.25	0.25	0.00	0.00	India
8	Mylliemngap & Barik [28]	2019	0.25	0.25	0.25	0.25	0.00	0.00	India
9	Yang Chen & Zhang [29]	2019	0.67	0.00	0.17	0.17	0.00	0.00	China
10	Jianhua Li et al. [16]	2019	1.00	0.00	0.00	0.00	0.00	0.00	China
11	Bao et al. [30]	2019	0.00	0.33	0.00	0.00	0.67	0.00	China
12	X. Yang et al. [31]	2019	0.33	0.00	0.33	0.33	0.00	0.00	China
13	Detheridge et al. [15]	2019	1.00	0.00	0.00	0.00	0.00	0.00	UK
14	Min Zhang et al. [32]	2019	0.00	0.00	1.00	0.00	0.00	0.00	China
15	Pihlap et al. [33]	2019	0.25	0.25	0.25	0.25	0.00	0.00	Germany
16	Hall et al. [34]	2019	0.00	0.00	1.00	0.00	0.00	0.00	USA
17	Kumari & Maiti [35]	2019	0.50	0.00	0.50	0.00	0.00	0.00	India
18	Brooks et al. [36]	2019	0.00	0.25	0.50	0.25	0.00	0.00	USA
19	Z. Zhang, Wang, & Feng [37]	2019	0.25	0.25	0.25	0.25	0.00	0.00	China
20	Agus et al. [38]	2019	0.17	0.17	0.50	0.17	0.00	0.00	Indonesia
21	Cheng & Sun [39]	2019	0.00	0.00	0.00	0.00	1.00	0.00	China
22	Franke et al. [40]	2019	0.00	0.17	0.67	0.17	0.00	0.00	USA
23	Lei et al. [41]	2019	0.33	0.33	0.00	0.33	0.00	0.00	China
24	Feng et al. [42]	2019	0.00	0.00	0.00	0.00	0.00	1.00	China
25	Desai et al. [43]	2019	0.00	0.00	0.33	0.67	0.00	0.00	UK
26	Yang et al. [18]	2019	0.67	0.00	0.17	0.00	0.17	0.00	China
27	Qiu et al. [44]	2019	0.25	0.00	0.50	0.25	0.00	0.00	China
28	Z. Zhang, Wang, & Li [45]	2019	0.33	0.11	0.11	0.11	0.33	0.00	China
29	Adeli et al. [46]	2019	0.20	0.40	0.40	0.00	0.00	0.00	USA
30	Atanassova et al. [47]	2019	0.00	0.25	0.00	0.75	0.00	0.00	Bulgaria
31	Miller et al. [48]	2019	0.20	0.00	0.00	0.80	0.00	0.00	Indonesia
32	Petrov [49]	2019	0.00	0.00	0.00	0.00	0.00	1.00	Bulgaria
33	Bandyopadhyay & Maiti [50]	2019	0.00	0.00	0.33	0.67	0.00	0.00	India
34	M. Zhang & Zhang [20]	2019	0.80	0.00	0.10	0.00	0.10	0.00	China
35	Badenhorst et al. [51]	2018	0.00	0.25	0.50	0.25	0.00	0.00	South Africa
36	Jinman Wang et al. [52]	2018	0.00	0.67	0.00	0.00	0.33	0.00	China
37	Priyono et al. [53]	2018	0.00	0.50	0.25	0.25	0.00	0.00	Indonesia
38	Bandyopadhyay et al. [54]	2018	0.00	0.00	0.33	0.67	0.00	0.00	India
39	Duo & Hu [55]	2018	0.33	0.33	0.00	0.33	0.00	0.00	China

Table 1. *Cont.*

No.	Author and Reference Number	Year	Category						Location
			C, N and SOM	Physical	Biological	Chemical	Technology	Review & Metadata	
40	Hu et al. [56]	2018	0.25	0.25	0.25	0.25	0.00	0.00	China
41	Haigh et al. [57]	2018	0.25	0.00	0.50	0.25	0.00	0.00	UK
42	Ahirwal et al. [58]	2018	0.25	0.25	0.25	0.25	0.00	0.00	India
43	Valenzuela et al. [59]	2018	0.33	0.33	0.33	0.00	0.00	0.00	Chile
44	Rawlik, Kasprowicz, Jagodziński, et al. [60]	2018	0.00	0.00	0.67	0.33	0.00	0.00	Poland
45	Guo et al. [61]	2018	0.13	0.13	0.13	0.13	0.50	0.00	China
46	Skousen et al. [62]	2018	0.00	0.00	0.67	0.33	0.00	0.00	USA
47	Franke et al. [63]	2018	0.00	0.00	0.80	0.20	0.00	0.00	USA
48	Hou et al. [64]	2018	0.00	0.10	0.70	0.20	0.00	0.00	China
49	Ahirwal & Maiti [65]	2018	0.40	0.20	0.20	0.20	0.00	0.00	India
50	Ye Yuan, Zhao, Niu, et al. [66]	2018	0.25	0.25	0.25	0.25	0.00	0.00	China
51	Kumar et al. [67]	2018	0.50	0.00	0.50	0.00	0.00	0.00	India
52	Sun et al. [17]	2018	0.50	0.00	0.00	0.00	0.50	0.00	China
53	Sena et al. [68]	2018	0.25	0.25	0.25	0.25	0.00	0.00	USA
54	Rana & Maiti [69]	2018	0.00	0.00	0.50	0.50	0.00	0.00	India
55	S. Li & Liber [70]	2018	0.00	0.10	0.50	0.30	0.10	0.00	China
56	Jing et al. [71]	2018	0.80	0.00	0.00	0.00	0.20	0.00	China
57	Angst et al. [72]	2018	0.70	0.10	0.10	0.10	0.00	0.00	USA
58	Tang et al. [73]	2018	0.00	0.00	0.00	1.00	0.00	0.00	China
59	Rawlik, Kasprowicz, & Jagodziński [74]	2018	0.00	0.00	1.00	0.00	0.00	0.00	Poland
60	Ye Yuan, Zhao, Li, et al. [19]	2018	0.70	0.00	0.10	0.10	0.10	0.00	China
61	T. Li et al. [75]	2018	0.50	0.00	0.00	0.50	0.00	0.00	China
62	Y. Huang et al. [76]	2018	0.50	0.00	0.00	0.50	0.00	0.00	China
63	J. F. Qu et al. [77]	2018	0.50	0.50	0.00	0.00	0.00	0.00	China
64	Nedyalkova et al. [78]	2018	0.00	0.33	0.67	0.00	0.00	0.00	Bulgaria
65	Merrill et al. [79]	2018	0.00	0.50	0.25	0.25	0.00	0.00	USA
66	Ahirwal & Maiti [14]	2018	1.00	0.00	0.00	0.00	0.00	0.00	India
67	Liu, Cao, et al. [80]	2017	0.50	0.00	0.50	0.00	0.00	0.00	China
68	Williams et al. [81]	2017	0.00	0.00	1.00	0.00	0.00	0.00	USA
69	Padmanaban et al. [82]	2017	0.00	0.00	0.00	0.00	1.00	0.00	Germany
70	Karan et al. [83]	2017	0.00	1.00	0.00	0.00	0.00	0.00	India
71	Swab et al. [84]	2017	0.10	0.10	0.70	0.10	0.00	0.00	USA
72	G. Bell et al. [85]	2017	0.10	0.10	0.40	0.40	0.00	0.00	USA
73	Pan et al. [86]	2017	0.00	0.67	0.33	0.00	0.00	0.00	China
74	Ahirwal & Maiti [87]	2017	0.50	0.17	0.17	0.17	0.00	0.00	India
75	Ahirwal, Maiti, & Satyanarayana Reddy [13]	2017	1.00	0.00	0.00	0.00	0.00	0.00	India
76	Majee et al. [88]	2017	0.00	0.00	0.00	0.50	0.50	0.00	India
77	Gang et al. [89]	2017	0.00	0.67	0.17	0.17	0.00	0.00	China
78	Plamping et al. [90]	2017	0.00	0.17	0.50	0.17	0.17	0.00	UK
79	Ye Yuan et al. [91]	2017	0.90	0.10	0.00	0.00	0.00	0.00	China
80	J. F. Qu et al. [92]	2017	0.50	0.17	0.17	0.17	0.00	0.00	China
81	Ahirwal, Maiti, & Singh [93]	2017	0.50	0.00	0.30	0.20	0.00	0.00	India
82	Yongchun Chen et al. [94]	2017	0.10	0.00	0.00	0.90	0.00	0.00	China
83	Bao et al. [95]	2017	0.33	0.00	0.00	0.00	0.67	0.00	China
84	Frouz [96]	2017	0.67	0.00	0.33	0.00	0.00	0.00	Czech Republic
85	Q. Zhang et al. [97]	2017	0.00	0.00	0.00	0.00	1.00	0.00	USA
86	Maiti & Rana [98]	2017	0.10	0.00	0.10	0.80	0.00	0.00	India
87	Bauman et al. [99]	2017	0.00	0.00	0.50	0.50	0.00	0.00	USA
88	Atanassova et al.	2017	0.25	0.00	0.00	0.75	0.00	0.00	Bulgaria
89	Jing Wang et al. [100]	2017	0.00	0.00	0.00	0.00	0.67	0.33	China
90	Shi et al. [101]	2017	0.13	0.00	0.13	0.75	0.00	0.00	China
91	Jinman Wang et al. [102]	2017	0.00	0.33	0.00	0.33	0.33	0.00	China
92	Liu, Bai, et al. [103]	2017	0.33	0.33	0.00	0.33	0.00	0.00	China
93	Y. Yuan et al. [91]	2017	1.00	0.00	0.00	0.00	0.00	0.00	China
94	Darmody & McSweeney [104]	2017	0.00	0.00	0.00	0.00	0.00	1.00	USA
95	Hou et al. [105]	2017	0.00	0.00	1.00	0.00	0.00	0.00	China
96	Maiti & Ahirwal [106]	2017	0.50	0.00	0.13	0.25	0.00	0.13	India
97	Mukhopadhyay & Masto [107]	2016	0.67	0.17	0.00	0.17	0.00	0.00	India
98	Ye Yuan et al. [108]	2016	1.00	0.00	0.00	0.00	0.00	0.00	China
99	Kołodziej et al. [109]	2016	0.11	0.67	0.11	0.11	0.00	0.00	Poland
100	Nash et al. [110]	2016	0.17	0.33	0.17	0.33	0.00	0.00	USA
101	Russell et al. [111]	2016	0.00	0.17	0.67	0.17	0.00	0.00	USA
102	Stumpf et al. [112]	2016	0.10	0.50	0.30	0.10	0.00	0.00	Brazil
103	Jinman Wang et al. [113]	2016	0.00	0.33	0.00	0.00	0.67	0.00	China
104	Maiti et al. [114]	2016	0.00	0.00	0.25	0.75	0.00	0.00	India
105	Wick et al. [115]	2016	0.40	0.50	0.00	0.10	0.00	0.00	USA
106	Das & Maiti [116]	2016	1.00	0.00	0.00	0.00	0.00	0.00	India
107	Ahirwal & Maiti [117]	2016	0.33	0.33	0.00	0.33	0.00	0.00	India

Table 1. *Cont.*

No.	Author and Reference Number	Year	C, N and SOM	Physical	Biological	Chemical	Technology	Review & Metadata	Location
108	Clark & Zipper [118]	2016	0.00	0.75	0.25	0.00	0.00	0.00	USA
109	Gypser et al. [119]	2016	0.25	0.50	0.25	0.00	0.00	0.00	Germany
110	Brown et al. [120]	2016	0.00	0.00	0.50	0.50	0.00	0.00	USA
111	Dutta et al. [121]	2016	0.75	0.13	0.13	0.00	0.00	0.00	USA
112	Mukhopadhyay et al. [122]	2016	0.25	0.25	0.25	0.25	0.00	0.00	India
113	Frasson et al. [123]	2016	0.00	0.00	0.75	0.25	0.00	0.00	Brazil
114	Cudlín et al. [124]	2016	0.33	0.00	0.33	0.33	0.00	0.00	Czech Republic
115	Hu et al. [125]	2016	0.00	0.00	0.00	0.00	0.50	0.50	China
116	X. R. Zhang et al. [126]	2016	0.25	0.50	0.25	0.00	0.00	0.00	China
117	Nadłonek & Cabala [127]	2016	0.25	0.00	0.00	0.75	0.00	0.00	Poland
118	Klojzy-Karczmarczyk et al. [128]	2016	0.00	0.33	0.00	0.67	0.00	0.00	Poland
119	Junjian Li et al. [129]	2016	0.10	0.10	0.10	0.70	0.00	0.00	China
120	Frouz et al. [130]	2015	0.17	0.00	0.00	0.67	0.17	0.00	Czech Republic
121	Kumar et al. [131]	2015	0.25	0.25	0.25	0.25	0.00	0.00	India
122	Lanham et al. [132]	2015	0.33	0.33	0.00	0.33	0.00	0.00	USA
123	Evans et al. [133]	2015	0.00	0.67	0.00	0.00	0.00	0.33	USA
124	Bauman et al. [134]	2015	0.00	0.00	0.67	0.00	0.17	0.17	USA
125	Weber et al. [135]	2015	0.25	0.25	0.25	0.25	0.00	0.00	Poland
126	Zhen et al. [136]	2015	0.25	0.25	0.25	0.25	0.00	0.00	China
127	Macdonald et al. [137]	2015	0.00	0.25	0.25	0.25	0.25	0.00	Canada
128	Jinman Wang, Yang, et al. [138]	2015	0.75	0.00	0.00	0.00	0.25	0.00	China
129	Saminathan et al. [139]	2015	0.00	0.00	0.75	0.25	0.00	0.00	USA
130	Dutta et al. [140]	2015	0.33	0.33	0.00	0.33	0.00	0.00	USA
131	Bartuška et al. [141]	2015	0.25	0.25	0.25	0.25	0.00	0.00	Czech Republic
132	Mathiba & Awuah-Offei [142]	2015	0.75	0.00	0.00	0.00	0.25	0.00	USA
133	Niu et al. [143]	2015	0.00	0.00	0.00	1.00	0.00	0.00	China
134	L. Zhang et al. [144]	2015	0.00	0.67	0.00	0.33	0.00	0.00	China
135	Shouqin et al. [145]	2015	0.00	0.50	0.25	0.25	0.00	0.00	China
136	Haigh et al. [146]	2015	0.00	0.50	0.25	0.00	0.25	0.00	UK
137	Jinman Wang, Zhang, et al. [147]	2015	0.13	0.50	0.00	0.13	0.25	0.00	China
138	Pallavicini et al. [148]	2015	0.11	0.11	0.67	0.11	0.00	0.00	Spain
139	Y. Li, Chen, & Wen [149]	2015	0.17	0.00	0.67	0.17	0.00	0.00	China
140	Sena et al. [150]	2015	0.25	0.25	0.25	0.25	0.00	0.00	USA
141	Hoomehr et al. [151]	2015	0.00	1.00	0.00	0.00	0.00	0.00	USA
142	Y. Li, Chen, Zhang, et al. [152]	2015	0.33	0.00	0.67	0.00	0.00	0.00	China
143	C. Huang et al. [153]	2015	0.33	0.33	0.00	0.33	0.00	0.00	Germany
144	Gruchot et al. [154]	2015	0.25	0.25	0.25	0.25	0.00	0.00	Poland
145	Hlava et al. [155]	2015	0.13	0.25	0.50	0.13	0.00	0.00	Czech Republic

After processing the results and excluding the six publications from 2020, which had yet to yield their other publications, it is noticeable that, for this topic and these search results, 2018 was the year with the largest number of publications (32) visible on the WoS website, followed by 2017 (30) and 2019 (28). The year 2015 had a slightly lesser number of visible publications (26), with 2016 being at the list's rear with 23 (Table 2).

Table 2. Number of points over the categories per year.

Years	C, N and SOM	Physical	Biological	Chemical	Technology	Review & Metadata	Number of Papers/Total Points
2015	4.98	6.89	6.12	5.73	1.58	0.70	26
2016	5.96	5.56	4.30	5.51	1.17	0.50	23
2017	7.51	3.80	6.42	6.48	4.33	1.46	30
2018	8.14	5.04	9.69	7.39	1.73	0.00	32
2019	7.45	3.01	7.61	5.66	2.27	2.00	28
2020	1.63	0.83	2.60	0.27	0.67	0.00	6
2015–2019	34.04	24.31	34.14	30.78	11.08	4.66	139
2015–2020	35.67	25.14	36.74	31.04	11.75	4.66	145

The Biological category gained the largest number of overall points, 34.14, closely followed by the C, N, and SOM category, with 34.04, Chemical with 30.78., Physical with 24.31 points, followed by Technology with 11.08, and Review & Metadata with 4.66. The results of the individual and summary values for all categories over the years are presented in Table 2.

The overall share and distribution of points over the years for the six mentioned categories are presented in Figure 1. After the observation of this distribution, as well as each category's respective linear trend lines (not shown), it can be said that there is noticeable growth in categories Biological and C, N, and SOM (which also obtained the greatest number of overall points). The categories Chemical, Technology, and Review and Metadata have shown some, but not as significant, growth, whereas the category Physical has shown a drastic decline during these five years.

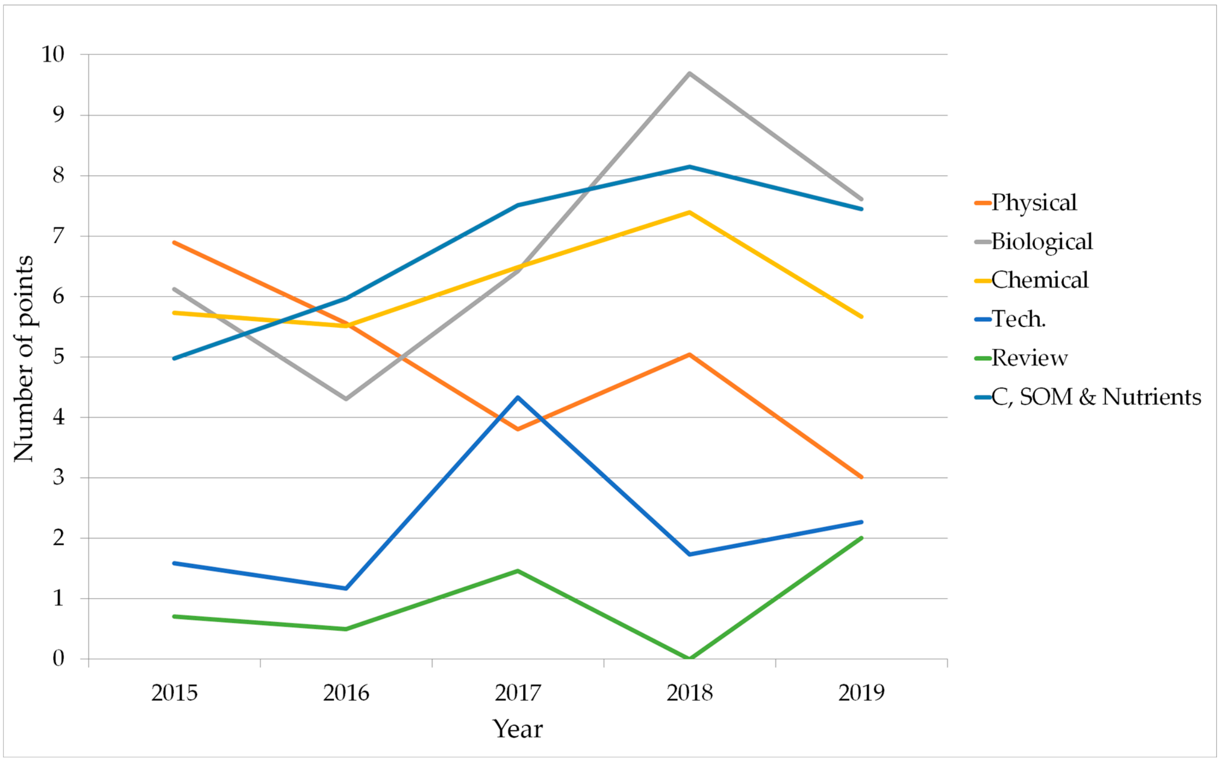

Figure 1. Trends of categories' number of points in publications from 2015 to 2019.

The research encompassed in these publications came from 14 different countries all across the globe, with the greatest number of publications originating from China, the USA, and India, with 39, 21, and 16% shares of the total number of publications, respectively. These values are presented in Table 3.

Table 3. Distribution of publications over the selected years, relative to the country of origin.

Country	No. of Papers	2015	2016	2017	2018	2019	2020
China	56	8	5	13	14	13	3
USA	30	8	6	6	5	4	1
India	23	1	5	7	6	4	0
Poland	7	2	3	0	2	0	0
Czech Republic	5	3	1	1	0	0	0
UK	5	1	0	1	1	2	0
Germany	4	1	1	1	0	1	0
Bulgaria	4	0	0	1	1	2	0

Table 3. *Cont.*

Country	No. of Papers	2015	2016	2017	2018	2019	2020
Indonesia	3	0	0	0	1	2	0
South Africa	2	0	0	0	1	0	1
Spain	2	1	0	0	0	0	1
Brazil	2	0	2	0	0	0	0
Chile	1	0	0	0	1	0	0
Canada	1	1	0	0	0	0	0

Another visible trend is the increase in the overall number of publications coming from China and India in more recent years compared to those coming from the USA. The USA was equal to China in 2015 in its number of publications, and was leading in 2016. Since then, in the last three years, it has shown a significant decline, whereas India's values caught up with it, and China's, in some cases, more than doubled.

4. Discussion

Ever since the Intergovernmental Panel on Climate Change (IPCC) was held in 1988, the sequestration of carbon in terrestrial and non-terrestrial ecosystems has been one of the strategies for mitigating the negative effects of climate change, and has been recognized as an effective and viable method for the reduction of greenhouse gases under the Kyoto Protocol [156]. Since then, many projects have been developed to fund research and strategies related to carbon sequestration.

Reclaimed mine lands offer significant potential for carbon sequestration in terrestrial ecosystems, according to some sources, up to the rate of one ton per hectare per year [157,158]. If the reclaimed land is converted to forests, it is stated that these values can reach up to roughly 2.5 tons per hectare per year, due to the ability of forests to store more carbon in their vegetative parts compared to other land use types, although the soil carbon levels among them can be similar [158]. Since organic carbon and organic matter levels on coal mining spoil heaps are usually severely depleted, these sites present big natural laboratories for monitoring the changes in carbon levels. It was also noticed that reclamation sites have shown great potential as soil organic carbon sinks [159,160] and that the pre-mining levels of soil organic carbon can be achieved after only 20 years [161]. These are some of the reasons that explain the results of the C, N, and SOM category and its trends.

Keeping in mind the fact that China, the USA, and India combined, according to the BP Statistical Review of World Energy [162], accounted for more than two thirds of the global increase in energy demand in 2018, and that, along with the Russian Federation and Australia, have the greatest coal reserves in the world, it is no wonder that these three countries have had such a share of research performed on reclaimed mine sites.

Around the world, RMS research topics can vary due to many reasons, depending not only on current scientific interests, but also, on a broader scale, on geographical, geological, socio-economic, financial, cultural, and other factors. In some European countries and the USA, for example, where some reclamation sites and strategies are close to a century old, the tendencies are to further improve and research the good techniques used, and suppress the ones that might, in the long run, cause certain risks. A good example of this would be the decline in choosing non-native afforestation species, like black locust (*Robinia pseudoacacia*) or red oak (*Quercus rubra*) in many developed European countries [9,10,163], due to their potential invasiveness, and despite their many benefits (in case of *R. pseudoacacia*, anti-erosion potential, nitrogen fixation, honey production, tolerance to various environmental factors, etc.), whereas, in many Asian, and even some developing European countries, it is still a common practice due to their mentioned benefits, low mortality rate, and, above all, low cost. The same applies for creating monoculture forest stands instead of mixed forests on RMS. On the other hand, in certain areas, where it is difficult to establish vegetation for various reasons (e.g., parent or overburden material which can be ecotoxic, compacted, or overly clayey, severe climatic conditions or erosion, the presence of water, etc.), this can direct the way that measures are taken and the course of action and subsequent research practices that are prioritized. The creation of younger RMS, especially in developing countries where the energy demand is great and funds for post-mining reclamation/restoration are scarce, can be limited due to these reasons.

The declining trends in research on soil's physical and hydrological properties in more recent years can be, among other things, explained by the recent tendencies of trying to make a change from technical reclamation practices to ecological restoration [5,9,164]. During the second half of 20th century, when technical reclamation was most widely used, some of the main goals of this approach were to create a stable landscape and support establishing vegetation. Thus, geotechnical, mining, and forestry engineering methods and research were more common. Nowadays, with tendencies towards ecological restoration, a vast number of developing sub-sciences from the field of ecology is involved, gathering scientists from many different branches and making the field much broader than before.

A potential problem when trying to assess research performed on coal mine sites can be defining the key words to use in the search, since sometimes the results encompass some other types of mining activity. Also, defining the R4 (reclamation, rehabilitation, restoration, and remediation) term that you want to use is a problem of greater significance, dating more than a few decades back, and is still an ever-present issue, as explained in a paper by Lima and associates [5,9]. In the mentioned paper, the definitions of each of the R4 terms are updated and more clearly given. This problem was more recently also explained by Gerwing et al. [164], where a new term, "ecological reclamation", was also introduced, and some other SER (Society for Ecological Restoration) standards and recommendations were also discussed. In everyday practice, these terms are still often considered as synonyms for each other, thus making precisely defined searches more difficult.

New advances in technology are not easy to assess and compare amongst one another, since, due to rapid information exchange, it often happens that a piece of equipment or a method that was experimentally used at some point becomes a standard or even a requisite in a very short period of time, especially if it proves to be a more feasible solution. Thus, it can be very demanding to decide what one might consider a "new" or "modern" solution, and what has already shown good results and is being widely used in practice, although it might still be considered new.

Another potential problem worth addressing is the delay of certain publications in their appearing in scientific databases on the internet, which can sometimes take months [165]. This was noticed during our research as well, where, as days passed, the number of search results with the same input parameters became greater, mostly due to a number of publications from 2019 appearing as late as the end of March 2020, when we stopped further revisions of the results. Thus, it can be stated that the number of publications, especially in later years such as 2019, is not yet certain, and will probably increase as time passes, providing us with yet more information. Some authors mentioned that one "should be cautious when using engines like WoS and Scopus as a measuring device for changes in research performance from an international perspective" [166]. Since the time data for this review were obtained, a change in the WoS database search algorithm occurred, and prohibited us from updating it with more recent information in early 2023. The input query words used before now give a much broader list of publications, most of which are completely off-topic, compared to the very narrow-focused results we obtained in 2020. When modified slightly and still using similar keywords (coal, soil, recla*), some of the most recent publications from 2023 visible in the WoS database related to the matter mainly originate from China [167–173], India [174–176], and Poland [177–180], with research coming from China definitely being the most abundant.

However, having in mind the presented trends from the processed period, the number of papers processed, and the most recently published publications visible in the WoS database, the expectations are not in favour of very significant trend changes, although the number and the research area might still vary slightly.

5. Conclusions

Although research on coal reclaimed sites can be very complex and comprehensive, thus inducing complications in the assessment process, and each research branch can have its own issues that can be addressed, the results have shown that much research has been performed in the five-year period between 2015 and 2019 on these localities, which provides us with much needed information on the direction in which certain reclamation/restoration strategies are heading and the results being or not being achieved. The vast majority of publications come from China, the USA, and India, which is understandable due to the fact that these countries have shown the greatest energy demands lately, and have vast coal reserves. It is presumed that, as time passes, China and India will, slowly or rapidly, take the lead in these research activities. New technological achievements are being incorporated into these activities, making them less expensive and more efficient. Research activities which dealt with the analysis of soil carbon, nitrogen, and organic matter have shown a significant increase in recent years, as well as those related to vegetation and micro- and macro-fauna. Research on reclaimed mine soil's chemical properties has shown a somewhat lesser but steady increase. Review papers and publications that deal with the processing of metadata were not as abundant in numbers visible on the Web of Science search engine, so their trends are not easily assessed. Research on reclaimed mine soil's physical properties has shown a decline in publishing. However, this paper's goal was only to assess the general trends in reclamation site research, and the overall direction it is going in. A greater time span would probably provide us with more comprehensive information for most of the categories processed here, but the trend of a rapid increase in research that deals with carbon and its pooling, nutrients, vegetation, and microbiology is visible even in a period as short as five years.

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7.1.3. Which trees form the best soil? Reclaimed mine soil properties under 22 tree species: 50 years later—assessment of physical and chemical properties

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ORIGINAL PAPER

Which trees form the best soil? Reclaimed mine soil properties under 22 tree species: 50 years later—assessment of physical and chemical properties

Marko Spasić[1] · Oldřich Vacek[1,2] · Kateřina Vejvodová[1] · Václav Tejnecký[1] · Petra Vokurková[1] · Petra Križová[1] · Filip Polák[1] · Radim Vašát[1] · Luboš Borůvka[1] · Ondřej Drábek[1]

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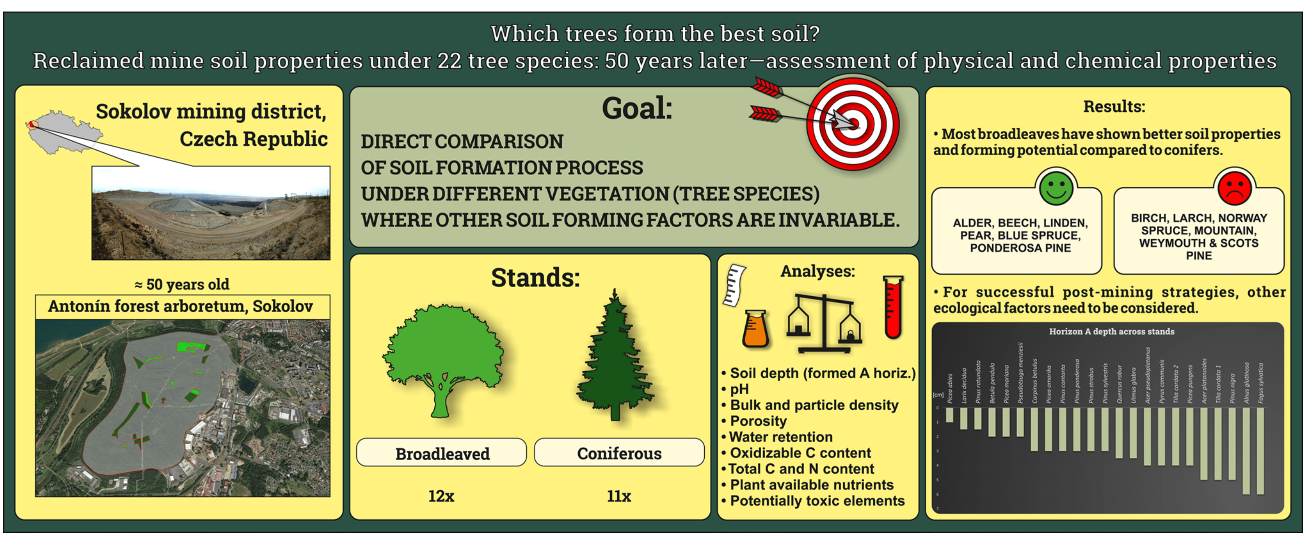
Abstract

Forest reclamations have been very commonly used on post-mining sites in central Europe and offer great opportunities for research of soil formation process. Antonín forest arboretum near Sokolov, Czech Republic, reclaimed and afforested between 1972 and 1974 was the opportunity to compare the influence of only the vegetation variable. In this research, physical and chemical soil properties from the uppermost mineral 5 cm of 23 stands (11 broadleaved and 12 coniferous) were analysed and compared. Soil pH, bulk density, porosity, water retention capacity, organic and total carbon and nitrogen content, plant available nutrients and potentially toxic elements were analysed. From the species tested, the soil properties that can generally be considered beneficial were noticed in *Alnus glutinosa*, *Fagus sylvatica*, *Tilia cordata*, *Pyrus communis*, *Picea pungens* and *Pinus ponderosa*. On the other hand, species that have not shown these soil properties were *Betula pendula*, *Larix decidua*, *Picea abies*, *Pinus rotundata*, *Pinus strobus* and *Pinus sylvestris*. It is also worth mentioning that, although some species have shown soil properties that can be considered more or less favourable from a pedological point of view, the choice of species for afforestation of post-mining sites needs to consider other factors as well, like stand health, growth potential, affinity to climatic, hydrological, and other factors, potential invasiveness, susceptibility to pathogens.

Graphical abstract



Keywords Pedogenesis · Forest reclamation · Tree species · Soil properties · Soil organic matter · Available nutrients

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Extended author information available on the last page of the article

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Introduction

Open-cast coal mining presents a vast global-scale problem, due to the various ecological, economical and aesthetical problems it causes on huge areas that it is performed on. During the course of the excavation process, productive soil is being converted to anthropogenic mine technosols, which are infertile and can't support normal ecosystem functions. Having in mind that soil was officially declared a non-renewable resource (FAO 2015) and the extent of mining activities all over the world, this problem causes a lot to worry about. Moreover, general loss of nutrients and microbial activity, drastic pH changes, leaching of potentially toxic elements, air, water and food contamination, unfavourable water regimes and even changes in microclimate of the area are just some of the other issues that affect these vast, man-made areas (Brom et al. 2012; Spasić et al. 2021).

To overcome the negative effects of these problems, many countries all over the world have incorporated compulsory reclamation strategies as an important part of their legislation. In the Czech Republic, a "Mining act" was imposed back in 1957 (Chuman 2015), making it obligatory for the carrier of mining operations to carry out the process of reclamation after the mining had been finished. Afforestation of post-mining sites has become widely used in the Czech Republic since the 1960s (Kohlová et al. 2021). According to Pietrzykowski (2019), most of the post-mining sites are being afforested due to the fact that this approach establishes the existence of long-term ecosystem sustainability, and, thus, landscape and environmental benefits. Soil quality improvement benefits habitat and ecosystem reconstruction, as well as productivity functions of these sites (Horodecki and Jagodziński 2019). Reforestation plans and strategies for these sites have changed and evolved over time, but questions related to introduction of certain species and the right time to do it, as well as choosing the species still remain. The effect of some pioneer, or early succession species, like alder and birch, have been proven to rapidly increase levels of carbon and nitrogen in the soil, but reports have also shown that in some cases, some late target successional stands have grown better at unreclaimed sites, compared to reclaimed sites covered by alder trees (Frouz et al. 2015; Pietrzykowski 2019). Lately, in central and eastern Europe, there has been a trend of replacing pine monocultures into mixed-stand forests, which is considered beneficial due to their potential of achieving greater biodiversity, being less prone to diseases and producing more litter and soil organic matter (Pietrzykowski 2019). Also, Norway spruce (*Picea abies*), one of the most common tree species in Europe, has been facing vast problems in recent years due to climatic change, long-term droughts and bark beetle outbreaks (Vacek et al. 2021), resulting in a lot of spruce stands being cut, which will probably enhance this trend further.

According to Borůvka et al. (2012), the development of soil on post-mining sites depends not only on pedogenetic processes and natural spatial distribution, but also greatly on the heterogeneity of the deposited material and its characteristics. Although the time-scale of reclaimed post-mining soils development is short for the soil-forming processes to have a significant impact, observing the development of these sites even at the initial stadiums is of great importance (Borůvka et al. 2012) and allows us to see processes which are difficult to see in mature soils (Frouz et al. 2013).

Influence of tree species on soil formation is not a new topic, and post-mining sites have often been used as large-scale laboratories for comparison of different physical, chemical, microbiological and other soil, water and litter properties (Frouz et al. 2013; Treschevskaya et al. 2019). However, due to regional and climatic conditions, different site age and spoil materials, as well as different analyses and approach, comparison of the obtained results can often prove to be very difficult.

Having the assumption that Antonín spoil heap material can be considered fairly homogenous across the locality, and that the age and climate conditions have been the same throughout its history for all the stands encompassed by this research, Antonín forest arboretum offers great opportunities for directly comparing the influence of the mentioned tree species as the main variability factor of soil formation between these stands.

The aim of this study is was to directly compare different physical and chemical properties of 50-year old forest reclamation site under 23 homogenous tree stands, located on the same spoil heap, and in close proximity to each other, and observe their differences, assuming that other soil-forming factors (parent material, time, climate and relief) except organisms (which are controlled mainly by the vegetation type) are similar between the stands. We hypothesised that broadleaved species would have formed more favourable overall physical and chemical soil conditions (higher pH, lower bulk density, higher content of carbon and micro- and macro-nutrients, etc.) compared to the conifers, due to their higher litter input, faster turnover rates and generally, less acidic litter and root exudates.

Material and methods

The study sites are located within the Antonín Forest Arboretum, located east of the city of Sokolov, and southwest of Medard lake, in the west part of the Czech Republic. The arboretum's altitude ranges from 396 to 444 m a.s.l., and the average annual temperature, according to Czech Hydrometeorological Institute, is 7.3° C (station Sokolov L3SOKO01, 407 m.a.s.l.—located approximately 4 km southwest of the city, and 1 km from the centre of Antonín Forest Arboretum). Average annual precipitation is 611 mm/year. July is the month with the greatest, whereas March has the lowest precipitation values (Vacek et al. 2021). After excavation works had been finished in 1965, technical operations have been done by 1972, and forest reclamation works have been completed by 1974. No additional nutrients or topsoil have been added. 220 different species, ecotypes and phenotypes of trees and shrubs in total have gradually been planted on the area of 165 ha, and more than 30 tree species planted there have been introduced species (Vacek et al. 2018), whereas 16% of the area was left to spontaneous succession. Rows of alder trees were planted in between the target species and were cut after 10 years, according to the legislation, leaving the formed biomass on-site. The parent material of the area is predominantly composed of cypress clay which forms the coal overburden material. The pH of the clayey parent (overburden) material on spoil heaps in Sokolov region usually ranges around 8 (Angst 2017). Spasić et al. (2022) have found the pH of the parent material (forest reclaimed soil layers deeper than 1m at 3 stands of different age) to range between 7.72 and 8.30. Within Antonín forest arboretum, these values ranged between 7.81 and 8.26. Cation exchange capacity ranged between 10.5 and 26.3 cmol(+)/kg across the localities, whereas the Antonín values ranged between 21.3 and 26.3 cmol(+)/kg (Spasić et al. 2022).

In the Antonín Forest Arboretum, after almost 50 years, 23 tree stands with areas large enough to be considered homogenous could be isolated. The stands include 10 broadleaved species native to the area (*Acer platanoides*, *Acer pseudoplatanus*, *Alnus glutinosa*, *Betula pendula*, *Carpinus betulus*, *Fagus sylvatica*, *Pyrus communis*, *Quercus robur*, *Tilia cordata* and *Ulmus glabra*), 3 native coniferous species (*Picea abies, Pinus sylvestris* and *Larix decidua*), and 9 introduced coniferous species (*Picea mariana, Picea omorika, Picea pungens*, *Pinus contorta*, *Pinus nigra*, *Pinus ponderosa*, *Pinus strobus*, *Pinus rotundata* and *Pseudotsuga menziesii*). Common, as well as Latin names of the species encompassed by this research can be seen in Table 1.

Two separate *Tilia cordata* stands, which are positioned on different slopes (*T. cordata* 1 ≈ 2.72% and *T. cordata* 2 ≈ 9.42%) and orientation, were processed in this research, to try assessing the potential differences caused by relief, which varies slightly across the locality. Map of the area with stand locations and names can be seen in Fig. 1.

In each stand, using ArcMap software, a stand centre has been determined according to the methodology described in Vacek et al. (2021). Using these coordinates, a shallow soil profile (< 30 cm) was dug in each of the stands, and after removing the organic horizons (L, F, H), the thickness of the newly formed organo-mineral soil horizon (A) was determined by using a measuring tape. Due to the horizon boundary, the measurements were done in increments of 0.5 cm.

5 undisturbed soil samples were taken from the uppermost organo-mineral soil layer (excluding the L, H and F horizons) from each of the 23 stands using 100 cm^3 Kopecky steel cylinders (Eijkelkamp, Ø53mm, L50mm). These samples were taken randomly within a radius of 5m from the stand centre, for statistical purposes. Due to the differences in horizon depths formed at the site, some cylinders encompassed exclusively A horizon, whereas some encompassed both the organo-mineral (A) topsoil and the subsoil cambic (Bv) or parent material (C) horizon, because the A horizons formed were not deep enough. Additional, mixed and disturbed organo-mineral (A) topsoil samples were collected, too. The sampling was done during August and September 2018.

Bulk density, particle density, porosity and water capacity (fully saturated, after 30min, 2h and 24h) were measured according to the standards described in Spasić et al. (2023). Water retention capacity was determined gravimetrically following the methodology of V. Novák (Spasić et al. 2023). The samples were air dried in an oven at 105° C until constant mass, crushed with a mortar and pestle, and homogenized. Particle density was determined by the pycnometer method. pH was measured in a $CaCl_2$ solution according to the manual by SFU Soil Science Lab (Murray 2011) using WTW pH7110 pH meter. Oxidizable carbon content was determined by the modified Tyurin (wet combustion using potassium dichromate) method (Pospíšil 1964). Total contents of carbon, nitrogen and sulphur were determined using Thermo Scientific Flash 2000 NCS Analyzer. Plant available concentrations of micro- and macro-nutrients were determined by the Mehlich III extraction method (ÚKZÚZ 2016) and analysed by using inductively coupled plasma optical emission spectrometer (ICP-OES) iCAP 7000 by Thermo Scientific™, USA. Average available nutrient values of each stand have been compared and classified according to the evaluation criteria for organo-mineral horizons of forest soils (both coniferous and broadleaved) in Czech Republic, given by Central Institute for Supervising and Testing in Agriculture of the Czech Republic (ÚKZÚZ, n.d.). Deficiency limits of plant available manganese (Mn), zinc (Zn) and copper (Cu), and toxicity limits of available potentially toxic elements (PTE) which are extractable by Mehlich III—lead (Pb), manganese (Mn), zinc (Zn), nickel (Ni), cadmium (Cd), and copper (Cu) were determined based on soil pH from the graphs in Monterroso et al. (1999) and compared to the analysed samples. The quality control and quality assurance of analytical procedures (and data) were done and controlled according to standard laboratory regulation including usage of referential materials (NIST) and processing blanks.

Table 1 List of species encompassed by this research—common and Latin names

Common name	Latin name
Norway maple	*Acer platanoides*
Sycamore maple	*Acer pseudoplatanus*
Black alder	*Alnus glutinosa*
White (silver) birch	*Betula pendula*
European hornbeam	*Carpinus betulus*
European beech	*Fagus sylvatica*
Common pear	*Pyrus communis*
Pedunculate (English) oak	*Quercus robur*
Small-leaved linden	*Tilia cordata*
Wych (Scots) elm	*Ulmus glabra*
European larch	*Larix decidua*
Norway spruce	*Picea abies*
Scots pine	*Pinus sylvestris*
Black spruce	***Picea mariana***
Serbian spruce	***Picea omorika***
Blue spruce	***Picea pungens***
Lodgepole pine	***Pinus contorta***
Black (Austrian) pine	***Pinus nigra***
Ponderosa (bull) pine	***Pinus ponderosa***
Weymouth pine	***Pinus strobus***
Mountain pine (Blatka pine)	***Pinus rotundata***
Douglas fir	***Pseudotsuga menziesii***

Native species are presented in normal font, whereas introduced species are marked bold

The sample groups were processed in Statistica software (StatSoft, TIBCO) with one-way analysis of variance (ANOVA) and Post hoc Tukey HSD test for every soil property measured on the undisturbed samples and compared between stands. Principal Component Analysis (PCA) was performed in order to see the correlations between the various soil properties that were analysed.

Results

Soil formation: A horizon thickness

The depth of soil horizons varied significantly across the stands. The lowest depth of newly formed soil was noticed in *Picea abies* (1.0 cm), followed by *Larix decidua* and *Pinus rotundata* (1.5 cm), *Betula pendula*, *Picea mariana* and *Pseudotsuga menziesii* (2.0 cm). Horizon A depth of 3.0 cm was found in *Picea omorika*, *Pinus contorta*, *Pinus ponderosa*, *Pinus strobus*, *Pinus sylvestris* and *Carpinus betulus*. *Quercus robur* and *Ulmus glabra* had a depth of 3.5 cm, whereas in *Picea pungens*, *Acer pseudoplatanus*, *Pyrus communis* and *Tilia cordata* 2 stands, 4.0 cm of recently formed A horizon was noticed. 5 cm was noticed in the case of *Tilia cordata* 1, *Acer platanoides* and *Pinus nigra*, whilst the deepest A horizon formation was observed in *Fagus sylvatica* and *Alnus glutinosa*. The thickness of the formed soil is graphically presented in Graph 1 (in ascending order).

Physical properties

Bulk density analysis has shown that the lowest mean bulk density values were noticed in the *Picea mariana* stand (0.66 g/cm^3), followed by *Tilia cordata* 2, *Picea pungens*, *Fagus sylvatica* and *Pyrus communis*, which all had bulk density values lower than 0.8 g/cm^3. *Pinus rotundata*, *Tilia cordata* 2, *Quercus robur*, *Pinus ponderosa*, *Acer pseudoplatanus* and *Ulmus glabra* average bulk density values varied between 0.84 and 0.9 g/cm^3. *Pinus strobus*, *Pseudotsuga menziesii, Picea omorika*, *Pinus contorta*, *Alnus glutinosa*, *Acer platanoides*, *Carpinus betulus* and *Pinus nigra* average values varied from 0.91 to 0.98 g/cm^3. *Betula pendula*, *Picea abies*, *Larix decidua* and *Pinus sylvestris* had the highest average bulk density values (ranging from 1.027 to 1.097 g/cm^3). The values are graphically represented in Graph 2.

The mean particle density values ranged between 2.17 for *Tilia cordata*, to 2.47g/cm^3 for *Pinus sylvestris*.

Mean porosity values ranged between 54.53% for *Larix decidua*, to 71.74% for *Picea mariana*. Apart from *Larix decidua*, low values were noticed in Betula pendula (55.06%) and *Picea abies* (55.17%), followed by *Pinus sylvestris*, *Carpinus betulus* and *Pinus nigra* (56.15%-59.27%) and *Pinus contorta* (59.98%). *Acer platanoides*, *Pseudotsuga menziesii*, *Picea omorika*, *Alnus glutinosa*, *Ulmus glabra*, *Quercus robur*, *Pinus ponderosa*, *Tilia cordata* (stand 1), *Pinus strobus*, *Acer pseudoplatanus*, *Pyrus communis* and *Pinus rotundata* porosity values varied between 60.88 and 64.83%. The stands which have shown the greatest porosity values were *Tilia cordata* (stand 2, 67.50%), *Fagus sylvatica* (68.21%), and *Picea pungens* and *Picea mariana* (68.38% and 71.74%, respectively). The differences are graphically represented in Graph 3.

Maximum capillary capacity (MCC) mean values ranged, between 33.46% for *Pinus strobus* to 54.42% for *Pinus ponderosa*. According to Rejšek (Spasić et al. 2023), soils which range between 30 and 50% MCC (*Pinus strobus*, *Tilia cordata* 2, *Pinus contorta*, *Pyrus communis*, *Carpinus betulus*, *Pseudotsuga menziesii*, *Pinus rotundata*, *Betula pendula*, *Fagus sylvatica*, *Pinus nigra*, *Tilia cordata* 1, *Picea mariana*, *Pinus sylvestris* and *Picea omorika*) have very strong water-holding capacity, whereas soils which have MCC greater than 50% (*Larix decidua*, *Acer platanoides*, *Quercus robur*, *Picea pungens*, *Picea abies*, *Ulmus glabra*, *Alnus glutinosa*, *Acer pseudoplatanus* and *Pinus ponderosa*) have extremely strong water-holding capacity. *Tilia cordata*

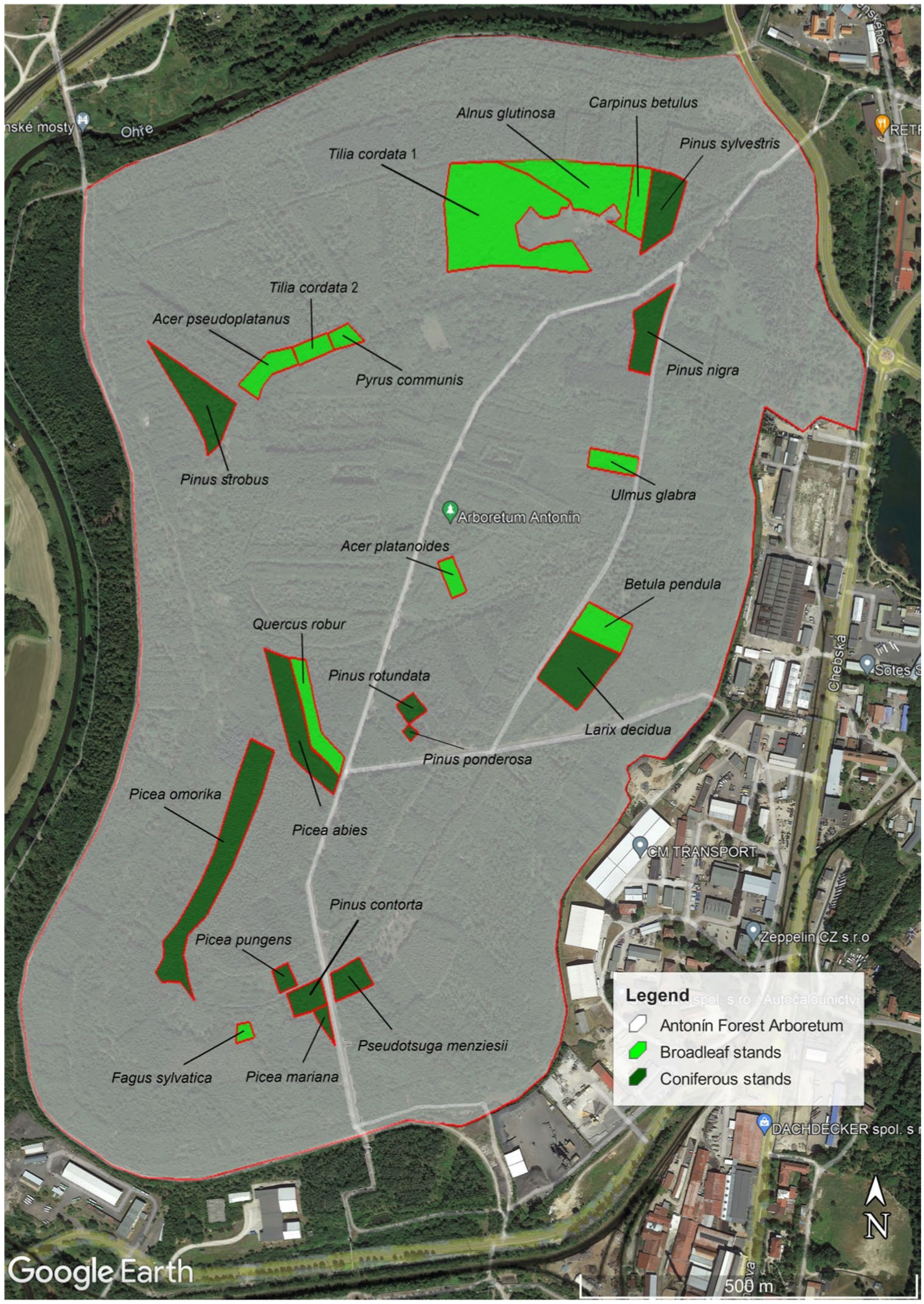
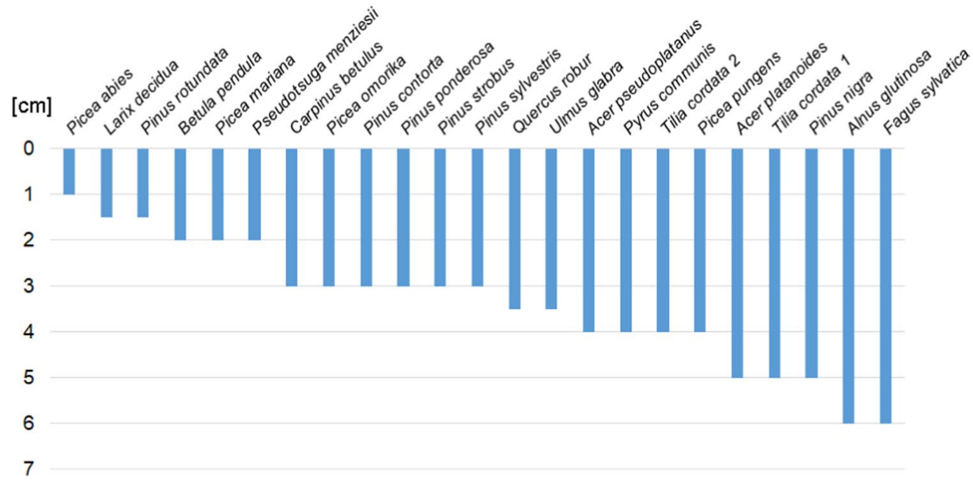


Fig. 1 Antonín Forest Arboretum with the selected stands. Broadleaved stands are marked light green, whereas coniferous stands are marked dark green (image source: Google Earth)

1 stand had a mean MCC of 46,71%, whereas *Tilia cordata* 2 had MCC of 35.86%.

Chemical properties

Mean soil pH values amongst stands varied between 4.80 and 7.07. Strongly acid soil (ranges between 4.6 and 5.55, according to Central Institute for Supervising and Testing in Agriculture of the Czech Republic—ÚKZÚZ) was noticed in *Picea mariana* (4.80) and *Picea abies* (5.43). *Pinus strobus*, *Carpinus betulus*, *Quercus robur*, *Pyrus communis*, *Picea pungens*, both *Tilia cordata* stands, *Pinus contorta*, *Fagus sylvatica*, *Acer pseudoplatanus*, *Betula pendula*, *Pseudotsuga menziesii*, *Pinus rotundata*, *Alnus glutinosa* and *Picea omorika* pH mean values ranged between 5.65 and 6.49, belonging to acid soil class (ranges 5.6–6.5). Weak acid to neutral soil reaction (6.6–7.2) was noticed in all remaining stands: *Pinus ponderosa*, *Larix decidua*, *Ulmus glabra*, *Acer platanoides*, *Pinus sylvestris*, and *Pinus nigra*. No soil

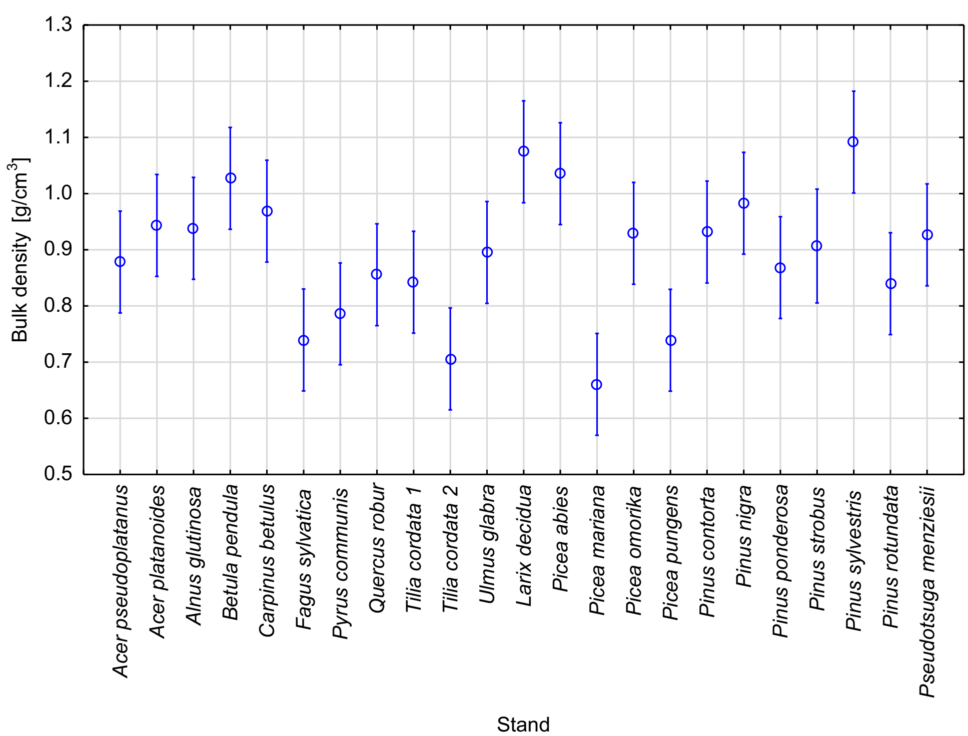


Graph 1 Organo-mineral (A) horizon thickness across stands

belonged to alkaline soil reaction (over 7.2). pH values and their variations across the stands are presented in Graph 4.

Oxidizable carbon content (C_{ox}) mean values ranged between 4.62 and 9.63%. The lowest average value was noticed in *Pinus sylvestris* (4.62%), followed by *Pinus nigra*, *Larix decidua* and *Pseudotsuga menziesii* (5.09%, 5.28%, 5.84%, respectively). *Alnus glutinosa*, *Pinus ponderosa*, *Pinus strobus, Ulmus glabra, Carpinus betulus*, and *Acer platanoides* C_{ox} mean values ranged from 6.21 to 7.00%. *Pinus contorta, Picea omorika, Tilia cordata* 1, and *Fagus sylvatica* C_{ox} values ranged from 7.17 to 7.46%, followed by *Betula pendula*, *Picea mariana*, *Pinus rotundata*, *Quercus robur*, and *Picea abies* (7.52–7.95%). *Acer pseudoplatanus* and *Picea pungens* had 8.30 and 8.50%, respectively, whereas the two highest and, considering the analysis of variance (apart from the lowest value noticed in *Pinus sylvestris*, *Pinus nigra* and *Larix decidua*), statistically significantly different C_{ox} values were noticed in *Pyrus communis* (9.37%) and *Tilia cordata* 2 (9.63%). The values are graphically represented in Graph 5.

Total carbon content means varied from 5.52 to 12.07%. The lowest values were noticed in *Pinus sylvestris* (5.52%), *Larix decidua* (6.25%), *P. nigra* (6.44%), *P. ponderosa* (6.47%), *Acer platanoides* (6.78%) and *Pseudotsuga menziesii* (6.89%). *Alnus glutinosa*, *Picea mariana*, *Picea omorika, Ulmus glabra*, *P. rotundata, Carpinus betulus,*



Graph 2 Bulk density values across stands (ANOVA, 0.95 confidence intervals)

Pinus strobus, *Pinus contorta, Quercus robur, Picea pungens, Betula pendula, Fagus sylvatica, Acer pseudoplatanus, Tilia cordata* 1 and *Picea abies* samples ranged from 7.35% to 9.63%. Like in the case with C_{ox}, the stands with the highest measured total C content were *Pyrus communis* (10.89%) and *Tilia cordata* 2 (12.07%). The values are graphically represented in Graph 6.

Total content of nitrogen mean values ranged from 0.24 to 0.67%. The lowest values were noticed in *Pinus sylvestris* (0.24%) and *Pinus strobus* (0.26%), whereas the highest ones were noticed in *Tilia cordata* 2 (0.63%) and *Pyrus communis* (0.67%) stands. The values can be seen in Graph 7.

C/N ratio mean values varied between 15.72 and 31.70. The lowest average ratio was noticed in *Ulmus glabra* (15.72) and *Acer platanoides* (15.73) followed by *Alnus glutinosa, Pyrus communis* and *Acer pseudoplatanus* (16.02–16.20). The highest mean ratio was noticed in *Pinus strobus* (31.70). Other species with relatively high C/N ratio were *Pinus contorta* (27.46) and *Picea abies* (28.34). The values can be seen in Graph 8.

Plant available nutrients and potentially toxic elements

The analysis of plant available nutrients has shown that the mean plant available phosphorus concentrations ranged from 0.66 mg/kg for *Larix decidua*, to 12.25 mg/kg in *Picea pungens*. Plant available Potassium values ranged between 214.62 mg/kg for *Picea abies* to 643.05 mg/kg for *Pinus ponderosa*. Mean available calcium level ranged from 1983.10 mg/kg for *Picea abies*, to 5769.83 mg/kg for *Pinus sylvestris*, whereas available magnesium values varied between 1249.95 mg/kg for *Acer platanoides* to 2732.34 mg/kg for *Picea pungens*. The values of these four elements concentrations can be seen in Graph 9.

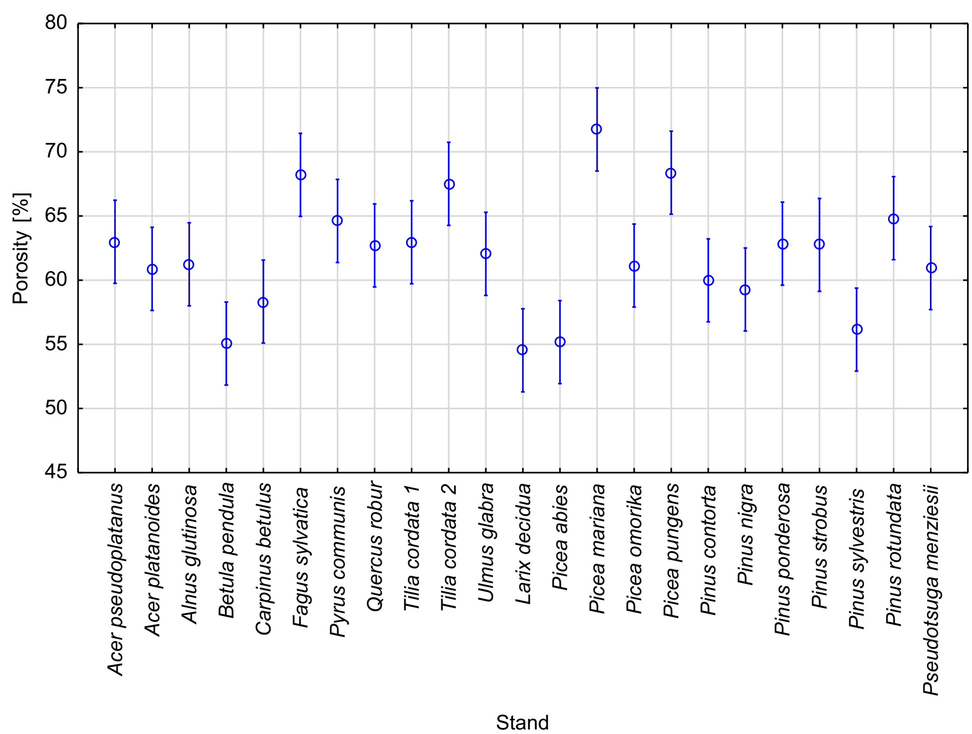
In Table 2, ranges of plant available macro-nutrients for broadleaved and coniferous forests in the Czech Republic are given.

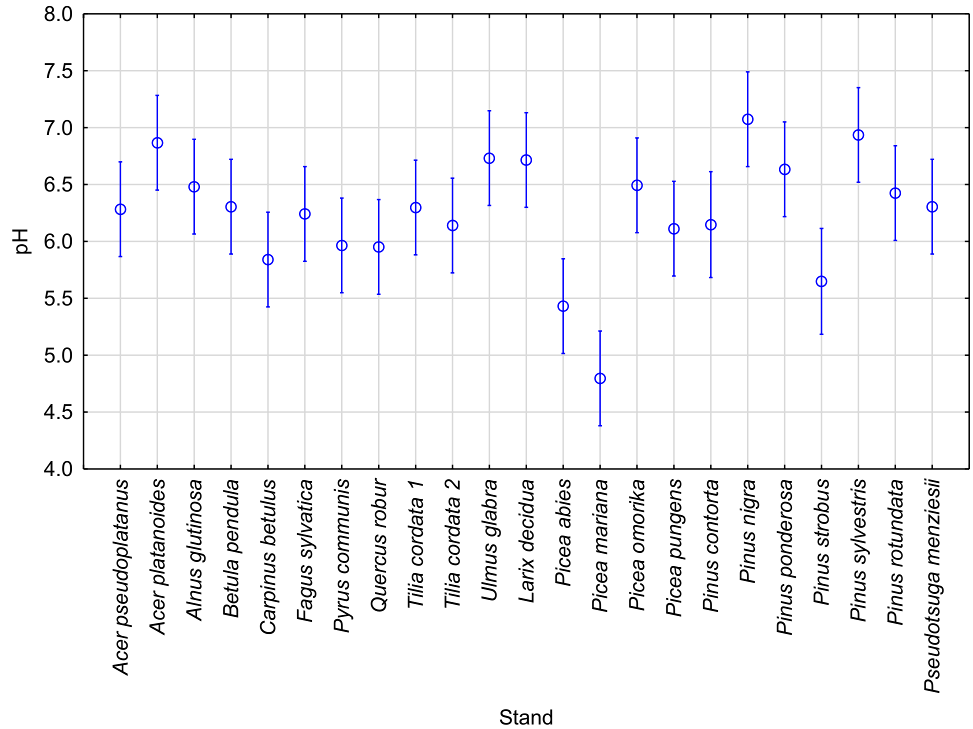
Average concentrations of cadmium ranged from 0.05 to 0.16 mg/kg, lead from 0.08 to 4 mg/kg, nickel from 1.35 to 4.08 mg/kg, manganese from 61.72 to 185.48 mg/kg, copper from 2.56 to 10.64 mg/kg, and zinc from 3.11 to 7.40 mg/kg. Toxicity limits of Cd, Pb, Ni, Mn, Cu and Zn and deficiency limits of Cu and Zn have been determined for each stand based on the average stand pH, according to Monterroso et al., (1999). Zinc and copper concentrations of all stands have shown to be deficient. Manganese toxicity limits have been exceeded in at least one of the measured samples in 13 stands, according to Monterroso et al. (1999). However, according to ÚKZÚZ (n.d.), these plant available Mn concentrations (using the same extracting agent as Monterroso et al. (1999)) are considered to be very low or low. Nickel exceeded the toxicity limits in *Picea mariana*. Concentrations of other elements were within the limits.

A summary of selected physical and chemical properties can be seen in Tables 3 and 4.

Results of Principal Component Analysis (PCA) are shown in Graphs 10 and 11.

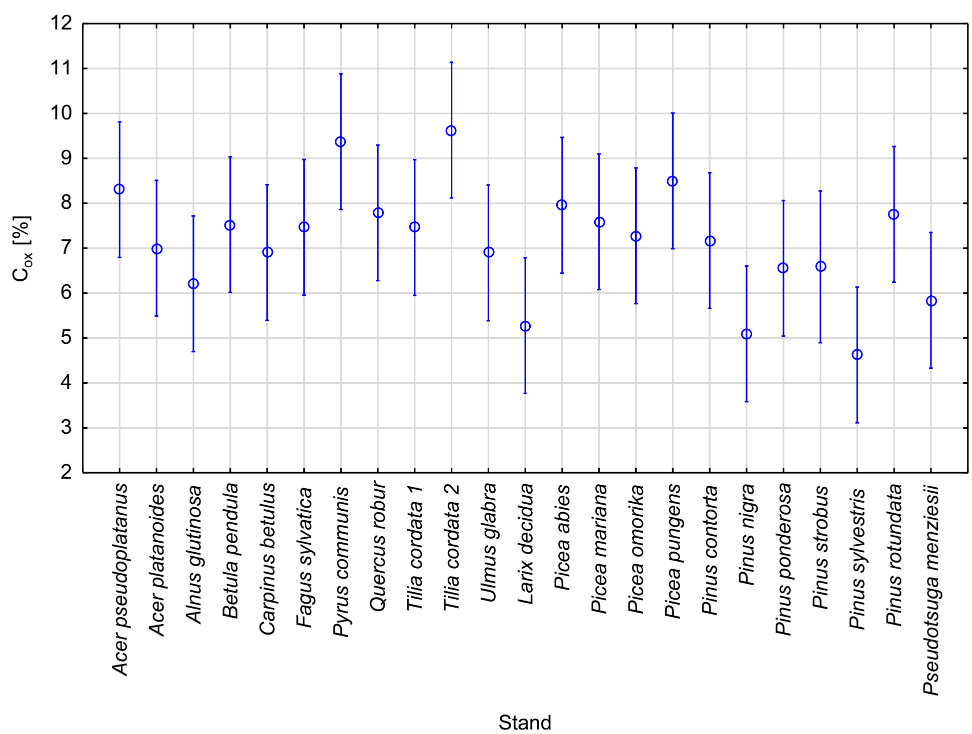
Graph 3 Porosity values across stands (ANOVA, 0.95 confidence intervals)





Graph 4 pH values across stands (ANOVA, 0.95 confidence intervals)

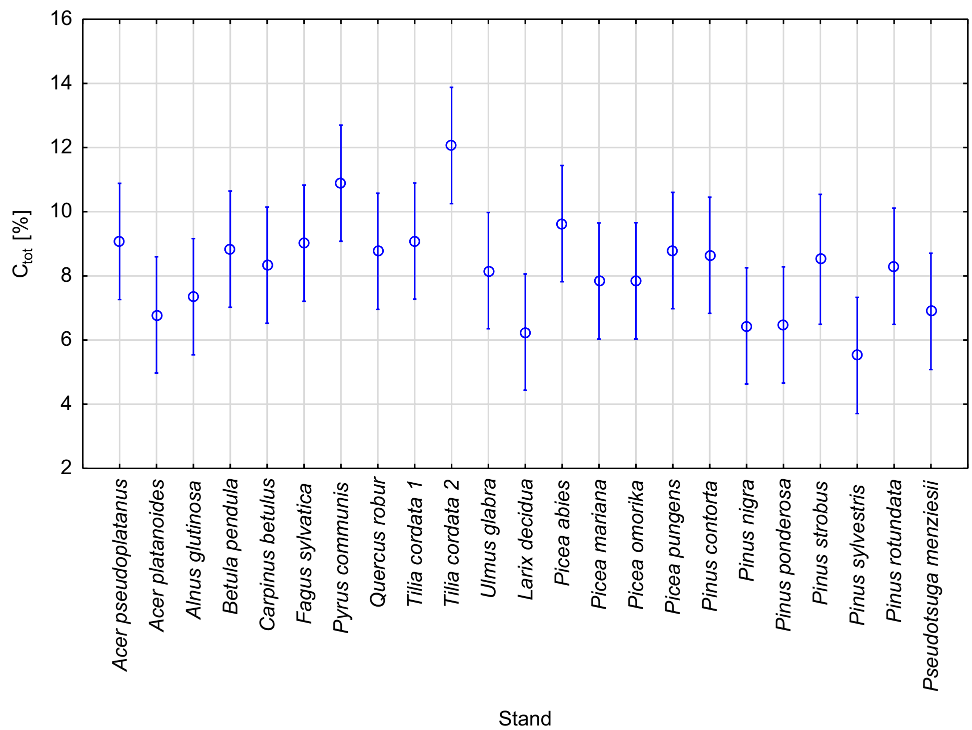
Oxidizable (C_{ox}) and total carbon (C_{tot}) have shown a strong positive correlation in all stands, and they negatively correlated with particle density, maximum capillary capacity, and pH. Bulk density has shown a strong negative correlation with total nitrogen (N_{tot}) and porosity. pH correlated with available Ca, whereas available K and Mg have shown a somewhat weaker positive correlation between each other.



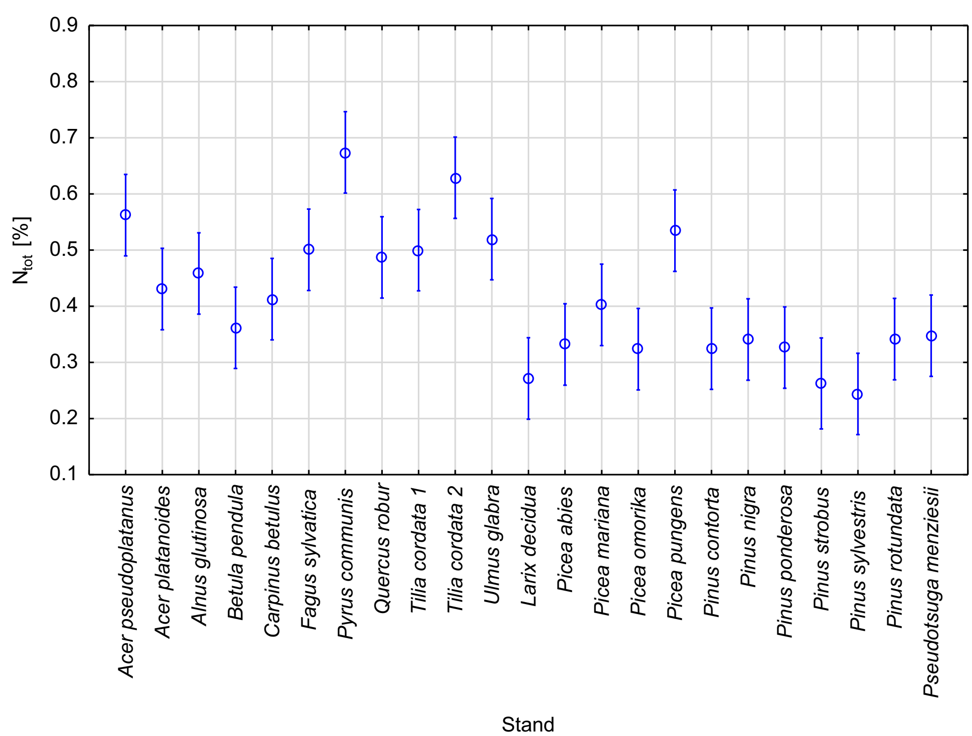
Graph 5 C_{ox} values across stands (ANOVA, 0.95 confidence intervals)

Discussion

By observing the thickness of the newly formed soil on Antonin soil heap amongst the stands incorporated in this research, high variability can be noticed. Some stands (*Picea abies*, for instance) have exhibited a very low level of soil formation ability (which was somewhat expected and hypothesized), barely reaching 1 cm, whereas others, like *Fagus sylvatica* and *Alnus glutinosa*, have developed



Graph 6 Total C content across stands (ANOVA, 0.95 confidence intervals)



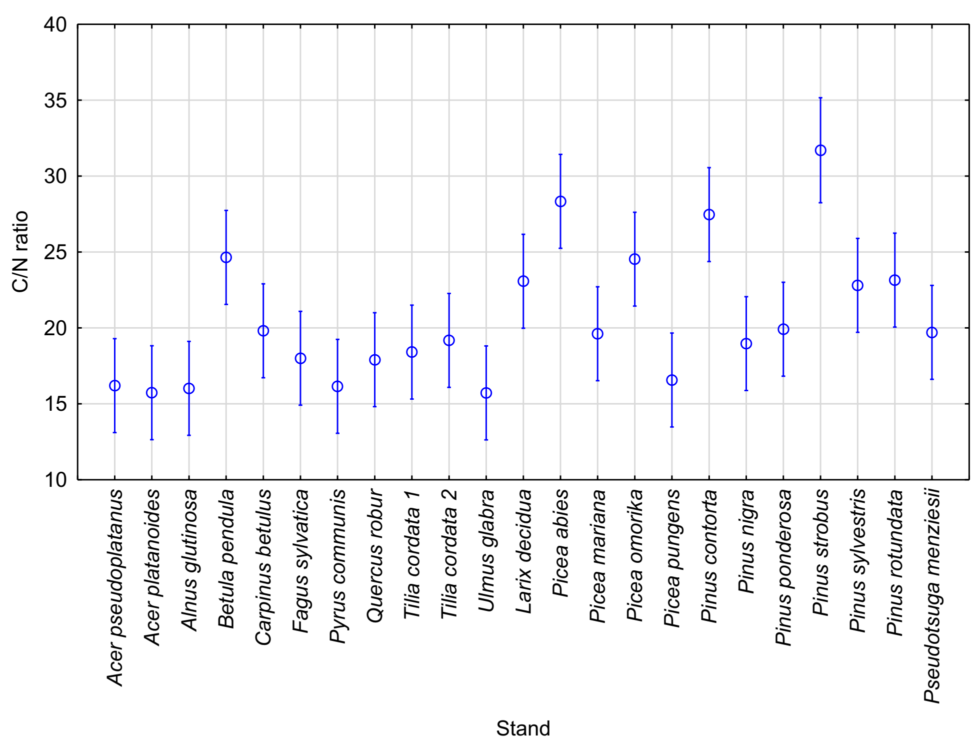
Graph 7 Total N content across stands (ANOVA, 0.95 confidence intervals)

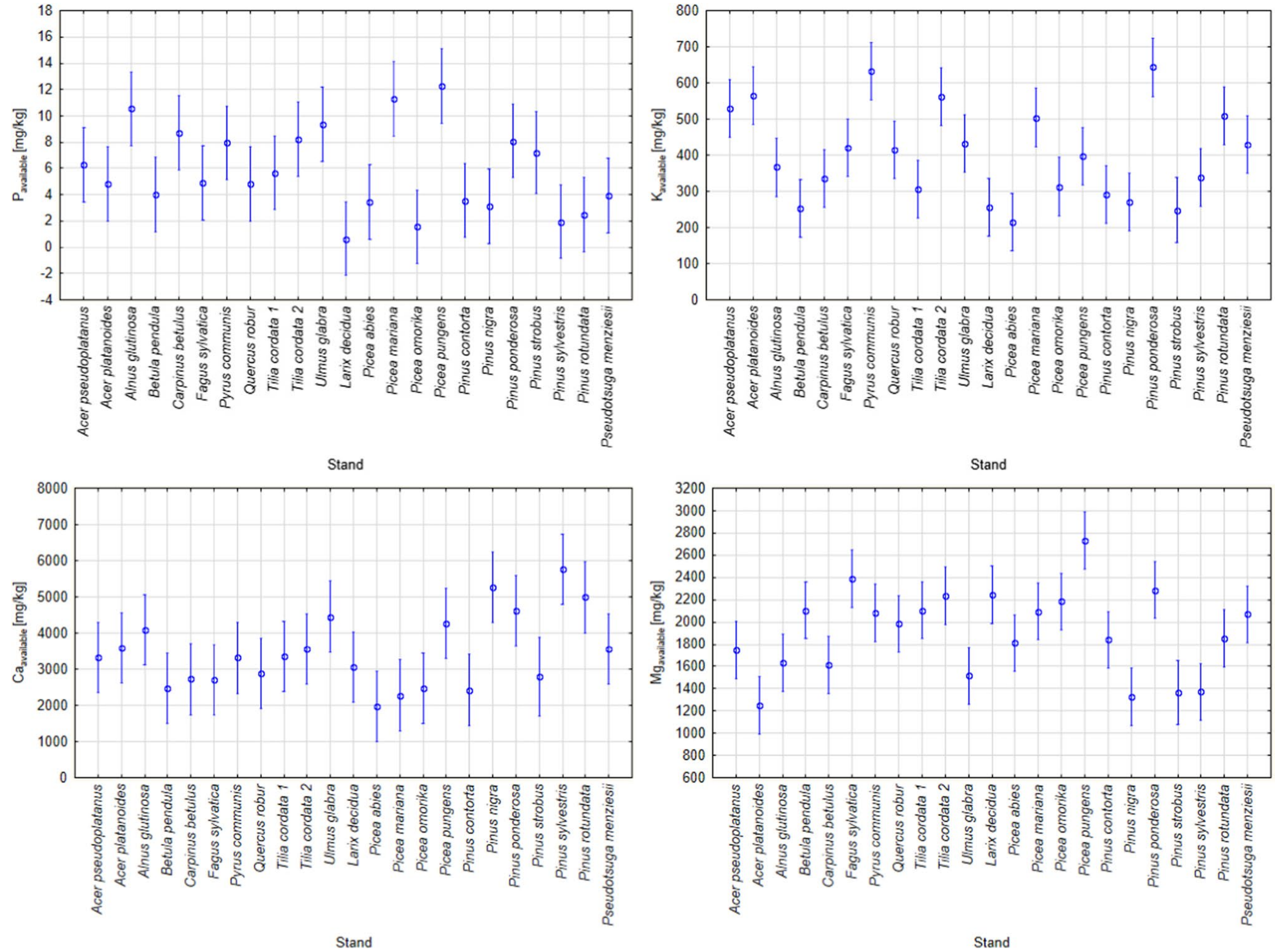
what can be considered a fairly thick, 6 cm A horizon during a period of only 50 years. The initial expectation regarding thickness was that most broadleaves will produce more organo-mineral soil, due to the higher litter input and turnover rates. Once again, alders (*Alnus* sp.), known from a number of studies on post-mining sites for their litter quality, biodiversity values, nitrogen fixation and nutrient input (Bradshaw 1997; Pietrzykowski 2019; Rawlik et al. 2021; Remeš and Šíša, 2007; Šourková et al. 2005), and changing the quality of humic substances (Borůvka and Kozák, 2001; Hendrychová 2008; Pietrzykowski 2019) have proved themselves to be valuable afforestation species for post-mining sites. Apart from some exceptions (*Pinus nigra* and *Picea pungens* from conifers, who have shown unexpectedly high values, and *Betula pendula* and *Carpinus betulus* from broadleaves, which have shown somewhat disappointing values), it was noticed that under most coniferous species, A soil layer thinner than 3 cm had been developed, whereas most broadleaves had developed an organo-mineral soil horizon 4–6 cm thick. Birch (*Betula pendula*), mentioned to support the most active and largest number of soil microbial communities (Chodak and Niklińska 2010), and hornbeam (*Carpinus betulus*), mentioned to support, alongside alders, lindens and elms, the creation of high quality humus, have shown the lowest values in terms of formation of the organo-mineral horizon. Larch (*Larix decidua*), known for being frequently planted on extreme sites because of its ameliorative properties (Hendrychová 2008), was also one of the poorest when formed A horizon thickness is taken into question. *Pinus nigra* has been observed to be able to form a thicker organo-mineral horizon than some broadleaved species (like *Robinia pseudoacacia*) on spoil heaps before (Filcheva et al. 2000). Frouz et al. (2009) have obtained similar trends to the results presented in this paper, on 22–30 year old reclamation sites near Sokolov, where alder, followed by lime, have created the thickest A layer (9.8 and 7.1 cm, respectively), and spruce (*Picea omorika* and *P. pungens*) created very shallow ones (0.2 cm). Larch, oak and pine (*Pinus contorta* & *P. nigra*) values were in between 2.2 and 5.1 cm.

The difference in A horizon thickness of linden stands on different slopes has shown that the stand on flatter terrain helped create somewhat thicker soil (1 cm difference). This can be attributed to factors such as water leaching and lodging, exposure to sunlight, erosion processes being more abundant with greater gradient and certainly requires further looking into.

Researches have compared bulk densities of soil formed under the same tree vegetation on reclaimed and semi-natural sites of the Sokolov area and shown that the bulk density of mineral layers of reclaimed sites was generally greater than in semi-natural ones (Šourková et al. 2005). By definition, mine restoration, the most complicated and sometimes impossible to do, is returning the area to the conditions that were present before mining operations (Bradshaw 1997; Lima et al. 2016), so it can be presumed that lower bulk density of the organo-mineral layer is something to strive to.

Graph 8 C/N ratio between the stands (ANOVA, 0.95 confidence intervals)





Graph 9 Available phosphorus, potassium, calcium and magnesium across the stands (ANOVA, 0.95 confidence intervals)

Table 2 Evaluation of ranges of significant, plant available nutrients determined by Mehlich III method (compiled from ÚKZÚZ, n.d.)

Element conc. (mg/kg)	Forest	1 Insufficient	2 Low	3 Sufficient	4 High	5 Very high
P	Coniferous	≤ 6	7–13	14–25	26–40	> 40
	Broadleaved	≤ 8	9–17	18–30	31–50	> 50
K	Coniferous	≤ 50	51–80	81–110	111–160	> 160
	Broadleaved	≤ 70	71–110	111–150	151–190	> 190
Ca	Coniferous	≤ 150	151–350	351–680	681–1270	> 1270
	Broadleaved	≤ 310	311–630	631–1200	1201–1870	> 1870
Mg	Coniferous	≤ 35	36–65	66–120	121–220	> 220
	Broadleaved	≤ 45	46–90	91–160	161–250	> 250

In sites reclaimed by utilising heavy machinery, especially on clayey substrates, where there is a greater risk of compaction, this is of even greater importance. Bulk density and particle density are used for calculating porosity, and thus, species who have shown to excel in this manner (low bulk, high porosity) were Fagus sylvatica, *Tilia cordata*, *Picea mariana* and *Picea pungens*. On the other hand, species which have shown more compacted soil in the initial 5 cm were *Picea abies*, *Larix decidua* and *Betula pendula*. However, this should be addressed carefully, since these were also the species who've had the thinnest A horizon values (1, 1.5, and 2 cm, respectively). Thus, a lot of underlying, clay-containing material has been incorporated in the Kopecky cylinders, as previously stated in the Materials and Methods.

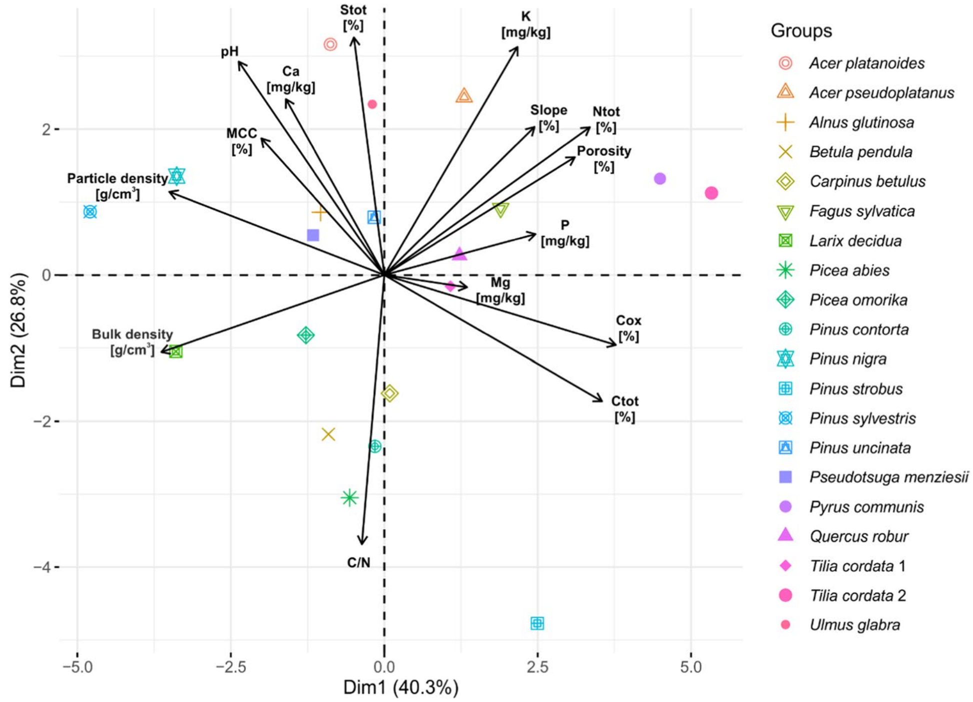
Table 3 Mean values and homogenous groups of selected soil properties

Stand name	pH	Bulk density (g/cm^3)	Particle density (g/cm^3)	Porosity (%)	Max. cap. porosity (%)	C_{org} (%)	C_{tot} (%)	N_{tot} (%)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)
Acer platanoides	6.90^{cd}	0.94^{bcde}	2.41^{bc}	60.88^{abcd}	50.91^{de}	7.19^{ab}	6.92^{abc}	0.43^{abcdef}	4.84^{abcdef}	565.03^{efg}	3588.04^{abcde}	1249.95^{a}
Acer pseudoplatanus	6.25^{bcd}	0.88^{abcde}	2.35^{abc}	62.99^{abcd}	53.34^{e}	8.66^{ab}	9.40^{abc}	0.56^{efg}	6.28^{abcdef}	529.45^{defg}	3328.12^{abcde}	1750.85^{abcde}
Alnus glutinosa	6.67^{cd}	0.94^{bcde}	2.42^{bc}	61.24^{abcd}	53.26^{e}	6.12^{ab}	7.61^{abc}	0.46^{bcdef}	10.53^{def}	366.84^{abcde}	4082.73^{abcde}	1636.15^{abcd}
Betula pendula	6.25^{bcd}	1.03^{de}	2.29^{abc}	55.06^{a}	45.37^{bcde}	7.59^{ab}	8.91^{abc}	0.36^{abcde}	4.00^{abcde}	253.61^{ab}	2462.26^{ab}	2105.73^{cdef}
Carpinus betulus	6.06^{bcd}	0.97^{cde}	2.28^{abc}	58.33^{ab}	40.19^{abc}	7.54^{ab}	9.17^{abc}	0.41^{abcde}	8.71^{bcdef}	335.67^{abcd}	2724.85^{abc}	1615.63^{abcd}
Fagus sylvatica	6.32^{bcd}	0.74^{abc}	2.29^{abc}	68.21^{de}	45.51^{cde}	7.85^{ab}	9.55^{abc}	0.50^{cdefg}	4.92^{abcdef}	421.04^{abcde}	2697.61^{abc}	2388.45^{ef}
Larix decidua	6.74^{cd}	1.07^{e}	2.37^{abc}	**54.53**^{a}	50.21^{de}	5.30^{ab}	**6.20**^{ab}	**0.27**^{ab}	**0.66**^{a}	256.80^{ab}	3066.33^{abcd}	2246.91^{def}
Picea abies	5.71^{abc}	1.04^{de}	2.31^{abc}	55.17^{a}	52.49^{de}	8.05^{ab}	9.65^{abc}	0.33^{abc}	3.44^{abcd}	**214.62**^{a}	**1983.10**^{a}	1810.97^{abcde}
Picea mariana	**4.76**^{a}	*0.66*^{a}	2.35^{abc}	*71.74*^{e}	47.21^{cde}	6.98^{ab}	7.50^{abc}	0.44^{abcdef}	11.28^{ef}	504.17^{cdefg}	2280.16^{ab}	2095.13^{cdef}
Picea omorika	6.56^{bcd}	0.93^{bcde}	2.40^{bc}	61.14^{abcd}	47.34^{cde}	7.67^{ab}	8.20^{abc}	0.32^{abc}	1.55^{ab}	312.76^{abc}	2464.65^{ab}	2183.77^{cdef}
Picea pungens	6.04^{abcd}	0.74^{abc}	2.33^{abc}	68.38^{de}	51.16^{de}	8.34^{ab}	8.89^{abc}	0.56^{defg}	*12.25*^{f}	397.85^{abcde}	4265.40^{abcde}	*2732.34*^{f}
Pinus contorta	6.15^{bcd}	0.93^{bcde}	2.31^{abc}	59.99^{abcd}	38.73^{abc}	7.67^{ab}	9.30^{abc}	0.32^{abc}	3.57^{abcd}	291.42^{ab}	2425.09^{ab}	1839.49^{abcde}
Pinus nigra	*7.16*^{d}	0.98^{cde}	2.40^{bc}	59.27^{abc}	46.43^{cde}	5.12^{ab}	6.31^{ab}	0.34^{abc}	3.10^{abcd}	270.23^{ab}	5266.88^{de}	1330.19^{ab}
Pinus ponderosa	6.59^{cd}	0.87^{abcde}	2.41^{bc}	62.85^{abcd}	*54.42*^{e}	6.64^{ab}	6.92^{abc}	0.35^{abcde}	8.08^{abcdef}	643.05^{g}	4628.92^{bcde}	2287.20^{def}
Pinus rotundata	6.30^{bcd}	0.84^{abcde}	2.43^{c}	64.83^{bcde}	44.82^{bcde}	8.06^{ab}	6.46^{ab}	0.34^{abc}	2.48^{abc}	508.67^{cdefg}	4989.16^{cde}	1854.95^{abcde}
Pinus strobus	5.27^{ab}	0.85^{abcde}	2.43^{c}	62.96^{abcd}	**32.56**^{abc}	6.58^{ab}	8.52^{abc}	0.34^{abc}	8.00^{abcdef}	231.79^{ab}	2788.21^{abcd}	**1209.95**^{a}
Pinus sylvestris	6.83^{cd}	**1.09**^{e}	**2.47**^{c}	56.15^{ab}	47.31^{cde}	**4.88**^{a}	**5.65**^{a}	**0.24**^{a}	1.95^{abc}	339.30^{abcd}	*5769.83*^{e}	1371.08^{ab}
Pseudotsuga menziesii	6.45^{bcd}	0.93^{bcde}	2.38^{abc}	60.94^{abcd}	43.30^{cde}	5.64^{ab}	6.63^{ab}	0.35^{abcd}	3.93^{abcde}	429.15^{bcdef}	3569.28^{abcde}	2069.27^{cdef}
Pyrus communis	5.94^{abcd}	0.79^{abcd}	2.20^{ab}	64.62^{bcde}	40.05^{abc}	9.72^{b}	11.38^{bc}	*0.67*^{g}	7.94^{abcdef}	633.26^{fg}	3312.54^{abcde}	2079.92^{cdef}
Quercus robur	6.13^{bcd}	0.86^{abcde}	2.28^{abc}	62.71^{abcd}	51.14^{de}	8.17^{ab}	9.05^{abc}	0.49^{cdefg}	4.83^{abcdef}	414.25^{abcde}	2893.86^{abcd}	1982.31^{bcde}
Tilia cordata 1	6.21^{bcd}	0.84^{abcde}	2.27^{abc}	62.96^{abcd}	46.71^{cde}	7.34^{ab}	8.81^{abc}	0.50^{cdefg}	5.66^{abcdef}	306.11^{abc}	3348.98^{abcde}	2104.72^{cdef}
Tilia cordata 2	6.19^{bcd}	0.71^{ab}	*2.17*^{a}	67.51^{cde}	35.86^{abc}	*9.76*^{b}	*11.86*^{c}	*0.63*^{fg}	8.20^{bcdef}	562.48^{efg}	3553.81^{abcde}	2237.23^{def}
Ulmus glabra	6.77^{cd}	0.90^{abcde}	2.36^{abc}	62.05^{abcd}	52.62^{de}	6.99^{ab}	8.05^{abc}	0.52^{cdefg}	9.34^{cdef}	433.11^{bcdef}	4455.16^{abcde}	1513.94^{abc}

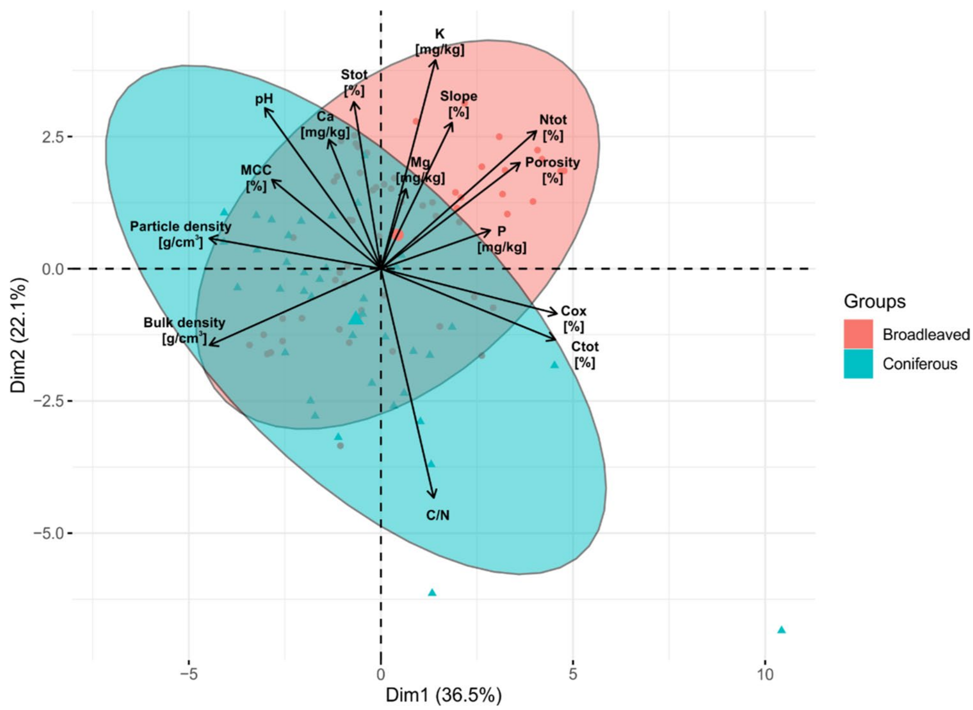
Values highlighted bold annotate negative, whereas italic annotate positive extremes

Table 4 Average values and standard deviations of selected soil properties

Stand name	Hor. A (cm)	Slope (°)	SD	pH (CaCl2)	SD	Bulk density (g/cm^3)	SD	Particle density (g/cm^3)	SD	Porosity (%)	SD	ϴMCC (%)	SD	C_{ox} (%)	SD	C_{tot} (%)	SD	N_{tot} (%)	SD	P (mg/kg)	SD	K (mg/kg)	SD	Ca (mg/kg)	SD	Mg (mg/kg)	SD
Acer platanoides	5	8.52	1.77	6.87	0.10	0.94	0.03	2.41	0.03	60.88	1.86	50.91	2.30	7.00	0.78	6.78	0.58	0.43	0.03	4.84	1.57	565	80	3588	149	1250	87
Acer pseudoplatanus	4	8.48	0.84	6.28	0.11	0.88	0.08	2.37	0.08	62.99	2.57	53.34	1.54	8.30	1.70	9.07	1.55	0.56	0.11	6.28	1.80	529	93	3328	226	1751	75
Alnus glutinosa	6	0.8	0.34	6.48	0.62	0.94	0.07	2.42	0.01	61.24	2.79	53.26	4.21	6.21	0.60	7.35	1.01	0.46	0.06	10.53	8.12	367	32	4083	1880	1636	178
Betula pendula	2	1.22	0.35	6.31	0.24	1.03	0.12	2.29	0.03	55.06	5.32	45.37	2.30	7.52	0.65	8.83	0.79	0.36	0.03	4.00	1.94	254	44	2462	342	2106	122
Carpinus betulus	3	1.16	0.26	5.84	0.56	0.97	0.17	2.31	0.13	58.33	5.16	40.19	9.24	6.90	2.46	8.33	3.06	0.41	0.13	8.71	5.56	336	38	2725	393	1616	146
Fagus sylvatica	6	2.74	1.01	6.24	0.21	0.74	0.06	2.32	0.07	68.21	1.58	45.51	3.23	7.46	0.91	9.02	1.21	0.50	0.06	4.92	2.03	421	40	2698	181	2388	162
Larix decidua	1.5	1.6	0.63	6.72	0.08	1.07	0.11	2.36	0.04	54.53	4.46	50.21	3.00	5.28	0.48	6.25	0.58	0.27	0.03	0.66	0.39	257	33	3066	619	2247	93
Picea abies	1	5.04	0.77	5.43	0.60	1.04	0.10	2.31	0.08	55.17	4.04	52.49	1.72	7.95	2.34	9.63	3.05	0.33	0.06	3.44	0.94	215	7	1983	406	1811	342
Picea mariana	2	12.13	0.00	4.80	0.48	0.66	0.07	2.32	0.09	71.74	3.00	47.21	1.47	7.59	1.84	7.84	1.92	0.40	0.10	11.28	3.26	504	118	2280	599	2095	211
Picea omorika	3	0.54	0.15	6.49	0.24	0.93	0.05	2.39	0.03	61.14	1.97	47.34	1.92	7.28	1.63	7.85	1.64	0.32	0.02	1.55	0.92	313	64	2465	220	2184	110
Picea pungens	4	1.37	0.00	6.11	0.49	0.74	0.07	2.33	0.04	68.38	2.88	51.16	3.25	8.50	0.86	8.79	1.06	0.53	0.09	12.25	0.99	398	41	4265	208	2732	181
Pinus contorta	3	1.16	0.66	6.15	0.61	0.93	0.10	2.32	0.06	59.99	3.61	38.73	6.36	7.17	1.62	8.64	2.16	0.32	0.07	3.57	2.29	291	102	2425	1016	1839	842
Pinus nigra	5	0.68	0.17	7.07	0.19	0.98	0.06	2.41	0.04	59.27	2.21	46.43	2.31	5.09	0.84	6.44	0.43	0.34	0.02	3.10	0.71	270	25	5267	1168	1330	116
Pinus ponderosa	3	2.38	0.00	6.63	0.18	0.87	0.05	2.41	0.02	62.85	2.31	54.42	2.70	6.55	0.48	6.47	0.50	0.33	0.04	8.08	2.49	643	62	4629	833	2287	217
Pinus rotundata	1.5	2.18	1.12	6.42	0.69	0.84	0.14	2.37	0.13	64.83	4.03	44.82	5.52	7.75	3.34	8.30	4.00	0.34	0.10	2.48	1.74	509	151	4989	2454	1855	86
Pinus strobus	3	0.9	0.16	5.65	0.26	0.91	0.05	2.43	0.12	62.75	0.83	33.46	1.88	6.58	2.32	8.52	2.91	0.26	0.06	7.21	3.22	248	33	2806	793	1366	259
Pinus sylvestris	3	2.06	0.57	6.94	0.54	1.09	0.05	2.49	0.05	56.15	1.48	47.31	1.34	4.62	1.17	5.52	0.61	0.24	0.02	1.95	0.85	339	54	5770	1918	1371	168
Pseudotsuga menziesii	2	1.5	0.30	6.31	0.53	0.93	0.10	2.37	0.03	60.94	3.95	43.30	2.48	5.84	0.98	6.89	1.19	0.35	0.04	3.93	2.25	429	69	3569	1164	2069	250
Pyrus communis	4	8.94	0.77	5.97	0.37	0.79	0.05	2.22	0.06	64.62	1.47	40.05	3.99	9.37	1.18	10.89	1.32	0.67	0.08	7.94	2.48	633	133	3313	414	2080	312
Quercus robur	3.5	5.06	0.74	5.95	0.60	0.86	0.11	2.29	0.12	62.71	3.53	51.14	2.73	7.79	1.50	8.77	2.06	0.49	0.09	4.83	1.49	414	175	2894	645	1982	183
Tilia cordata 1	5	2.72	0.34	6.30	0.43	0.84	0.15	2.26	0.10	62.96	5.41	46.71	2.80	7.46	1.65	9.09	2.40	0.50	0.15	5.66	3.37	306	29	3349	1239	2105	309
Tilia cordata 2	4	9.42	0.99	6.14	0.25	0.71	0.07	2.17	0.08	67.51	2.48	35.86	3.46	9.63	0.88	12.07	1.27	0.63	0.06	8.20	2.12	562	92	3554	143	2237	114
Ulmus glabra	3.5	2.76	0.27	6.73	0.17	0.90	0.03	2.36	0.01	62.05	1.03	52.62	1.41	6.90	0.69	8.16	0.46	0.52	0.03	9.34	2.35	433	43	4455	407	1514	185



Graph 10 Principal Component Analysis (average values of 5 samples per stand are presented)



Graph 11 Principal component analysis (individual samples of broadleaved and coniferous samples, and their distribution are presented)

In contrary to this, *Picea mariana*, which also had only 2 cm of A horizon developed, was one of the best in this manner. A study in the Czech Republic on afforested, previously agricultural sites (Vopravil et al. 2021), has shown that soil under *Pinus sylvestris* had a greater bulk density than soils under a mixed *Acer platanoides* and *Quercus robur* stand, which corresponds to the data obtained in this research.

High water retention values in all stands can probably be attributed to the clayey parent material; however, they did not seem to show any particular trends related to the observed A horizon depth or the stands being broadleaved or coniferous. A relatively high difference in maximum capillary capacity and other water retention parameters of *Tilia cordata* stands can be explained by the higher underground water levels in the stand with flatter terrain (*Tilia cordata* 1), more humid overall conditions, and direct infiltration of water to the soil on one hand, and processes of surface and internal erosion being more pronounced in the stand with the greater slope (*Tilia cordata* 2) on the other. *Pinus sylvestris* has shown lower maximum capillary retention values compared to both *Acer platanoides* and *Quercus robur* which is comparable to the results gained by Vopravil et al. (2021).

Differences amongst stands in terms of oxidizable carbon content (C_{ox}) were the most noticeable in the stand with the lowest (*Pinus sylvestris*) and two stands with the highest content (*Pyrus communis*, *Tilia cordata* 2). In a research from Poland, Rawlik et al. (2021) have shown differences in C content amongst *Pinus sylvestris*, *Betula pendula* and *Alnus glutinosa*. In their research, *Alnus glutinosa* has shown the greatest C values, with 2–3 times greater values then the other two species, depending on the textural class they were on. In our research, birch and alder had greater values than Scots pine, which has shown the lowest value out of all 23 stands.

C/N ratio results were in accordance with ICP Forests ranges of mineral topsoils in Europe (Cools et al. 2014), which ranged between 10 and 32, whereas ours were between 15.72 and 31.70. According to Cools et al. (2014), tree species are the most important explanatory variable for C/N in forest floors and topsoils. In their comprehensive research, N-fixing species like *Robinia pseudoacacia* and *Alnus glutinosa* have shown the lowest C/N values, whereas *Pseudotsuga menziesii* had the greatest ones. They have stated that in the topsoil, the biggest differences in C/N ratio were observed between broadleaved and coniferous species, which is, with the exceptions of *Betula pendula* and *Carpinus betulus* (which were also the broadleaved species with the shallowest A horizon developed), true for our research. Moreover, in our research, amongst the conifers, the lowest values (< 20) were noticed in *Picea pungens*, *Pinus nigra* and *Pseudotsuga menziesii*, whereas some others, like *Picea omorika*, *Picea abies* and certain pines (*P. contorta*, *P. strobus*) had values way over 25. Compared to the results from Mudrák et al. (2010), whose research was performed in Sokolov mining region, our C/N ratios were fairly similar in *Alnus glutinosa*, *Tilia cordata* and *Picea pungens*, but our values were significantly higher in *Larix decidua*, *Picea omorika*, *Pinus contorta* and *Pinus nigra*. Compared to the results obtained by Woś et al. (2022), who've shown that the C/N ratio in alder, Scots pine and birch was *Alnus* < *Betula* < *Pinus*, (14, 17 and 18, respectively) in our case, it was *Alnus* < *Pinus* < *Betula*, and all of our C/N values were slightly greater (~ 16, 23 and 25, respectively).

Major plant available nutrients (P, K, Ca, Mg) analysis has shown that contents of K, Ca and Mg were very high in all stands, but P levels were either insufficient or low. Phosphorus is often referred to as a deficient element on post-mining sites (Coppin and Bradshaw 1982; Sheoran et al. 2008, 2010). According to the criteria from ÚKZÚZ, n.d., *Larix decidua*, *Picea omorika*, *Pinus sylvestris*, *Pinus rotundata, Pinus nigra*, *Picea abies*, *Pinus contorta*, and *Pseudotsuga menziesii* were coniferous stands where insufficient levels of P were recorded. *Pinus strobus*, *Pinus ponderosa*, *Picea mariana* and *Picea pungens* stands have shown a low level of P. In broadleaved stands, insufficient P was noticed in *Betula pendula*, *Quercus robur*, *Tilia cordata*, *Pyrus communis* and both maple stands (*A. pseudoplatanus, A. platanoides*), whereas low P concentrations were noticed in *Carpinus betulus*, *Ulmus glabra* and *Alnus glutinosa*.

Rawlik et al. (2021) have analysed soil properties of reclaimed mine soil under *Betula pendula*, *Alnus glutinosa* and *Pinus sylvestris* in Belchatow, Poland, and have also determined insufficient and low levels of available phosphorus. In their research, however, *Alnus glutinosa* has shown the lowest levels out of all three species analysed, whereas in our research, it was, following *Picea pungens* and *Picea mariana*, one of the stands with the highest average P levels tested, and a stand where the greatest P levels in a single sample were noticed. Results obtained by Mudrák et al. (2010) at a spoil heap near Sokolov have shown that soil under *Tilia cordata*, *Quercus robur*, *Alnus glutinosa*, *Larix decidua*, *Picea omorika* and *Picea pungens*, *Pinus contorta* and *Pinus nigra* stands had also exhibited low levels of water-soluble phosphorus, not exceeding 20 mg/kg. Although the highest content was measured under *Tilia cordata*, no statistical significance between the stands was found.

It is noticeable that, in our research, we have got very high values of Mg (10–20 fold) and K (4–8 fold) compared to the ones in Rawlik et al., (2021), whereas the Ca values have not shown such great variations. However, from their work, there is a noticeable difference between the concentrations of available elements in locations on different textural classes, which seems to affect the elemental concentrations way more than the tree species can. Mudrák et al. (2010) have also noted high available Ca levels in Sokolov.

After determining the toxicity limits from Monterroso et al. (1999), it was shown that in 8 out of 23 stands, the average manganese levels exceeded toxicity limits, and in 13 out of 23 stands (*Carpinus betulus*, *Fagus sylvatica*, *Pyrus communis*, *Quercus robur*, *Tilia cordata* 2, *Ulmus glabra*, *Larix decidua*, *Picea abies*, *Picea mariana*, *Picea omorika*, *Picea pungens*, *Pinus contorta* and *Pinus ponderosa*), at least one of the 5 samples per stand has been above the limit values. The distribution of manganese concentrations does not seem to be influenced by either conifer/broadleaf type, pH, depth of formed A horizon, nor the proximity of stands to each other. It is worth noting that Monterroso et al. (1999) did not specify which exact plant species are affected by the elemental toxicity described in their publication, and some more recent findings show that various plants can have very different tolerances and accumulation potentials for toxic elements (Michopoulos et al. 2021). Moreover, according to the values defined by ÚKZÚZ (n.d.), available manganese concentrations observed within the Antonín forest arboretum fall between very low and low. The concentrations noted as "very high", according to this source, range from 1000 to 1300 mg/kg, and no values are mentioned as potentially toxic. Michopoulos et al. (2021) have performed available manganese measurements (however, using different extracting agent—DTPA solution) of different forest soils in Greece, where the available Mn ranged between 114 and 196 mg/kg, and concluded that these ranges were sufficient for plant growth, and that the lower limit was 3.5 mg/kg. Once again, no toxicity limits for forest soils were mentioned.

4 out of 5 samples in *Picea mariana* stand have exceeded nickel toxicity values, whereas other stands have been within the limits. This is most probably caused by the strongly acid soil under *Picea mariana*, because pH is a known factor of increased mobility of PTE in the soil, and directly affects the toxicity and deficiency limits given by Monterroso et al. (1999). Other analysed PTEs (Cd, Pb, Cu and Zn) have been under the toxicity limits, and Cu and Zn were, in all of the stands, below deficiency limits. The problem of mining site soils exhibiting toxic Mn, and deficient Zn and Cu levels have previously been reported by Monterroso et al. (1999).

When the results of the mentioned physical and chemical analyses are compared amongst the species (stands), and points (positive or negative) are added depending on significant differences observed, the species which exceled in properties which are generally considered benefitial (deeper A horizon—faster soil formation, low bulk density, high porosity, pH and nutrient levels), were *Alnus glutinosa*, *Fagus sylvatica*, *Tilia cordata*, *Pyrus communis*, *Picea pungens* and *Pinus ponderosa*. Species with a greater number of negative points were *Betula pendula*, *Larix decidua*, *Picea abies*, *Pinus rotundata*, *Pinus strobus* and *Pinus sylvestris*. It is, however, worth noting that these results are exclusively the results obtained from analyses of physical and chemical properties of the soil of these stands and do not encompass other very important ecosystem factors and functions, nor aesthetical or production benefits. Vacek et al. (2021) have investigated some of these stands from a more production and biodiversity oriented perspective. There, it was shown that overall, *Pinus sylvestris*, *Larix decidua*, *Pseudotsuga menziesii* and *Pinus nigra* were conifers that have shown great production potential. *Picea pungens*, which has shown soil properties which are generally considered beneficial in this analysis, is highly susceptible to pathogens, together with some others, like *Pinus strobus* and *Pinus rotundata*, and its stand area had been significantly reduced over the years. *Pinus sylvestris* was awarded negative points from chemical soil properties, but, according to Vacek et al. (2021), was the species that used nutrients the most efficiently, had shown one of the best growth rates in the arboretum, and is generally considered a good and common choice for reclaimed mine areas. Thus, with having the mentioned in mind, it is worth noting that the conifers that have proved suitable for the reclaimed sites of the Sokolov region, from all standpoints, were *Pinus ponderosa* and *Pinus nigra*, but, if rapid soil formation is not the main goal to reach, some other species, like *Pinus sylvestris*, *Larix decidua* and *Picea omorika*, could also be good choices. On the other hand, if we exclude the lower production function and aesthetic appeal in the broadleaved stands, from solely a soil formation perspective, many of the broadleaf species have shown more desirable soil properties. From those investigated here, the good ameliorative effects of alder (*Alnus glutinosa*) were proved once again, and others like *Fagus sylvatica*, *Pyrus communis*, *Tilia cordata* and both *Acer pseudoplatanus* and *Acer platanoides* are also worth mentioning from positive aspects. *Betula pendula* and *Carpinus betulus*, although known as pioneers and/or species used on post-mining sites, have not shown very favourable soil properties and soil-forming potential this time. Having the aforementioned in mind, it can be stated that our hypothesis was proven correct up to a certain extent, but that some coniferous species have shown unexpectedly favourable properties (*Pinus nigra*, *Pinus ponderosa*), whereas some broadleaves have not lived up to the expectations (*Carpinus betulus*, *Betula pendula*). Besides that, a valuable lesson learned was that the success rate of species chosen for afforestation of post-mining sites should not be based solely on soil-forming potential and soil properties, but other important ecological parameters as well.

Principal component analysis has shown that in all stands, pH negatively correlated with the amount of carbon in the soil and C/N ratio, which was to be expected, considering that greater amounts of organic matter tend to make the soil more acid. pH positively correlated with the amount of calcium in the soil, which was, again, expected, as well as the fact that porosity and bulk density have shown a strong negative correlation, due to the way porosity is calculated based on bulk and particle density. Available phosphorus negatively correlated with bulk density, which can again be attributed to the faster turnover rates and creation of more available forms of nutrients in soils with a greater content of organic matter. This was noticed in other locations in Sokolov region by Spasić et al. (2022) where available P (determined by the same extraction method—Mehlich III) was detectable in the uppermost, organo-mineral (A) horizon of 3 forest reclamations of different age, whereas in the underlying horizons, it was, in most cases, under the detection limit.

In order to get more information about the influence of vegetation type on soil formation process, further analyses of these stands are planned, including the analysis of structural aggregates stability, quality of humic substances, low molecular mass organic acids concentrations and enzymatic activity in both litter, and organo-mineral layer, as well as litter decomposition experiments.

Conclusions

In this research, a significant number of physical and chemical soil parameters from 23 stands of the same age on Antonín reclaimed spoil heap was investigated in order to determine which tree species are the most suitable for afforestation of post-mining sites. Our results have shown that the species which have had a statistically significant advantage of multiple soil properties were *Alnus glutinosa*, *Fagus sylvatica*, *Tilia cordata*, *Pyrus communis*, *Picea pungens* and *Pinus ponderosa*. Species which have shown a greater number of negative soil properties were *Betula pendula*, *Larix decidua*, *Picea abies*, *Pinus rotundata*, *Pinus strobus* and *Pinus sylvestris*. However, previous findings from this very area, mentioned in the Discussion, together with the results presented here, show that observing solely soil properties can also be misleading, shown here by two examples: *Pinus sylvestris* and *Larix decidua*, which have shown relatively poor results from the soil analyses investigated, but are some of the best growing species on this site, and *Picea pungens*, which has shown unexpectedly favourable soil properties, but is highly susceptible to pathogens, droughts and lack of precipitation, and is dying out in this locality. Already known, and somewhat expected positive effects of broad-leaved species like *Alnus glutinosa*, *Fagus sylvatica*, *Acer* sp. and *Tilia cordata* were proven once again, whereas species like *Betula pendula* and *Carpinus betulus* have not shown soil properties that were expected from literature. Further, more comprehensive research of soil's various physical, chemical, and biological properties is needed in order to understand soil formation process and vegetation influence better.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Financial support was provided by Ministry of Education Youth and Sports of the Czech Republic.

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Authors and Affiliations

Marko Spasić[1] · Oldřich Vacek[1,2] · Kateřina Vejvodová[1] · Václav Tejnecký[1] · Petra Vokurková[1] · Petra Křížová[1] · Filip Polák[1] · Radim Vašát[1] · Luboš Borůvka[1] · Ondřej Drábek[1]

✉ Marko Spasić
spasic@af.czu.cz

1 Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic

2 Department of Landscape Architecture, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic

7.1.4. Production potential, biodiversity and soil properties of forest reclamations: Opportunities or risk of introduced coniferous tree species under climate change?

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ORIGINAL PAPER

Production potential, biodiversity and soil properties of forest reclamations: Opportunities or risk of introduced coniferous tree species under climate change?

Zdeněk Vacek[1] · Jan Cukor[1,2] · Stanislav Vacek[1] · Rostislav Linda[1,2] · Anna Prokůpková[1] · Vilém Podrázský[1] · Josef Gallo[1] · Oldřich Vacek[3] · Václav Šimůnek[1] · Ondřej Drábek[3] · Vojtěch Hájek[1] · Marko Spasić[3] · Jakub Brichta[1]

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Abstract

In the time of ongoing climate change and the increasing area of post-mining landscape, the successful afforestation of reclamation sites by suitable adaptive tree species is gaining in importance. One of possible ways may be the use of introduced tree species, which is, however, a controversial topic in relation to risks for forest management and nature conservation. The objective of this study was to comprehensively evaluate the forest stands (age 48 years) of 9 introduced and 3 native coniferous tree species in lowland post-mining coal site of the Czech Republic. The research was focused on production potential, health status, resistance to climate change, carbon sequestration, biodiversity and soil properties. The highest timber production, biomass and carbon stock (49–95% above average), was observed in case of *Pinus sylvestris, P. nigra* and *Pseudotsuga menziesii*. On the other hand, unsuitable habitat, insect and pathogens caused poor health status and extremely low production parameters (by 55–62% than average) in *Pinus strobus* and *P. rotundata*. In terms of climate, *Pinus sylvestris, P. nigra, Larix decidua*, *Pseudotsuga menziesii* and *Picea omorika* were the most resistance tree species in relation to climatic extremes. Conversely, *Pinus rotundata, P. strobus, P. ponderosa, Picea pungens* and *P. abies* were very sensitive to climate events, especially to the lack of precipitation in vegetation period with synergism of high temperature. In terms of soil parameters, the content of plant available nutrients (K, Ca, Mg) was adequate except P deficiency. The highest soil reaction was detected for *Pinus nigra* and *P. sylvestris* (pH 6.9–7.1) compared to *Picea mariana* (pH 4.8). The benefits of “suitable” introduced tree species (*Pinus nigra, Pseudotsuga menziesii*) are high timber production potential and good adaptation and mitigation of the changing climate; however, native tree species (*Pinus sylvestris, Larix decidua*) can provide better environmental benefits on reclamation sites.

Keywords Post-mining landscape · Radial growth · Climate resistance · Forest structure · Central Europe

Introduction

Introduced tree species are represented worldwide on ca. 25% of the forest plantation area (FAO 2010). In Europe, introduced tree species occupy approximately 4.4% of the forest area and their share varies greatly from one country to another (Forest Europe 2015). The highest proportion is found in Ireland, where introduced tree species especially [*Picea sitchensis* (Bong.) Carr. (Sitka spruce)] occupy more than 70% (Forest Service, 2017). On the other hand, in the Czech Republic, the share of introduced tree species is only 1.8% of the forest area, while their potential is estimated at up to 7% (Beran 2018; Hrib 2008) with a significant predominance of coniferous trees (Beran 2018). The first introduced tree species in Europe were mainly conifers, such as *Thuja*

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✉ Zdeněk Vacek
vacekz@fld.czu.cz

[1] Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague 6, Suchdol, Czech Republic

[2] Forestry and Game Management Research Institute, Strnady 136, 252 02 Jíloviště, Czech Republic

[3] Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 165 00 Prague 6, Suchdol, Czech Republic

occidentalis L. (white cedar), *Pinus strobus* L. (white pine) or *Pseudotsuga menziesii* (Mirbel) Franco (Douglas fir) (Essl 2005; Maloy 1997; Schmidt et al. 2016; Wein 1930).

The growing share of introduced tree species is mainly due to their ability to achieve increased production of quality wood (Davies et al. 2020; Dodet and Collet 2012; Richardson 1998). At the same time, introduced tree species can diversify wood production as part of the efforts to mitigate climate change (Felton et al. 2010; Frischbier et al. 2019). The ongoing climate change has an imminent effect on wind disturbances, heat waves, changes in precipitation regime and increasing the risk of fires, producing an increase of extreme weather events (Dale et al. 2001; Flannigan et al. 2009; Gregow et al. 2017; Hlásny et al. 2014; Venäläinen et al. 2020). These factors have a direct impact on the health and growth of forest trees and their populations through forest disturbances (Boczoń et al. 2018; Hlásny et al. 2011; Mikulenka et al. 2020; Naudts et al. 2016; Vacek et al. 2020, 2019a).

With the advancing climate change, there is a redistribution of tree species onto potentially new suitable habitats, i.e., to higher altitudes (Dulamsuren et al. 2017; Kolář et al. 2017; Sedmáková et al. 2019) and north in terms of latitude (Boisvert-Marsh et al., 2019; Monleon and Lintz 2015; Pearson et al. 2013). Considering the influence of climate change, it is necessary to select potentially suitable trees for the original habitats (Brundu et al. 2020; Podrázský, 2019) in order to increase not only production and biodiversity, but especially the stability of forest ecosystems (Nicolescu et al. 2020; Nilsson et al. 2011; Queirós et al. 2020; Remeš et al. 2020). At the same time, introduced tree species can have a positive effect on soil conditions, including carbon sequestration (Nicolescu et al. 2020). In particular, the introduction of conifers has considerable potential in terms of non-productive functions, as conifers have been shown to have a higher accumulation of carbon in overlying humus compared to deciduous trees (Cukor et al. 2017; Grüneberg et al. 2014), leading to the mitigation of global climate (Lal 2004; Lal et al. 2007; Lawrence et al. 2018; Mandal et al. 2020; Powlson et al. 2011).

However, the use of introduced tree species also involves ecological risks that need to be addressed (Brundu et al. 2020; Felton et al. 2013; Nicolescu et al. 2020; Novoa et al. 2020; Richardson and Rejmánek 2011). Approximately 60% of the introduced tree species used in the forestry sector can be considered invasive (Haysom and Murphy 2003). In particular, significant coniferous trees used in commercial forestry become more often naturalized or invasive compared to trees used in horticultural or landscaping (Castro-Díez et al. 2011; Essl et al. 2010). The use of introduced tree species in plantations has mostly caused a decrease in biodiversity at the stand level (Peterken 2001). Another risk is the introduction of pests and pathogens into forest ecosystems (Goßner and Ammer 2006; Roques et al. 2006; Tomoshevich 2019; Wingfield et al. 2001). Hybridization may also occur locally (Goto et al. 2011; Koivuranta et al. 2012; McKay et al. 2005). In terms of biodiversity and stability of forest stands, it is appropriate to grow stands in mixtures (Felton et al. 2010; Vacek et al. 2021), or to appropriately incorporate introduced tree species into stands of domestic species (Podrázský, 2019).

Because of above mentioned reasons, it is necessary to carefully consider the economic benefits and ecological risks when creating strategies for the use of introduced tree species in the forestry practice (Frischbier et al. 2019). Efforts to reduce environmental risks must go hand in hand with a broader consideration of other environmental links and impacts of specific management activities (Hulme 2006). For example, several studies highlight the potential benefits for plant biodiversity of introduced plants within a stand by placing them near source populations of endemic plants (Brunet 2007; Tullus et al. 2012) or invertebrates (Finch and Szumelda 2007; Goßner and Ammer 2006; Goßner et al. 2009). The decision to plant specific species of introduced trees should therefore be based on long-term ecological prediction (stability) and evaluation of possible risks from the point of view of economic perspectives of stakeholders, especially forest owners (Hulme 2006; Ruesink et al. 1995). This often requires many trade-offs between different ecological risks and forest introduction strategies (Richardson et al. 2014; Rytter 2006; Schlaepfer et al. 2009). Key risks should also be reflected by political authorities with regard to decision-making in conservation (Bazzichetto et al. 2018; Lozano et al. 2020). In the context of the European continent, for example, Regulation No. 1143/2014 of the European Parliament and of the Council on the prevention and management of the introduction and spread of invasive alien species, which lays down the basic rules for the most problematic invasive species from the point of view of the European Union.

Plantings of introduced tree species are especially suitable for specific areas, often negatively affected by human activity, with less favorable conditions for the growth of forest tree species. These extensive transformations of landscapes as a result of human management still occur in recent years (Lanz et al. 2018; Stephens et al. 2019). Undoubtedly, one of the most serious interventions in the landscape with a significant impact on the environment is surface mining and subsequent reclamation (Fagiewicz and Łowicki 2019; Pietrzykowski and Krzaklewski 2007; Pietrzykowski and Socha 2011; Vacek et al. 2018). In the Czech Republic alone, more than 1,400 km^2 of land is devastated by coal mining (approximately 2% of the country's area), while the area of national parks is less than 1,200 km^2 (Vacek et al. 2012). The potential of the properties of the introduced tree species can therefore be effectively verified within the framework of forest reclamations. Moreover, the tree species is the main driver of the soil formation of these extreme sites (Chodak and Niklińska 2010; Šourková et al. 2005).

The aim of this study was to evaluate the production, biodiversity and soil conditions in the stands of 12 species of conifers, of which 3 domestic and 9 introduced. The specific objectives were to determine: (i) production potential, carbon stock, health status, structural differentiation, vertical and horizontal structure and overall diversity of stands of individual tree species, (ii) influence of tree layer of examined 12 tree species on basic soil conditions, (iii) influence of climatic extremes, temperatures and precipitation on radial growth of individual tree species and their adaptation to climate change and (iv) interactions between production, health status, diversity and soil conditions and differences between these parameters related to individual tree species.

Material and methods

Study area

The study was conducted in 39 permanent research plots in the Antonín Forest Arboretum in post-mining landscape of the Sokolov area, in the west part of the Czech Republic (Fig. 1). According to Czech Hydrometeorological Institute Sokolov station (4 km SW from town Sokolov, 402 m a. s. l.), the average annual temperature in study area is 7.3 °C. The highest altitude of the Antonín Arboretum is 444 m. a. s. l., and the elevation to the surrounding terrain is 48 m (Dimitrovský et al. 2007; Kupka and Dimitrovský, 2011). Long-term annual precipitation ranges from 327 to 658 mm, and the average sum in the Sokolov station is 611 mm year^{-1}. The most precipitation falls in July (78 mm), and the least in March (34 mm). The vegetation period ranges between 220 and 227 days (Vacek et al. 2018). The study territory is characterized by warm dry summers and cold dry winters with a narrow annual temperature range (Cfb) according to Köppen climate classification (Köppen 1936). Annual air temperature has increased by 1.8 °C and sum of precipitation by 95 mm in the period 1961–2019, which implies an intensive influence of climate change on forest systems. Fluctuation (standard deviation) of monthly sum of precipitation has increased by 20% and temperature by 3% in the same period.

Soils are currently in the initial stages of development. Initial dynamics of ground vegetation shows the trend towards potential association of *Querceto-Fagetum acidophilum* and *Querceto-Fagetum lapidosum acidophilum*, despite a significant proportion of ruderal species in the first period of spontaneous succession. In waterlogged areas, the vegetation development corresponds to the association

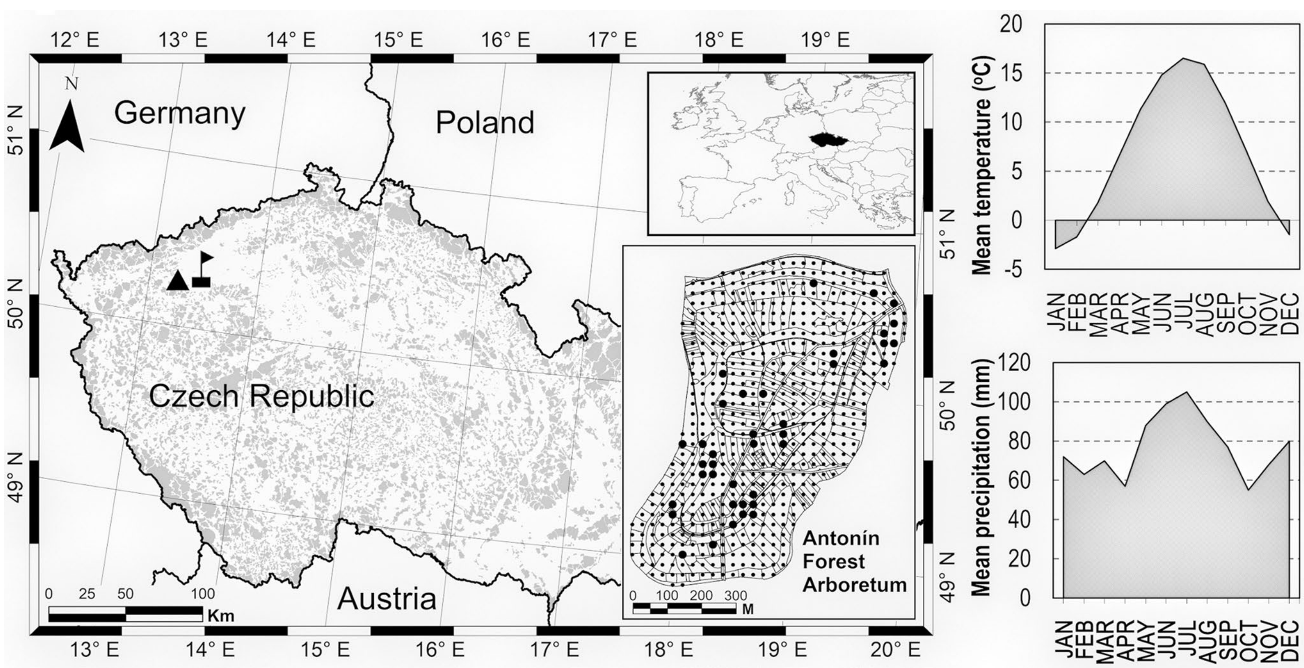


Fig. 1 Localization of the study area Antonín Forest Arboretum in Sokolovsko region (*closed triangle*) with highlighted 39 permanent research plots (*closed circles*) and the mean monthly climatic values (1975–2019); meteorological station is marked by symbol ( ); map was made in ArcGIS 10 (Esri)

Querceto-Abietum variohumidum acidophilum and *Fraxineto-Alnetum alluviale* (Vacek et al. 2018).

Historically, the Antonín-Sokolov coal mine was in operation between 1881 and 1965, first as a deep, later as a surface brown coal mine. In the last 20 years (1945–1965), 22.5 million t of coal and 10.8 million m^3 of overburden materials were mined (Jiskra 1997). The study Antonín Forest Arboretum was established in 1969–1974 on the Antonín coal spoil heap (dump) close to the town of Sokolov. Technical operations, i.e., transporting and spreading the topsoil, were completed in 1971–1972, followed by forest reclamation. A wide assortment of 220 species of trees and shrubs was gradually planted on the study area of 165 ha, where a part of spoil heap was left to self-development to spontaneous succession (Dimitrovský et al. 2007). Resulting forest stands were left without silvicultural interventions, and thinning was focused only to understory and sanitary treatments (Vacek et al. 2018). Recently, there has been an extensive development of fungal and insect pathogens, especially bark beetles.

Data collection

Data were collected on a total of 39 rectangle permanent research plots (PRP) of 10 × 15 m in the period 2019–2020 (stand age ca. 48 years). The research plots were divided according to the tree species composition of monospecific coniferous stands into 12 variants (domestic 3 tree species—12 PRP, introduced 9 tree species—27 PRP). Three native tree species were as follows: Norway spruce (*Picea abies* [L.] Karst.), Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua* Mill.). Nine introduced tree species were as follows: black spruce (*Picea mariana* [Mill.] Britt., Sterns & Poggenburg), Serbian spruce (*Picea omorika* [Pančić] Purk.), blue spruce (*Picea pungens* Engelm.), bog pine (*Pinus rotundata* Link), black pine (*Pinus nigra* J. F. Arnold), lodgepole pine (*Pinus contorta* Douglas ex Loudon), ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), white pine (*Pinus strobus* L.) and Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco). For all tree species, 4 replicates (respectively, 4 PRPs) were measured, only for *Picea mariana*, *Pinus ponderosa*, and *P. rotundata*, only one PRP was established from each tree species due to their small area. Plots were randomly (RNG in MS excel) chosen from a plot network of 50 × 50 m (consisting of 580 PRPs), representing different coniferous tree species (Fig. 1).

FieldMap technology (IFER) recorded positions of individual trees with diameter at breast height (dbh) ≥ 4 cm, and their crown projection was measured in four directions. Diameter at breast height was measured with a Mantax Blue caliper (Haglöf, Sweden) with an accuracy of 1 mm, and the height of the individual trees and the height of the green crown base with a Vertex laser hypsometer (Haglöf, Sweden) with an accuracy of 0.1 m. Foliation was determined from the percentage of foliage (needles) from the supposed amount of foliage on a healthy tree (of the same species) in 5% scale. All these data were collected by one experienced and well-trained researcher, in accordance with the ICP Forests monitoring program methodology (UNECE 2006).

For the analysis of radial growth, core samples were obtained from the trees with Pressler auger (Haglöf, Sweden) at a height of 1.3 m in the direction up/down the slope. From each of 12 tree species, 24 samples were randomly taken (RNG function, Excel) from the predominant and dominant trees according to the Kraft classification (Kraft 1884). A total of 288 core samples of were taken, of which subsequently 266 samples were used for dendrochronological analyses. Six core samples were taken evenly on each PRP for a particular tree species (except *Picea mariana*, *Pinus ponderosa*, and *P. rotundata*—all samples from one PRP). The annual increments of the tree rings were then measured with an accuracy of 0.01 mm using an Olympus binocular microscope on a LINTAB measuring table and recorded in TsapWin software (Rinntech).

Measurements from meteorological station were used to derive effect of climate and stress factors on radial growth. Available data from the station Karlovy Vary—Olšová Vrata meteorological station (602 m a.s.l.; distance 20 km; GPS 50°12′5.71"N, 12°54′51.71"E)—were used for the analysis of the temperature and precipitation conditions (1986–2018). The development of temperature and precipitation conditions was based on the data of the average annual temperature, temperature in the vegetation period, temperature in individual months, annual total precipitation, total precipitation in the vegetation period, monthly total precipitation and extreme climatic events.

In terms of soil data collection, four intact soil samples were taken for each tree species, i.e., one sample on one PRP (only for *Picea mariana*, *Pinus rotundata* and *P. ponderosa* only, four samples were taken on one PRP). Soil samples were randomly selected in each stand within a radius of 5 m from the geometric center of the selected stand. The geometric center of the stand was determined as the centroid coordinate of the polygon delimiting the boundaries of the sampled stand in ArcMap 10.5 software (ArcGis, Esri). Intact samples were taken by Kopecký cylinders with a height of 51 mm and an internal diameter of 50 mm (Eijkelkamp Soil & Water, Nederland). Overlying organic layers were removed from the soil surface, and the cylinders were incorporated into the surface mineral soil horizon A directly from its surface. Intact soil samples were transported to the laboratory inside the Kopecký cylinders packed in PE bags, weighed and saturated with water.

Data analysis

The basic structure, diversity and production characteristics of the tree layer were evaluated by the SIBYLA Triquetra 10 software (Fabrika and Ďurský 2005). The PointPro 2.1 (Zahradník & Puš, ČZU) program was used to calculate the characteristics of the horizontal structure of the individuals on PRPs. The volume of trees was calculated by the volume equations published in Petráš and Pajtík (1991). Aboveground tree biomass (stem, branches and needles) was derived from models provided by Petráš et al. (1985), Petráš and Pajtík (1991), Lederman and Neumann (2005) and Seifert et al. (2006). The biomass of tree roots was calculated using a model by Drexhage and Colin (2001). The content of carbon (C) in trees was calculated according to Bublinec (1994) using the unit content of elements in 10 mg kg^{-1} of dry matter. A crown closure (Crookston and Stage 1999) and stand density index (Reineke 1933) were then calculated from the stand density indicators.

The research team evaluated the horizontal structure (Clark and Evans 1954), the vertical structure using Arten-profile index (Pretzsch 2006) and vertical diversity index (Jaehne and Dohrenbusch 1997), the structural differentiation of the stand using the indices of diameter and height differentiation (Füldner 1995) and crown differentiation (Jaehne and Dohrenbusch 1997; Table 1). The stand diversity index was calculated in terms of complex biodiversity (Jaehne and Dohrenbusch 1997).

Tree-ring increment series were individually crossdated (to remove errors caused by missing tree rings) using statistical tests in the PAST application (Knibbe 2007) and subsequently subjected to a visual inspection according to Yamaguchi (1991). If a missing tree ring was revealed, a tree ring of 0.01 mm in width was inserted in its place. Individual curves from PRPs were detrended, and an average tree-ring series was created in the ARSTAN program (Cook, Tree Ring Laboratory). Negative exponential spline and subsequently 0.67n spline were used for age detrending (Grissino-Mayer et al. 1992). The analysis of negative pointer years (NPY) was carried out by Schweingruber (1996) and Desplanque et al. (1999). For each tree, the pointer year was tested as an extremely narrow tree ring that does not reach 40% of the increment average from the four preceding years. The occurrence of the negative year was proved if such a strong reduction in increment occurred in at least 20% of trees on the plot. To express the relationship between climate characteristics (monthly average temperatures and monthly sum of precipitation in particular years) and radial growth, the DendroClim software was used (Biondi and Waikul 2004).

After the completion of the physical analysis of intact soil samples dried at 105 °C to constant weight, the soil samples from each of the Kopecký cylinders were homogenized, adjusted to the first fine soil and subjected to basic chemical analyzes. Soil reaction (pH) measurement was taken according to the methodology of Murray (2011), oxidizable carbon (Cox) according to Valla et al. (2008). Extraction of the monitored nutrients was performed according to the methodology of Melich (1984) and determined by inductively coupled plasma atomic emission spectroscopy (iCAP-7000, Thermo Fisher Scientific, USA).

The DBH, tree height and stem volume were compared between plots with different tree species (variants) using Kruskal–Wallis test, as assumptions of analysis of variance (ANOVA) were not met in all cases (the data showed non-normal distribution for some variants, tested by Shapiro–Wilk normality test). Multiple comparisons after Kruskal–Wallis test were performed using method described by Siegel and Castellan Jr. (1988). Significant differences are depicted by character indexes above each variant in boxplots. Significantly different variants are marked with different character.

The soil, production and diversity parameters were separately evaluated for all variants (plots with different tree

Table 1 Overview of indices describing the stand diversity and their common interpretation

Criterion	Quantifiers	Label	Reference	Evaluation
Horizontal structure	Aggregation index	R (C&Ei)	Clark and Evans (1954)	Mean value $R=1$; aggregation $R<1$; regularity $R>1$
Vertical structure	Arten-profile index	A (Pri)	Pretzsch (2006)	Range 0–1; balanced vertical structure $A<0.3$; selection forest $A>0.9$
	Vertical div	S (J&Di)	Jaehne and Dohrenbusch (1997)	Low S < 0.3, medium S = 0.3–0.5, high S = 0.5–0.7, very high diversity S > 0.7
Structure differentiation	Diameter dif	TM_d (Fi)	Füldner (1995)	Range 0–1; low $TM<0.3$; very high differentiation $TM>0.7$
	Height dif	TM_h (Fi)		
	Crown dif	K (J&Di)	Jaehne and Dohrenbusch (1997)	Low $K<1.0$, medium $K=1.0$–1.5, high $K=1.5$–2.0, very high differentiation $K>2.0$
Complex diversity	Stand diversity	B (J&Di)	Jaehne and Dohrenbusch (1997)	Monotonous structure $B<4$; uneven structure $B=6$–8; very diverse structure $B>9$

species) by hierarchical clustering method using UPGMA algorithm (Sokal and Michener 1958). Data were scaled before the analysis. The results are presented in the form of dendrograms. All computations and plots were made in R software (R Core Team 2020) using packages "pgirmess" (Giraudoux 2018) and "ggplot2" (Wickham 2016).

Principal component analysis (PCA) was performed in the CANOCO 5 program (Microcomputer Power) to evaluate the relations between the stand structure, production parameters and species composition variants. Prior to the analysis, the data were standardized and centralized. Results of PCA were illustrated by ordination diagram. Pearson correlations were done in Statistica 12 software (Statsoft, Tulsa).

Results

Production potential and health status

The comparison of dendrometric characteristics (DBH, tree height and stem volume) showed significant differences across all tree species (K–W test, df = 11, $p < 0.001$ in all cases; DBH—Chi-squared: 211.2, tree height—Chi-squared: 307.4, stem volume—Chi-squared: 229.7; Fig. 2). The observed DBH was highest in case of *Picea omorika* by 31% compared to all tree average (19.4 cm) and *Pseudotsuga menziesii* by 28% (19.1 cm), while it was the lowest in *Pinus rotundata* by -35% (9.7 cm) and *Picea mariana* by -30% (10.4 cm). The height was the significantly ($p < 0.05$) highest in *Pinus sylvestris* (17.1 m), *Pseudotsuga menziesii* (16.9 m) and *Larix decidua* (15.3 m), while it was significantly ($p < 0.05$) the lowest in *Pinus strobus* (10.6 m), *Pinus ponderosa* (10.6 m), *Picea mariana* (10.8 m) and *Picea pungens* (10.8 m). The observed stem volume was highest

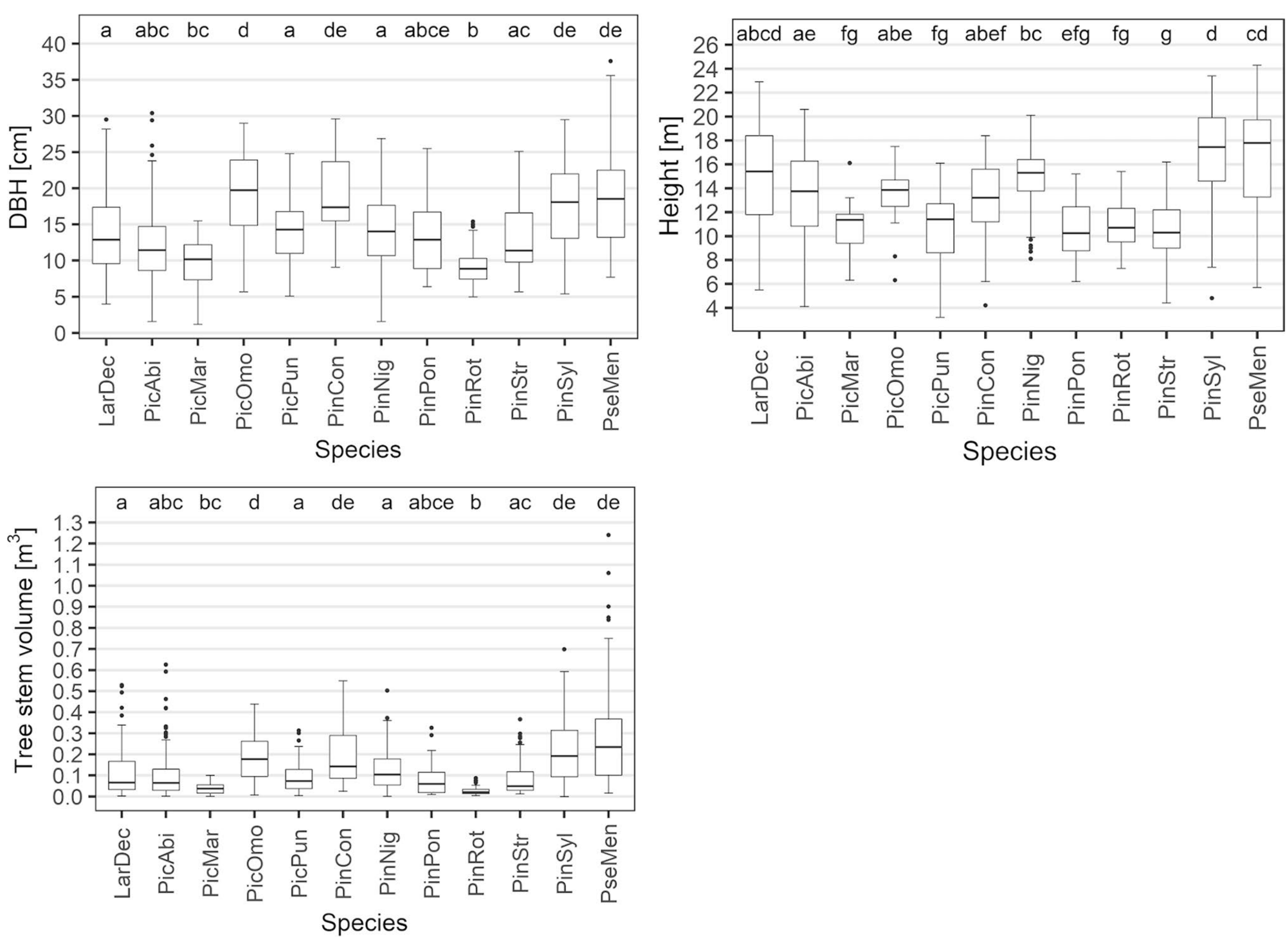


Fig. 2 The differences between tree species in DBH, tree height and tree stem volume; different letter indexes above variants in boxplots depict statistically significant differences ($p < 0.05$)

Table 2 Structural and production characteristics of forest stand on the permanent research plots differentiated by tree species; the highest values are in bold

Species	dbh (cm)	h (m)	v (m^3)	N (trees ha^{-1})	BA (m^2 ha^{-1})	V (m^3 ha^{-1})	HDR	MAI (m^3 ha^{-1} y^{-1})	CC (%)	SDI	BIO (t ha^{-1})	C_{BIO} (t ha−1)	FOL (%)
Native tree species													
LarDec	14.8	16.1	0.114	1969	31.6	200	110	4.38	83.2	0.81	246	135.6	65.9
PicAbi	14.3	13.7	0.114	2034	29.3	191	98	4.17	80.7	0.62	156	82.0	51.8
PinSyl	18.5	**17.5**	0.221	1700	**45.1**	**364**	94	**7.92**	86.2	**1.05**	**319**	**167.1**	**72.4**
Introduced tree species													
PicMar	10.4	10.8	0.040	2000	16.8	80	104	1.74	75.1	0.40	76	39.7	60.6
PicOmo	20.7	13.6	0.191	933	29.9	169	66	3.67	72.9	0.51	131	68.5	71.2
PicPun	14.5	10.8	0.083	1417	23.9	118	74	2.56	76.2	0.49	100	52.3	50.2
PinCon	20.1	13.3	0.200	617	19.4	124	66	2.69	64.6	0.44	108	56.7	56.1
PinNig	15.4	15.1	0.125	2334	41.9	277	99	6.01	88.1	1.04	259	135.6	64.7
PinPon	15.1	10.6	0.092	2000	35.6	183	69	3.98	87.8	0.90	171	89.6	52.9
PinRot	9.7	10.9	0.027	**4400**	32.2	117	**113**	2.54	**92.5**	0.97	132	69.1	42.1
PinStr	14.7	10.8	0.091	884	14.1	71	75	1.54	61.1	0.40	68	35.6	49.8
PseMen	**20.8**	16.3	**0.275**	1250	40.6	343	80	7.47	83.5	0.80	252	132.3	68.1

dbh mean quadratic diameter at breast height, *h* mean height, *v* mean tree volume, *N* number of trees per hectare, *BA* basal area, *V* stand volume, *HDR* height-to-diameter ratio, *MAI* mean annual increment, *CC* canopy closure, *SDI* stand density index, *BIO* biomass in dry matter, C_{BIO} carbon stock in biomass, *FOL* foliation in case of *Pseudotsuga menziesii* by 102% (0.283 m^3) and *Pinus sylvestris* by 58% (0.221 m^3), while it was the lowest in *Pinus rotundata* by -81% (0.027 m^3) and *Picea mariana* by -72% (0.040 m^3). The highest individual stem volume was observed in tree of *Pseudotsuga menziesii* of 1.240 m^3 (mean tree volume of all tree species 0.140 m^3). Generally, stem volume of native tree species was higher by 9% (0.148 m^3) compared to introduced tree species (0.134 m^3).

Structural and production characteristics of the stand on PRPs are shown in Table 2. In case of native tree species (*Larix decidua, Picea abies, Pinus sylvestris*), the highest average tree value (DBH, height, stem volume) on PRPs was observed in *Pinus sylvestris*. Number of trees was in range 1700–2034 trees ha^{-1}. Basal area ranged from 29.3 (*Picea abies*) to 45.1 m^2 ha^{-1} (*Pinus sylvestris*). Similarly, the highest stand volume (364 m^3 ha^{-1}), mean annual increment (7.92 m^3 ha^{-1} $year^{-1}$), biomass (319 t ha^{-1}) and carbon stock (167.1 t ha^{-1}) were observed in *Pinus sylvestris*, while it was the lowest in *Picea abies* on all cases (volume—191 m^3 ha^{-1}, MAI—4.17 m^3 ha^{-1} $year^{-1}$, biomass—156 t ha^{-1}, carbon stock—82 t ha^{-1}). The best health status was found in *Pinus sylvestris* (foliation—72.4%). On the other hand, the lowest foliation (51.8%) was in *Picea abies* due to starting attack of bark beetle (*Ips typographus*).

In case of introduced tree species, the highest average tree value (DBH, height, stem volume) on PRPs was observed in *Pseudotsuga menziesii*, while it was lowest in *Pinus rotundata* (Table 2). Number of trees ranged from 617 (*Pinus contorta*) to 4400 trees ha^{-1} (*Pinus rotundata*). The number of *P. rotundata* trees was higher by 150% than average of all PRPs across tree species due to high proportion of stem bifurcation to height 1.3 m. This is also associated with the highest crown closure (92.5%) and slenderness coefficient (113) in *P. rotundata*. The highest basal area was in *Pinus nigra* (41.9 m^2 ha^{-1}) followed by *Pseudotsuga menziesii* (40.6 m^2 ha^{-1}), similarly such as biomass (259 and 252 t ha^{-1}). Conversely, it was the lowest in *Pinus strobus* (14.1 m^2 ha^{-1} and 68 t ha^{-1}) and *Picea mariana* (16.8 m^2 ha^{-1} and 76 t ha^{-1}). Comparing stand volume, it was the highest by 108% than average in *Pseudotsuga menziesii* (343 m^3 ha^{-1}) and the lowest in *Pinus strobus* by -56% (71 m^3 ha^{-1}). In terms of carbon stock in biomass, border of 130 t ha^{-1} (average 75 t ha^{-1}) reached also *Pinus nigra* and *Pseudotsuga menziesii*. Poor health status was found in *Pinus rotundata* (foliation 42.1%) due to bark beetle, *P. strobus* (49.8%) due to blister rust (*Cronartium ribicola*) and *Picea pungens* (50.2%) due to *Gemmamyces piceae*. On the other hand, *Picea omorika* showed the highest foliation (71.2%).

Comparing all tree species together (native and introduced), the highest production potential showed *Pinus sylvestris* and *Pseudotsuga menziesii* compared to poor production of *Pinus rotundata* and *Picea mariana*. Also, Fig. 3 shows that *Pinus rotundata* was substantially different from other tree species as it performed poorly in both structure and production parameters. Furthermore, we can separate tree species into two production groups: low-production group (*Picea mariana, P. omorika, P. pungens, Pinus contorta* and *P. strobus*) and high-production group (*Pseudotsuga menziesii, Pinus sylvestris, P. nigra, P. ponderosa, Picea abies* and *Larix decidua*). All native tree species belong to the latter group.

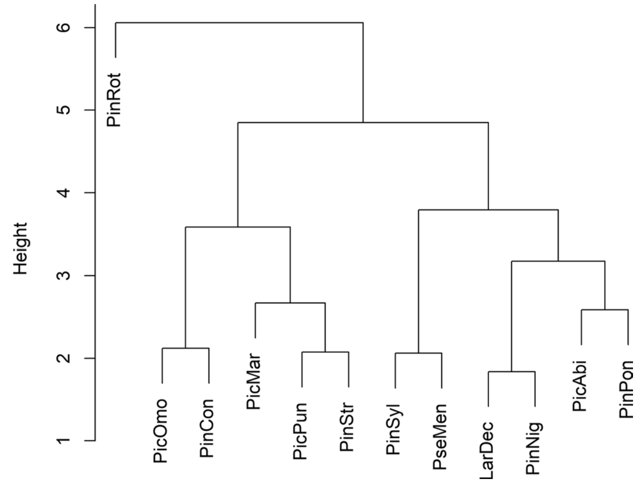


Fig. 3 The results of hierarchical clustering analysis of plots with different species using production parameters presented in the form of dendrogram constructed by UPGMA method

In terms of production quality of all tree species, the *Pinus strobus*, *Picea abies* and *Larix decidua* stands reached significantly highest continuous stem (93–100%) compared to *Pinus sylvestris*, *P. nigra* and *P. contorta* (42–56%), where simple and complex stem curvature was often observed. Significantly the highest cleaning stem from branches was processed in *Larix decidua* [dead crown base (DCB)—4.6 m]; in contrast, it was the lowest in *P. mariana*, *P. pungens* and *P. omorika* (DCB—0.2–0.4 m). The tree breaks were insignificant up to a share of 4% without a difference between different tree species.

Biodiversity of tree layer

Regarding native tree species, horizontal structure was random in all cases (Table 3). Vertical structure was high in native tree species, whereas it was the highest in *Picea abies* and the lowest in *Larix decidua*. Vertical diversity according to *K* index was in *Picea abies* the highest not only from native tree species, but also from all tree species. In other cases/indices diversity was higher in terms of introduced tree species. A similar situation was observed for both tree species (the highest value in *Picea abies* and the lowest value in *Larix decidua*) in structural differentiation (height, diameter and crown), but it reached low to medium diversity. Total

Table 3 Indicators of stand biodiversity on permanent research plots differentiated by the tree species; the highest values are in bold; arrows indicate diversity value size

Species	R* (C&Ei)		A (Pi)		TM_d(Fi)		TM_h (Fi)		S (J&Di)		K (J&Di)		B (J&Di)	
Native tree species														
LarDec	1.032		0.528	→	0.283	↘↘	0.174	↘↘	0.551	→	0.919	↘	3.386	↘↘
PicAbi	1.039		0.676	→	0.322	↘	0.206	↘↘	**0.705**	↗	1.620	↗	4.507	↘
PinSyl	1.090		0.505	→	0.280	↘↘	0.195	↘↘	0.603	→	1.024	→	3.576	↘↘
Introduced tree species														
PicMar	1.112		0.543		0.298	↘	0.156	↘↘	0.609	→	**1.887**	↗	**4.642**	↘
PicOmo	1.075		0.294	↘↘	0.237	↘↘	0.112	↘↘	0.387	↘	1.206	→	3.320	↘↘
PicPun	1.131		0.719	↗	0.267	↘↘	0.198	↘↘	0.626	→	1.240	→	3.911	↘↘
PinCon	1.285*	R	0.602	→	0.262	↘↘	0.218	↘↘	0.587	→	1.189	→	3.275	↘↘
PinNig	1.134		0.456	↘	0.267	↘↘	0.147	↘↘	0.513	→	1.161	→	3.425	↘↘
PinPon	**1.384***	R	**0.750**	↗	0.220	↘↘	0.173	↘↘	0.592	→	1.071	→	3.106	↘↘
PinRot	0.831*	A	0.645	→	0.201	↘↘	0.141	↘↘	0.526	→	0.921	↘	3.444	↘↘
PinStr	0.828*	A	0.631	→	0.274	↘↘	0.220	↘↘	0.537	→	1.191	→	3.598	↘↘
PseMen	1.166		0.652	→	**0.364**	↘	**0.312**	↘	0.632	→	1.121	→	3.700	↘↘

The highest values are marked in bold

R aggregation index, *A* Arten-profile index, TM_d index of diameter differentiation, TM_h, index of height differentiation, *S* index of vertical diversity, *K* index of crown differentiation, *B* stand diversity index

Statistically significant ($p<0.05$) for horizontal structure (A, aggregation, R, regularity); arrows: ↘↘, low, ↘, low-medium, →, medium, ↗, high, ↗↗, very high value of diversity

diversity indicated monotonous stand structure in *Larix decidua* ($B=3.4$) and *Pinus sylvestris* ($B=3.6$), respectively, even stand structure in *Picea abies* ($B=4.5$).

Regarding introduced tree species, prevailing random distribution was observed, while spatial pattern was significantly ($p<0.05$) regular in *Pinus contorta* and *P. ponderosa* (Table 3). On the other hand, horizontal structure was significantly aggregated in pines with poor health status and high proportion of dead trees—*Pinus rotundata* and *P. strobus.* Vertical diversity was prevailingly medium to high, while it was low in *Picea omorika* and very high in *P. pungens* and *Pinus ponderosa*. Height and diameter differentiations were low in all tree species except *Pseudotsuga menziesii*, where differentiation was medium and the highest from all tree species. Crown differentiation was the highest in *Picea mariana*, while it was the lowest in *Pinus rotundata. Picea mariana* also showed the highest total diversity (including comparison to native tree species; $B=4.6$), in all other cases, total diversity was on poor level ($B<4.0$).

Generally, native tree species showed relatively low differences between each other, while they were substantial among introduced tree species. Stands of *Picea omorika,* characterized by very poor diversity, showed the highest differences from other tree species (Fig. 4). On the other hand, stands of *Picea mariana* and *P. abies* showed high values of diversity indicators. *Pseudotsuga menziesii* was also distinguished in dendrogram due to its high structural differentiation. There was noticeable similarity in diversity of introduced pines—*Pinus contorta* and *P. ponderosa* and native tree species—*Larix decidua* and *Pinus sylvestris.*

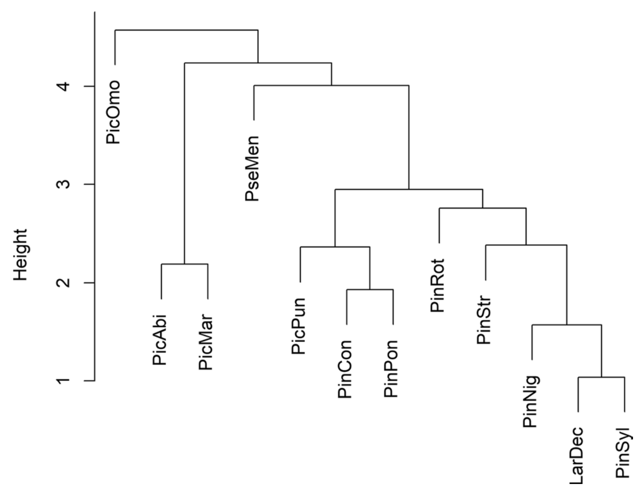


Fig. 4 The results of hierarchical clustering analysis of plots with different species using diversity parameters presented in the form of dendrogram constructed by UPGMA method

Radial growth and climate effect

The fastest growing tree species after planting (growth up to 1.3 m) were *Pinus sylvestris, P. contorta* and

Table 4 Characteristics of basic tree-ring chronologies of coniferous tree species on permanent research plots

Tree species	Cores (n)	Age of core (years)	RW min–max (mm)	RW mean (mm)	RWI SD (mm)	Negative pointer years
Native tree species						
LarDec	23	38	1.056–5.657	2.523	1.218	–
PicAbi	22	33	0.753–4.716	2.575	1.116	2012, 2015
PinSyl	24	42	1.377–6.445	3.848	1.489	–
Introduced tree species						
PicMar	21	33	0.500–3.749	1.962	1.040	2008, 2011
PicOmo	21	35	1.291–3.480	2.113	0.555	–
PicPun	20	33	0.585–3.681	2.177	0.891	2012, 2013
PinCon	21	41	1.103–4.783	2.717	1.026	2011, 2012
PinNig	22	34	0.710–5.500	2.846	1.593	2012
PinPon	24	34	1.110–3.839	2.472	0.807	2012, 2018
PinRot	24	38	0.363–4.590	1.708	0.973	2003, 2011, 2015
PinStr	20	36	0.330–4.100	1.803	1.159	2006, 2012, 2015
PseMen	24	40	1.090–6.420	3.491	1.373	2010, 2011

Cores number of used samples, *Age of core* age of tree in diameter at breast height (130 cm), *RW* tree ring width, *SD* standard deviation

Pseudotsuga menziesii, while slow growth in initial phase after afforestation was observed in *Picea pungens, P. mariana* and *P. abies* (Table 4). The maximum annual diameter increment was registered in *Pinus sylvestris* (13.0 mm) and *Pseudotsuga menziesii* (12.8 mm). The highest variability in radial growth was observed in tree species with the highest radial growth—*Pinus sylvestris* and *Pseudotsuga menziesii*. On the other hand, *Picea omorika* showed very stable annual radial growth although relatively height increment. The annual radial growth of the most productive tree species (*Pinus sylvestris* and *Pseudotsuga menziesii*) was higher by 52% and 39%, respectively, than the average of all tree species. Conversely, the lowest radial growth was observed in case of *Pinus rotundata* (-33% than average) and *Pinus strobus* (-28% than average).

In terms of NPYs, the highest number of years characterized by significant low radial growth was observed in *Pinus rotundata* and *P. strobus* (3 NPYs; Fig. 5). On the other hand, stable radial growth was in *Larix decidua, Picea omorika* and *Pinus sylvestris* (no NPY), followed by *P. nigra* (1 NPY). In terms of specific NPYs, these years were mostly repeated across tree species: 2012 (6×), 2011 (4×) and 2015 (3×). Year 2012 was characterized by the historically (1985–2018) highest daily temperature (35.8 °C in 20th August) and extreme low precipitation in vegetation period. Above-average temperatures in vegetation season were observed in year 2011 together with extreme precipitation fluctuation (one month 1 mm, second month 128 mm). Year 2015 was characteristic by its extremely high temperatures (8.1 °C, average 7.1 °C) and historically warmest month of August (19.9 °C, average 15.9 °C). Moreover, the driest February (2 mm, average 30 mm) and extremely dry vegetation period (-21% precipitation) were observed in this year, too. Similarly, NPYs 2003 and 2018 were characterized by the historically driest vegetation period (288–291 mm, average 402 mm) and also with the highest temperature (14.5–15.2 °C, average 13.0 °C). Comparing other NPYs with historical annual and monthly climatic milestones, warmest July (20.7 °C, average 16.5 °C) was in 2006 and the cloudiest May (91 h of sunshine, average 200 h) was in 2013.

Comparing correlation of radial growth with the monthly air temperatures, the lowest effect of temperatures was observed in case of *Larix decidua, Pinus sylvestris* [1 significant ($p < 0.05$) months], followed by *P. contorta*, *Picea omorika* and *Pseudotsuga menziesii* (2 months; Fig. 6). On the other hand, the most sensitive tree species to temperature were *Pinus ponderosa* and *Picea pungens* (7 months). February was the most significant ($r = 0.30$–0.52) month affecting the radial growth across all tree species. Generally, temperature had the prevailing positive effect except *Picea abies*, *P. pungens* and *Pinus rotundata*.

Monthly sum of precipitation had higher effect on radial growth compared to air temperature (Fig. 6). The highest significant ($p < 0.05$) effect of precipitation was observed in case of *Picea abies* (7 significant months), *P. pungens* and *Pinus ponderosa* (6 months). On the other hand, adaptive tree species to lack of precipitation was *Pinus contorta* (1 month), *P. sylvestris*, *P. nigra* and *Pseudotsuga menziesii* (2 months). Prevailing positive effect of precipitation was observed in all tree species. Lack of precipitation in growing season (especially in July) and high amount of precipitation in December ($r = -0.29$—-0.52) were limiting factors for the growth of coniferous tree species.

Soil conditions

Comparing native tree species, the highest porosity and content of Cox and P were observed in case of *Picea abies*, while there was the lowest pH, content of Ca, Fe, K and ratio of Ca/Mg (Table 5). On the other hand, the highest ratio of Ca/Mg, pH, content of Ca, K, Na were registered in *Pinus sylvestris*. This tree species was also characterized by the highest specific density (2.5 g cm^{-3}) from all tree species (not only native tree species). On the other hand, the highest bulk density (1.12 g cm^{-3}) and the lowest porosity and content of P were registered in *Larix decidua* and the lowest content of oxidizable carbon in *Pinus sylvestris* from all tree species. Other maximum milestones (except specific and bulk density) were discovered in case of the introduced tree species.

The lowest specific density from all tree species was registered in *Pinus strobus*, respectively, and the lowest bulk density in *Picea pungens*. In terms of porosity, the highest value was registered in *Picea mariana* (71.4), such as in case of content of Fe (71% higher amount than average; Table 5). The highest content of oxidizable carbon was in *Pinus strobus* (10.4%), followed by *P. rotundata* (9.0%). The highest soil reaction was analyzed in *Pinus nigra* (pH 7.1), while extremely acidic soils were found in the stand of *Picea mariana* (pH 4.8) and *Pinus strobus* (pH 5.2). Comparing maximum values of studied exchangeable elements/nutrients, the highest value of Fe was in *P. mariana*, of Na in *Pinus rotundata* and the highest ratio of Mg/Ca in *Pinus nigra*. The greatest primacy had *Picea pungens* in maximum content of elements, where content of Mg was higher by 37%, respectively, P by 140% and S by 54%.

Dendrogram of soil parameters showed significant difference of *Picea mariana* together with *P. pungens* and *Pinus ponderosa* from other tree species and these tree species were characterized by above average content of Mg, P and S and low density (Fig. 7). Also, very different by specific soil parameters was *Pinus strobus.* Outstanding timber productive pines (*Pinus sylvestris* and *P. nigra*) were similar due to high soil density, pH, content of Ca and ratio of Ca/Mg and low porosity and content of Cox. On the other hand, separate group was created by *Pseudotsuga menziesii* and *Pinus contorta* together with *Picea omorika*.

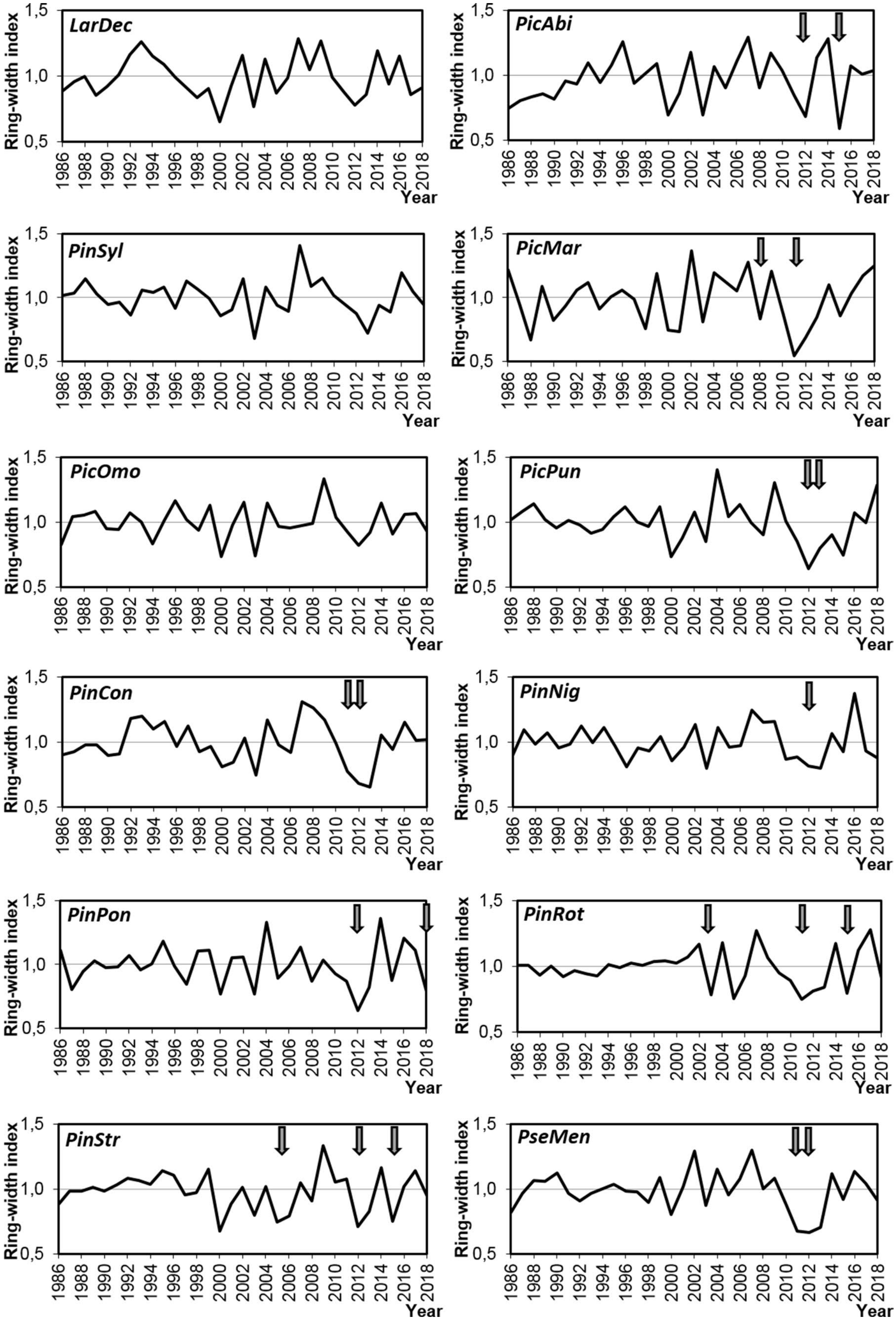
Interaction among production, biodiversity, health status, soils and tree species

The results of PCA are presented in an ordination diagram showing relationship among production, biodiversity, health status, soils and tree species (Fig. 8). The first ordination axis explains 36.2% of data variability, and the first two axes together explain 57.0% and the first four axes 81.4%. The x-axis illustrates the stand volume and carbon stock in biomass together with content of oxidizable carbon in soil. The y-axis illustrates the diameter differentiation together with number of trees and content of S and K. Stem volume was significantly positively correlated with DBH ($r = 0.94$, $p < 0.001$), height ($r = 0.75$, $p < 0.01$) and stand volume ($r = 0.72$, $p < 0.01$), while it was negatively correlated with number of trees ($r = -0.58$, $p < 0.05$). Stand volume was significantly positively correlated with tree parameters (height, stem volume; r = 0.71–0.86, $p < 0.01$), carbon stock in biomass ($r = 0.94$, $p < 0.001$), basal area ($r = 0.90$, $p < 0.001$), SDI ($r = 0.71$, $p < 0.01$), foliation ($r = 0.64$, $p < 0.05$), bulk density ($r = 0.62$, $p < 0.05$) and pH ($r = 0.62$, $p < 0.05$), while it was negatively correlated with oxidizable carbon in soil ($r = -0.81$, $p < 0.001$). Total diversity was significantly increasing with increasing diameter differentiation ($r = 0.60$, $p < 0.05$) and crown differentiation ($r = 0.87$, $p < 0.001$), while SDI had significant negative effect on crown differentiation ($r = -0.59$, $p < 0.05$). In terms of soil parameters, pH was significantly correlated with stand parameters (basal area, stand volume, crown closure, SDI; r = 0.59–79, $p < 0.05$), content of Ca ($r = 0.74$, $p < 0.01$), while pH was negatively correlated with content of Cox ($r = -0.74$, $p < 0.01$) and P ($r = -0.59$, $p < 0.05$). Oxidizable carbon in soil was negatively correlated with carbon storage in biomass ($r = -0.90$, $p < 0.001$). Soil porosity was significantly increasing with decreasing bulk density ($r = -0.99$, $p < 0.001$) and increasing content of P ($r = 0.83$, $p < 0.01$). Content of K, S and Mg was significantly positively correlated to each other (r = 0.61–0.79, $p < 0.05$).

Comparing introduced and native species, better health status (foliation), higher production (DBH, height, volume, basal area) and soil bulk density were characteristic for native tree species, while higher vertical diversity, soil porosity, content of P and Cox were typical for introduced tree species. Differences among all parameters were remarkable for introduced tree species as marks of each records were relatively distant one from another, whereas marks symbolizing native tree species were relatively closely to each other (low differences between parameters). *Pinus sylvestris, P. nigra, Larix decidua* and *Pseudotsuga menziesii* proved to be the most suitable tree species in relation to production and soil parameters, while *Picea mariana, P. pungens, Pinus strobus* and *P. rotundata* showed unsatisfactory results for afforestation of reclamation sites in given climatic and site conditions according to ordination diagram (Fig. 8).

Discussion

Coniferous tree species showed high production potential in post-mining sites. The stand volume ranged from 71 to 364 m^3 ha^{-1} and biomass from 68 to 319 t ha^{-1}, respectively. The timber production of broadleaved tree species stands was


LarDec
PicAbi
PinSyl
PicMar
PicOmo
PicPun
PinCon
PinNig
PinPon
PinRot
PinStr
PseMen
Ring-width index
1,5
1,0
0,5
1986
1988
1990
1992
1994
1996
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2000
2002
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2006
2008
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2012
2014
2016
2018
Year

◂**Fig. 5** Standardized mean chronology of coniferous tree species in 1986–2018 after removing the age trend expressed by the tree-ring width index and significant low radial growth expressed by negative pointer years (arrows)

significantly lower, ranging from 28 m^3 ha^{-1} in *Salix caprea* L. (nature succession) to 97 m^3 ha^{-1} in *Betula pendula* Roth stands (artificial afforestation) on the same reclamation site (Vacek et al. 2018). In our study, the highest stand volume was observed in case of native tree species—*Pinus sylvestris* (364 m^3 ha^{-1}; 1700 trees ha^{-1}). The production could be compared with the results from oil shale reclamations afforested in Northeast Estonia where the production of 40-year-old *P. sylvestris* stands fluctuates from 167 to 291 m^3 ha^{-1} in stands with high average tree density of 2610 trees ha^{-1} (Metslaid et al. 2016). High production potential of *P. sylvestris* is also documented by studies from coal mine spoils in Czech Republic (Dragoun et al. 2015), oil shale mine spoils in Estonia (Pensa et al. 2004) and lignite mine spoils in Germany (Knoche 2005). Therefore, *P. sylvestris* is often used in afforestation of post-mining sites and reclamations areas due to production parameters and ecological tolerance (Jagodziński et al. 2019; Kuznetsova et al. 2010; Pajak et al. 2016; Pietrzykowski and Socha 2011).

Pseudotsuga menziesii was the second tree species with the highest stand volume (343 m^3 ha^{-1}) on the studied reclamation site. The above average *P. menziesii* production was in European conditions evaluated in original forest soils according to several factors like stand density (Henin et al. 2018; Kantor 2008; Podrázský et al. 2013; Rais et al. 2020); unfortunately, the data from forest restorations are missing. However, when we compare above-average production and comparable wood quality (with native *Picea abies* and *Pinus sylvestris*), *P. menziesii* is a suitable introduced tree species for afforestation (Kubeček et al. 2014; Remeš and Zeidler 2014). The third most productive tree species was the *Pinus nigra* (277 m^3 ha^{-1}), which belongs also to introduced tree species. *P. nigra* is frequently used for afforestation of abandoned agricultural land in Mediterranean, especially in Croatia, Italy or Turkey (Barčić et al. 2006; Mercurio et al. 2010; Poljanšek et al. 2019; Yildiz et al. 2018). However, this tree species starting to be planted more and more often on reclamation sites and it can achieve better growth results (e.g., amount of biomass) under the conditions of Central Europe than native *P. sylvestris* (Baumann et al. 2006; Fettweis et al. 2005; Gerke et al. 2001; Keplin and Hüttl 2001). *P. nigra* was followed by native tree species *Larix decidua* (200 m^3 ha^{-1}) and *Picea abies* (191 m^3 ha^{-1}). Lõhmus, et al. (2007) reported that species of *Larix* having the best growth among coniferous trees in Estonian oil shale miming areas. Moreover, *L. decidua* showed the highest quality of stem (straight stem, high base of crown) in our research. Third most productive introduced tree species was *Pinus ponderosa* (183 m^3 ha^{-1}). This result is in contrary to the research of Podrázský et al. (2020) where *P. ponderosa* was the most productive (age 35 years, 430 m^3 ha^{-1}) from all pine tree species in medium rich habitats in the Forest Arboretum Kostelec (Czech Republic). However, higher production could be associated with low tree density per hectare (460 trees ha^{-1}) and favorable soil conditions.

On the other hand, the lowest production was found in *Pinus strobus* stands (-62% above average, 71 m^3 ha^{-1}). The low production parameters of *P. strobus* were confirmed also on medium-rich habitats in the above-mentioned Arboretum where the production was lowest from six evaluated introduced pine species (112 m^3 ha^{-1}; Podrázský et al. 2020). However, in the natural expansion range (Eastern North America), the *P. strobus* belongs to one of the most economically, socially, and culturally important tree species (Santala et al. 2019; Uprety et al. 2014). *P. strobus* was followed by *Picea mariana* (-57%, 80 m^3 ha^{-1}), *Pinus rotunda* (-37%, 117 m^3 ha^{-1}) and *Picea pungens* (-37%, 118 m^3 ha^{-1}). The comparable production parameters of mentioned introduced tree species were confirmed also by the cluster analysis except for the *P. rotundata* with more than doubled number of trees per hectare (4400 trees ha^{-1}).

Low production of these tree species was related not only to the unsuitability for the given site, but also to poor health status and the susceptibility to insects and fungal pathogens (Itter et al. 2019; Vacek et al. 2015a, 2019b). The lowest production, as well as poor health status (foliation 49.8%), of *P. strobus* can be explained by damage of blister rust (*Cronartium ribicola*). Blister rust is definitely one of the most serious fungal pests of *P. strobus* not only in the Czech Republic, attacking young trees and causing their death in most cases (Radu 2013). Similarly, *Picea pungens* reached very low foliation (50.2%) studied sites due to bud blight (*Gemmamyces piceae*). Historically, this North American Colorado tree species was very often planted in the Czech Republic after decline by SO_2 pollution in 1980th, but nowadays these large forest stands rapidly decline due to this disease (Černý et al. 2016; Šefl et al. 2020). In recent years, bark beetles have also caused a rapid decline and death of *Pinus rotundata* and especially *Picea abies* in Antonín Forest Arboretum. Climatic change, repeated long-term droughts and subsequent bark beetle outbreaks (especially *Ips typographus*) are currently a huge problem not only for *Picea abies* stands in our study area, but for the whole Europe (Kärhä et al. 2018; Netherer et al. 2019). As for the situation in the Czech Republic, the percentage of sensitive *P. abies* forests reached 49.5% in 2019 (Ministry of Agriculture 2019). Therefore, timber harvest has more than doubled in the last 5 years, and salvage logging caused by bark beetles accounted for 73% of total timber harvest in 2019 (Šimůnek et al. 2020; Zahradník and Zahradníková, 2019).

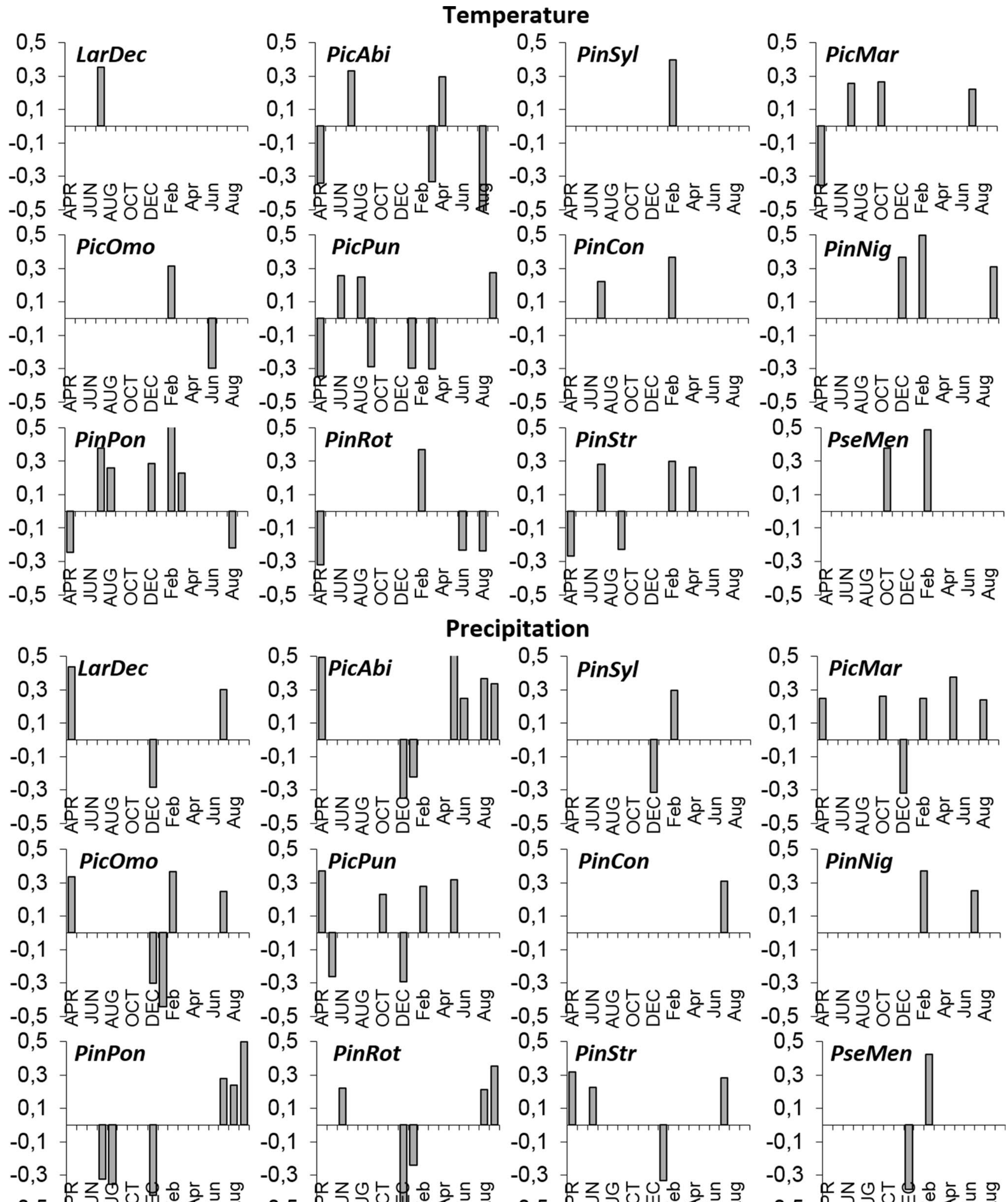

Fig. 6 Coefficients of correlation of the regional residual index tree-ring chronology of coniferous tree species with monthly average air temperature and sum of precipitation from April of the previous year (capital letters) to September of the current year (lower-case letters) in the period 1986–2018; only statistically significant ($p < 0.05$) values are shown

Table 5 Soil parameters of permanent research plots differentiated by the tree species; the highest values are in bold

Species	ρz	ρd	por	Cox	pH	Ca	Fe	K	Mg	Na	P	S	Ca/Mg
	(g cm^{-3})	(g cm^{-3})	(%)	(%)	($CaCl_2$)	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	
Native tree species													
LarDec	2.37	**1.12**	52.70	5.08	6.68	2797	461.6	245.1	2220	58.36	0.53	146.4	1.26
PicAbi	2.29	1.01	56.06	8.62	5.31	1986	373.7	213.9	1820	62.54	3.44	119.1	1.09
PinSyl	**2.50**	1.10	56.00	4.10	6.90	5159	448.7	342.6	1360	81.24	1.95	118.4	3.80
Introduced tree species													
PicMar	2.30	0.67	**71.36**	7.87	4.83	2335	**918.3**	484.7	2187	60.27	11.74	163.3	1.07
PicOmo	2.38	0.92	61.55	7.77	6.44	2548	484.9	326.3	2217	79.96	1.74	135.5	1.15
PicPun	2.31	0.72	69.23	8.81	6.05	4265	462.5	397.7	**2677**	54.20	**12.38**	**216.7**	1.60
PinCon	2.31	0.91	60.58	7.65	5.98	2837	480.5	338.2	2155	63.14	4.02	119.0	1.32
PinNig	2.41	0.96	59.91	4.72	**7.08**	**5207**	460.0	274.8	1350	73.47	3.09	131.1	**3.96**
PinPon	2.42	0.87	62.81	6.38	6.71	4800	451.8	**670.6**	2369	35.62	7.03	201.7	2.03
PinRot	2.37	0.85	64.65	9.00	6.31	4050	593.2	497.8	1877	**93.08**	2.24	124.2	2.18
PinStr	2.28	0.84	63.31	**10.38**	5.20	2477	575.4	220.5	1098	60.06	8.89	86.7	2.59
PseMen	2.36	0.88	62.53	6.22	6.11	3276	501.9	434.4	2038	76.23	4.83	130.0	1.61

The highest values are marked in bold

ρz specific density, *ρd* bulk density, *por* soil porosity, *Cox* oxidizable carbon, *pH* soil reaction, exchangeable elements – calcium (*Ca*), iron (*Fe*), potassium (*K*), magnesium (*Mg*), sodium (*Na*), phosphorus (*P*) and sulfur (*S*)

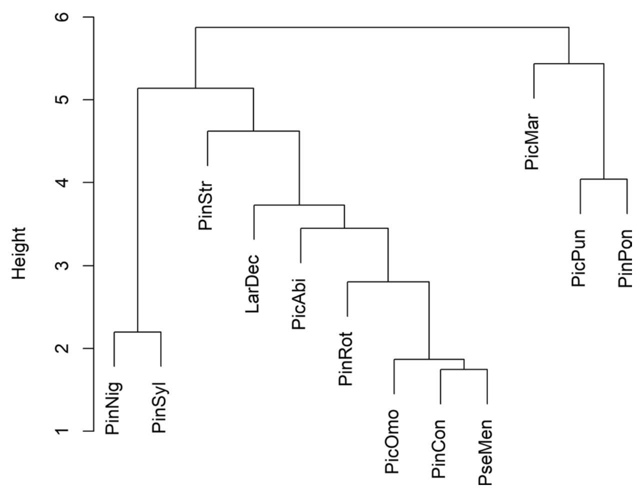

Fig. 7 The results of hierarchical clustering analysis of plots with different species using soil parameters presented in the form of dendrogram constructed by UPGMA method

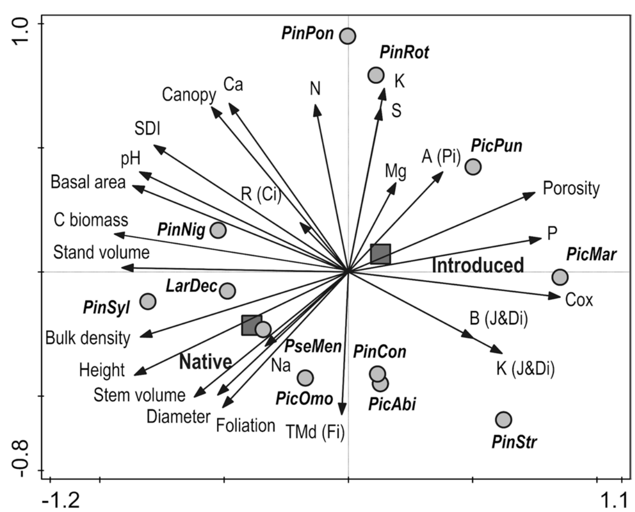

Fig. 8 Ordination diagram showing results of the principal component analysis of relationships between stand characteristics (stand volume, tree volume, basal area, diameter, height, tree number, canopy—crown closure, stocking—stand density index, carbon storage in biomass), health status (foliation), structural diversity [R (C&Ei), A (Pi), TMd (Fi), TMh (Fi), S (J&Di), K (J&Di), B (J&Di); notes see Table 1], soil parameters (bulk density, pH, porosity, content of Cox, P, K, Mg, S, Ca) and 12 tree species (notes see Method section); symbols indicate closed circle 12 tree species and closed rectangle introduced vs. native tree species

In the context of poor health status and subsequent mortality of trees, the horizontal structure of forest stands may change (Vacek et al. 2015b; Vacek et al. 2017a, b), such as in our case. As a result of the attack of the above-mentioned diseases, the spatial distribution of *Pinus strobus* and *P. rotundata* changed from regular and aggregated distribution. In terms of other biodiversity indices, the higher height and diameter differentiation were observed in case of *Pseudotsuga menziesii*, but the highest total diversity ($B=4.6$) was in *Picea mariana* characterizing by low timber production. Similarly, the highest total diversity ($B=3.7$) was observed in case of very below average production of *Pinus peuce* in other Forest Arboretum (Podrázský et al. 2020). However, significantly higher total diversity on reclamation site was observed in broadleaved tree species stands, both artificially planted ($B=4.7$–5.5) and especially established from nature succession ($B=5.6$–8.2; Vacek et al. 2018). On the other hand, the lowest biodiversity across all indices was in *Picea omorika*.

Regarding *Picea abies*, also dendrochronology confirmed the highest sensitivity of this tree species to lack of precipitation, followed by *P. pungens* and *Pinus ponderosa*. Sensitivity of *Picea abies* in lowland areas to droughts together with high temperature in vegetation period confirmed also other studies (Cukor et al. 2019, 2020; Vacek et al. 2019a). Generally, importance of precipitation increased from the north to the south and downward in the altitude gradient (Mäkinen et al. 2002). On the other hand, adaptive tree species to low amount of precipitation were *Pinus contorta*, *P. sylvestris*, *P. nigra* and *Pseudotsuga menziesii*. Study from Germany showed that *P. menziesii* stands were more resistant and adaptive to long-term droughts compared to *P. abies* (Vitali et al. 2017). As in the case of precipitation, the highest effect of monthly temperatures on radial growth was observed in *Picea pungens* and *Pinus ponderosa.* Conversely, low effect of temperature was observed in case of *Larix decidua, Pinus sylvestris*, followed by *P. contorta*, *Pseudotsuga menziesii* and *Picea omorika.* The resistance of *P. omorika* to climatic factors and air pollution (compared to native *P. abies*) in the Czech Republic were also demonstrated by Král (2002).

In general, the prevailing limiting factor of the radial growth of the studied tree species was the synergism of i) the lack of precipitation with high temperatures in the vegetation period and ii) the high sum of precipitation with low temperatures in the winter period. Specifically, the most important month in terms of temperature was February (positively response of growth to high temperature), such as in other cases in the Czech Republic (Mácová, 2008). Mentioned study also observed that *P. strobus* were significantly more sensitive to climatic stress compared to *P. sylvestris*. This was also confirmed by our analysis of NPYs with significantly low radial growth, where the highest number of NPYs was observed in case of *Pinus strobus* and *P. rotundata*. On the other hand, stable radial growth in terms of climate change was in *Pinus sylvestris, P. nigra, Larix decidua* and *Picea omorika.* Moreover, these first tree species achieved the highest carbon stock in biomass, whereas carbon sequestration can significantly affect the course and mitigate the climate change (Bellassen and Luyssaert 2014; Canadell and Raupach 2008).

Carbon efficiency (storage of CO_2 in the biomass of living trees) could be increased by afforestation in order to reduce the future damages of climate change (Sohngen 2009), for example, on reclamation sites such as Antonín. In relation to this statement, the most significant decrease in radial growth was caused by long-term droughts with extremely high temperatures in vegetation periods, which is a result consistent with other papers dealing with radial growth of studied tree species (Kohler et al. 2019; Vacek et al. 2016; Vacek et al. 2017a, b; Zang et al. 2012). Suitable climatic conditions in June and July are especially important, when the major part of xylem formation and radial increment are recorded (Mäkinen et al. 2003; Putalová et al. 2019). This is closely related to climate change (warming, uneven precipitation) and the need to plant resistant tree species, and the shift of growth optimum of native tree species (to north and higher altitudes) in future (Boisvert-Marsh et al. 2019; Dulamsuren et al. 2017; Sedmáková et al. 2019). However, the effects of climate change on the growth of forest stands depend critically on thinning strategy and site productivity (Bosela et al. 2016; Garcia-Gonzalo et al. 2007).

In terms of soil conditions, the initial development of newly formed forest soils reflected the general rules of pedogenesis (Binkley 1986), vegetation being one of the basic factors of soil formation (Frouz et al. 2008; Šály 1978; Šourková et al. 2005). This is also the case of spoil heaps reclamations after brown coal surface mining (Helingerová et al. 2010; Kuter 2013), connected with totally abiotic soil substates and new soil formation. These activities encompass usually relatively large areas and present many problems related to soil erosion, environment pollution and load (Brom et al. 2012). The terminology in the post-mining activities is not clear enough yet, and different terms are used in the practice as well as scientific evaluation of the post-mining processes—i.e., reclamation, rehabilitation (functional recovery of ecological processes), restoration (return to pre-mining state) or simply remediation (Bradshaw 1997; Lima et al. 2016). Also, the techniques used are designed in different terms; in the Czech conditions, technical and biological reclamation are traditionally used for technical terrain modeling and vegetation measures (Doležalová et al. 2012; Markéta Hendrychová 2008), and in some other references, the biological reclamation term is used for succession only (Tropek et al. 2012). In the presented case, limited species assortment was evaluated, composed of native as well as introduced coniferous tree species. The substrates used for site reclamation were relatively rich from the point view of bases content and related soil reaction (Dimitrovský et al. 2010), the weathering of them resulting in clay-rich, base-rich and pH high initial material for soil formation. The content of plant available nutrients (K, Ca, Mg) was good (very good) from the viewpoint of potential forest tree species nutrition and soil adsorption complex saturation (Šrámek et al. 2013). Only the phosphorus contents were relatively very low, indicating this nutrient (together with nitrogen) is limiting at these early development sites.

The plantations at the studied locality are relatively young (48 years), and the soil state is corresponding to this fact. The nutrients and carbon are sequestered prevailingly in the standing biomass, and the particular tree species are converting relatively small proportion of carbon and nutrients into the surface soil layers. Especially the deficient phosphorus is fixed in the living biomass effectively. Fixation of the deficient nutrients by intensively growing tree species is documented in more cases also in common forest stands (Mondek and Baláš 2019). The soil reaction is reflecting local substrate composition and general geologic substrate state more than initial forest stand composition (Augusto et al. 2003).

Higher standing volume also corresponds with lower soil carbon content and connected higher volume soil density, determined to high extent with soil organic matter content. Higher soil carbon is affecting lower soil reaction, which on the contrary increases with higher soil calcium concentration in the same sense. Higher specific as well as bulk density is negatively correlated with organic matter and porosity too, all in relation to the initial soil development stages and general trends (Binkley 1986; Pourbabaei et al. 2020; Šály 1978). These differences, connected also with soil microbial activities, are expected to increase with more differentiated tree species composition, especially including broad-leaved tree species (Bahnemiri et al. 2019; Remeš and Šíša 2007). In longer time period, more litter and plant residues formation are to be expected reflected also by the soil state (Špulák and Kacálek 2020). Overall, in terms of tree species, *Pinus sylvestris* and *P. nigra*, in combination with above-average biomass production, also achieved good soil properties. On these extreme sites, *P. sylvestris* used nutrients most efficiently compared to other tree species [*Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth] commonly grown on reclamation areas (Kuznetsova et al. 2011).

For successful afforestation of reclamation sites, it is important to use an appropriate tree species for the given habitat and soil conditions and adaptive to climate change (Pietrzykowski 2019, 2014). Forest management is highly beneficial on post-mining sites, which are very specific for their soil conditions (Vacek et al. 2018; Woś and Pietrzykowski 2019) Thinning on reclaimed sites may increase radial growth of dominant trees reducing the competition between trees after canopy closure (Metslaid et al. 2016). Moreover, suitable tree species in a mixture can significantly increase production potential of stands in the reclamation areas (Dragoun et al. 2015), increase the resistance to negative abiotic and biotic factors and reduce the uncertainty of production sustainability due to disturbances (Bello et al. 2019; Pretzsch et al. 2020; Vacek et al. 2019c). In addition to tree species, provenance also plays an important role in production potential and adaptation to climate change (Kapeller et al. 2012; Novotný et al. 2017).

Conclusion

In the past, only the techniques leading to the establishment of any vegetation cover were used for the reclamation of habitats after surface coal mining. This approach was short-sighted, as it did not consider the importance of ecosystem processes. At present, when the area of the post-mining landscape is increasing due to the growth of the demands of human population and forest stands are increasingly threatened by climate change, it is necessary to comprehensively focus on the selection of suitable tree species for afforestation these extreme sites. In terms of timber production, tree biomass and carbon store, stands of *Pinus sylvestris*, *P. nigra* and *Pseudotsuga menziesii* showed by 49–95% higher values than the average of all tree species studied. However, it is not only the production potential that is important, but also the stability of the stands and the adaptability to climate change. Relatively resistant species in terms of the influence of climatic extremes, high temperatures or lack of precipitation were *Larix decidua*, *Picea omorika, Pinus sylvestris*, *P. nigra* and *Pseudotsuga menziesii*. In general, the limiting factor of the radial growth of the studied tree species was the synergism of the lack of precipitation and high temperatures in the vegetation period and the high total precipitation with low temperatures in the winter. In addition, *Pinus sylvestris* was found to have the best physical and chemical properties of the soil, as well as the best state of health. However, the content of plant available nutrients in soils was generally good for all tree species, except phosphorus. Overall, *Pinus sylvestris, Pseudotsuga menziesii*, *Pinus nigra* and *Larix decidua* are the most suitable (adaptive) of the studied conifers for the given habitat ratios of reclaimed areas after surface coal mining in connection with advancing global climate change. The least suitable tree species proved to be *Pinus strobus*, *P. rotundata*, *P. ponderosa*, *Picea abies* and *P. pungens*, which are sensitive not only to climate change, but suffer from periods of drought and have been increasingly attacked by insect and fungal pathogens in recent years. From an ecological and production point of view, however, it is recommended to cultivate appropriately selected tree species on post-mining sites in mixtures.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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7.1.5. Profile development and soil properties of 3 forest reclamation chronosequences in Sokolov mining basin, Czech Republic

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Profile development and soil properties of 3 forest reclamation chronosequences in Sokolov mining basin, Czech Republic

Marko Spasić[1], Oldřich Vacek[1,2], Kateřina Vejvodová[1], Luboš Borůvka[1], Václav Tejnecký[1] and Ondřej Drábek[1,*]

[1] Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Prague 6 - Suchdol
[2] Department of Landscape Architecture, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129, 16500 Prague 6 - Suchdol
* Correspondence: drabek@af.czu.cz

Abstract: Forestry reclamation practices have been very popular in the second half of the last century, and many spoil heaps have been converted to forests since. In our experiment, three forest chronosequences of different age (~90,~50 and~30 years) and three soil vegetation covers (I - maple and cherry, II – maple, and III - alder) from Sokolov, Czech Republic, have been investigated. In each of the three stands, two soil profiles have been dug, and both disturbed and undisturbed soil samples have been taken from all recognized horizons. Samples have been 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. 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 anthropogenic mine Technosol to evolve into 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, 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

Coal mining presents a serious issue of a modern society. Open-cast coal mining significantly changes the landscape and utterly destroys soil functions, making these vast sites practically desolate, thus positioning itself as probably the most disputed industry in the world [1]–[4]. Besides disturbing landscape and soil, it also affects 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 done [3], [6]–[9], and our knowledge expands every year with various research results that we get from these localities.

Though many researches have shown that technical reclamation, a process widely used in the 20th century, might have its flaws, and there are other, in many cases more feasible and effective solutions, such as natural succession [8], [10], the fact that many of these sites have been reclaimed, either for environmental, scientific (experimental) or legislative purposes, still remains. The full effects of 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 [11], [12] and allows us to see some processes difficult to see in mature soils [13]. Researches which show that soil formation process on post-mining sites can be observed within a shorter time period compared to natural sites have also been conducted [14]. Karan et al. [15] stated that 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, 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" [16]. According to Hugget [17], 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 big limitations of the chronosequence approach is 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 same extraction techniques used over a longer period of time, constantly creating new sites. Because of this, chronosequence approach is very often used in post-mining reclamation research [18].

Sokolov mining basin, in northwestern Bohemia, Czech Republic, is one of the largest and most extensively exploited coal deposits in this part of Europe. In the Czech Republic, technical reclamation practice became compulsory in 1957, when a "Mining Act" was issued [19], and it was extensively used throughout the second half of the 20th century, mainly focusing on forest and agricultural reclamations, and sometimes creation of artificial lakes – methods still widely used today [20]. A significant number of research experiments took place on both the reclaimed spoil heaps of Sokolov mining region, and the ones left to natural succession, many of them observed as chronosequences [18], [21]–[27]. 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 to a lesser or greater extent [9]. With time and continuous monitoring, these sites can provide valuable input on soil formation process.

2. Materials and Methods

The study area is located in Sokolov mining basin, in the northwestern part of the Czech Republic. Within it, 3 forest reclamation localities of different age 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's 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 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 have been planted together with the target tree species, and cut after a period of 10 years, leaving the formed biomass on-site [12]. At all three localities, reclamation was done without the application of topsoil. The localities are presented on a map in Figure 1. Parent material of all three spoil heaps is consisted primarily of cypress clays, which have been known for their soil improvement properties and pH increase [28].

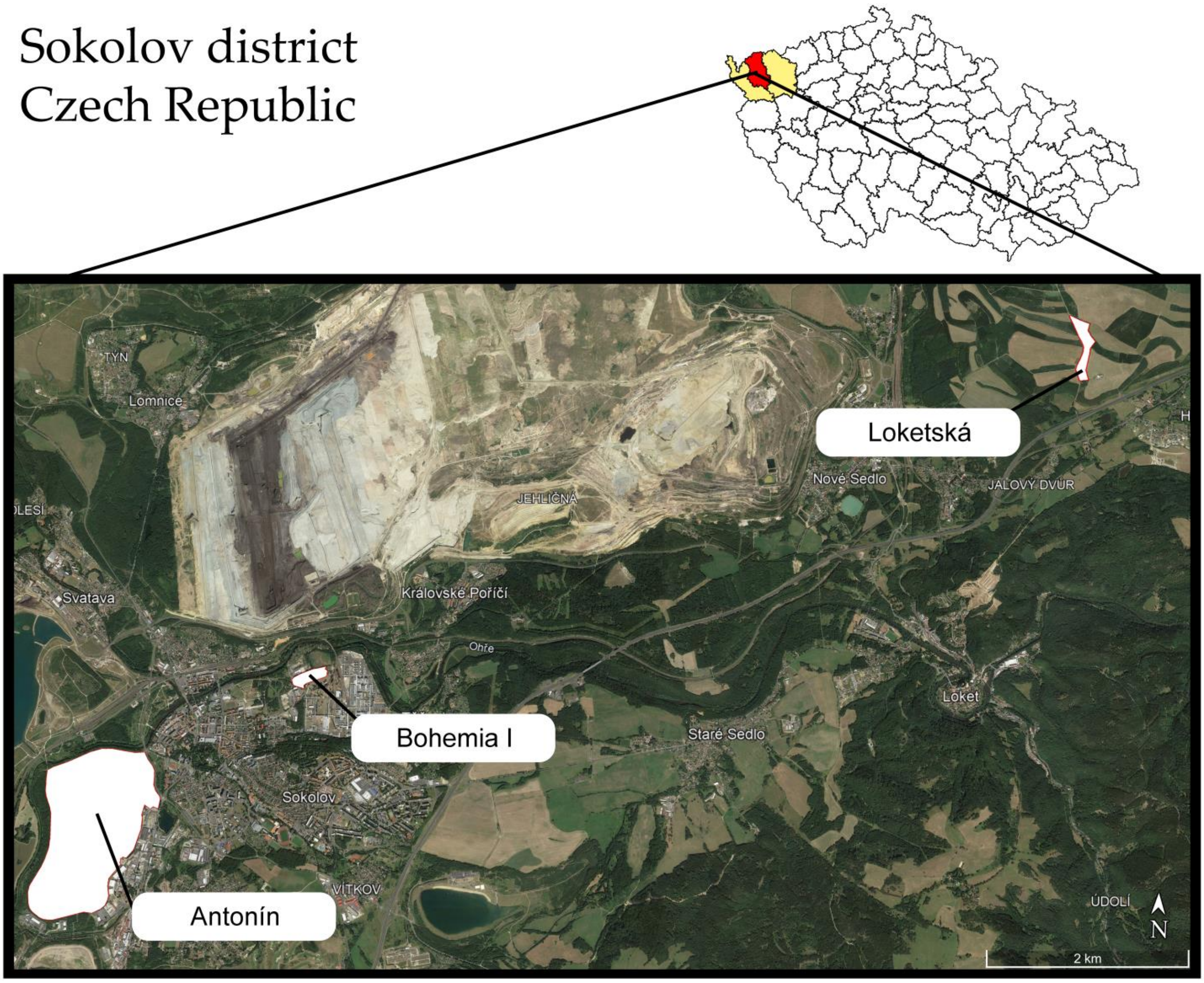

Figure 1. Study area (Sokolov mining region) with sampling locations - Bohemia I, Antonín and a part of Loketská spoil heap (source: Google Earth)

In all three localities, soil profiles have been dug (2 profiles at each location, one on flat terrain, one on a slope) and thoroughly described. Thickness of all 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 if 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 [29]. 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 [30]. Cation exchange capacity (CEC) was measured by inductively coupled plasma optical emission spectrometer (ICP-OES) iCAP 7000 by Thermo Scientific™, USA, following the standards from ICP Forest's Sampling and Analysis of Soil Manual [31]. Plant available nutrients (Mehlich III extraction method, ICP-OES iCAP 7000, Thermo Scientific™, USA) were determined according to the 30068.1 standard from ÚKZÚZ [30]. Oxidizable carbon content (Cox) was determined by modified Tyurin's method, [32] by wet combustion (sulphuric 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 (Hewlett Packard 8453 UV/VIS Spectrophotometer), according to the standards from Pospíšil [33].

Due to the complexity of statistically comparing the differences between individual formed horizons, as well as between the stands/chronosequences, which have a hierarchial 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 physical and chemical properties of the studied localities would 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 3 broadleaved stands of different age. We hypothesized that:

1. considering the alkaline clayey parent material and broadleaved vegetation cover in all locations - the soil type would tend to evolve from an anthropogenic mine Technosol to a forest Cambisol in this climate region;
2. reclamation time would strongly affect the development and thickness of formed horizons, as well as soil quality. A partial aim was investigating the effect of different forest vegetation (tree species) on horizon thickness and soil properties;
3. the profiles positioned on the slopes would manifest somewhat poorer physical and chemical properties compared to their plain terrain counterparts, due to the effects of surface runoff, surface and internal erosion processes and lack of water logging.

3. Results

In all 3 studied localities where the soil profiles were made (Bohemia I, Antonín and Loketská), the sites have shown a similar profile evolution - from a mine Technosol to a forest Cambisol. In all 3 locations, horizon differentiation (A-Bv-C) was visible. Horizon transitions 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 Loketská stand on plain terrain, whereas it was 4 cm in the same stand on the slope. 50 year old Antonín stand had the same A horizon thickness (5 cm) in both plain and slope terrain. In Bohemia I, the thickness of A horizon on plain terrain was greater than 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 plain 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 plain terrain in Bohemia I (50.5 and 44 cm for plain vs. slope). Within all sites, in the deeper layers, coal residues and cypress claystones were found. The development of the soil horizons is presented in Figure 2.

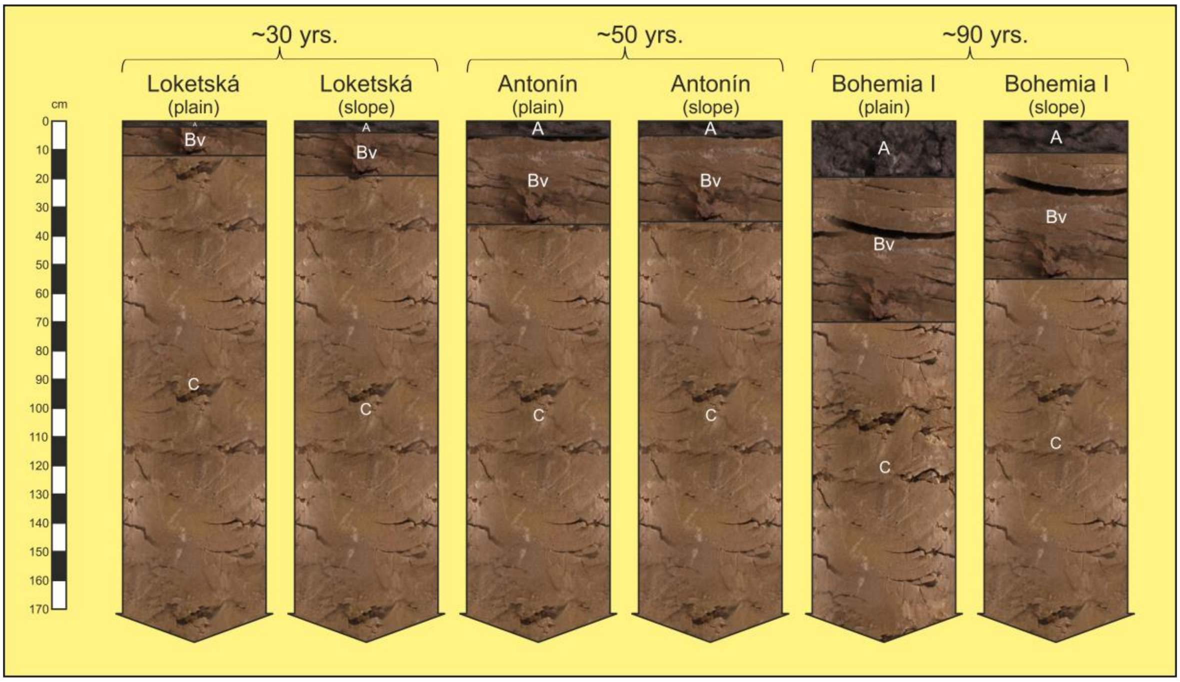

Figure 2. Schematic representation of the profile development of soil pits from 3 chronosequences

Bulk density analysis has shown that the bulk density varied, on average, between 0.79 and 1.39 g/cm³. The clearest distinction could be noticed between horizons - all of the A horizon samples had lower values (0.75-1.03 g/cm³) than the Bv and C horizons (1.08-1.39 g/cm³), and the A horizon values of pairs on plain 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.

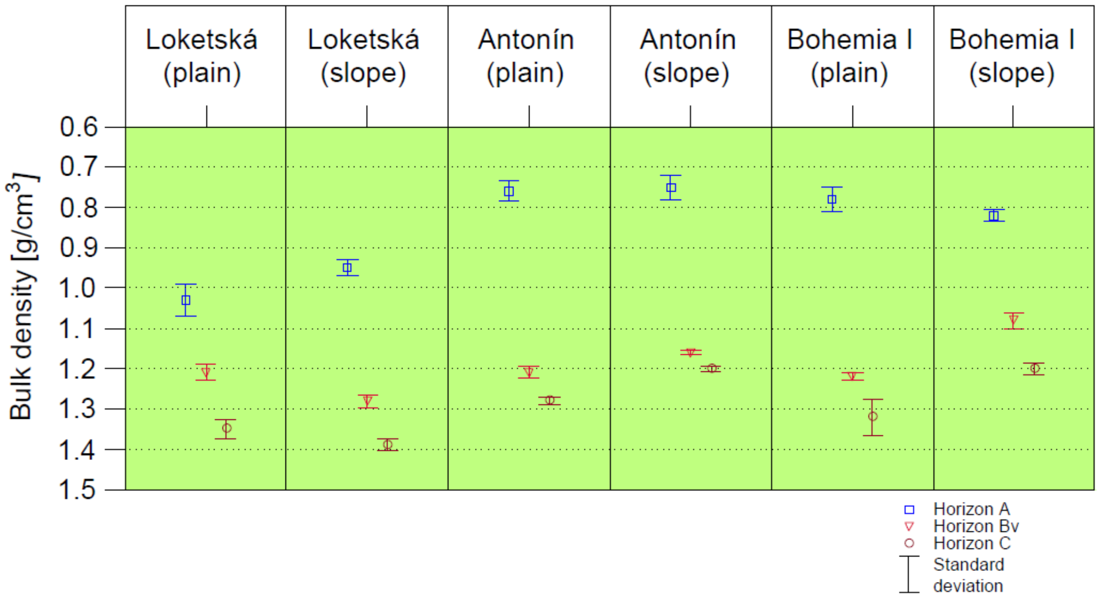

Figure 3. Bulk density values on Loketská, Antonín and Bohemia I sites on plain and slope terrain

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 50 years old Antonín stand on flat terrain. Porosity values mostly corresponded with bulk density values, as can be seen in Figure 4. The average values ranged between 46.56 and 67.61%. Average porosity of the A horizon in Antonín and Bohemia I ranged between 64.28 and 67.61%, whereas Loketská values ranged between 57.30 and 60.93%.

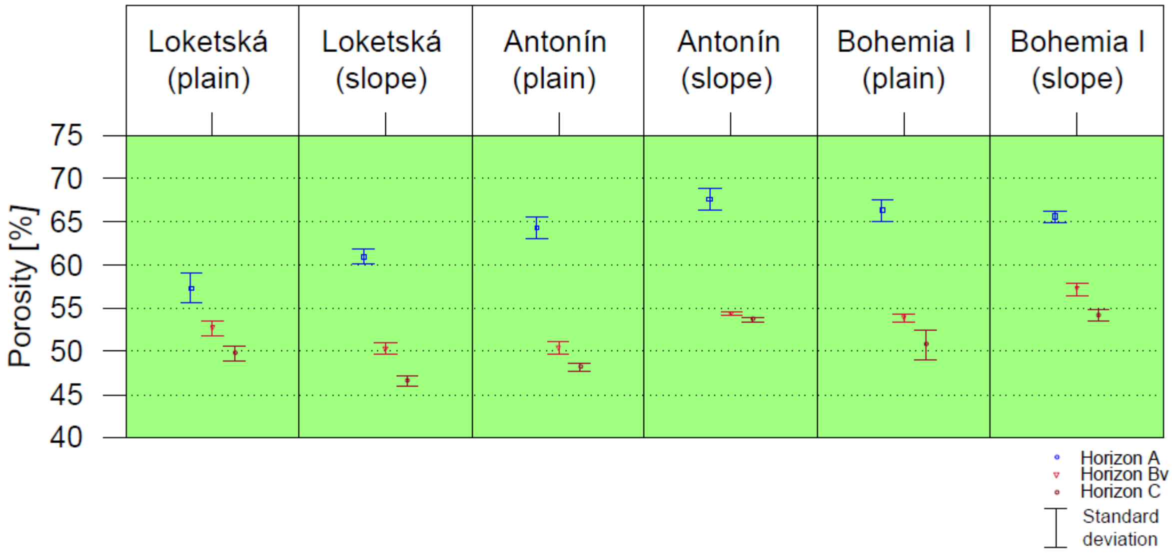

Figure 4. Porosity values on Loketská, Antonín and Bohemia I sites on plain and slope terrain

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 [29]. At most of the locations, the water retention values dropped with horizon depth (A>Bv>C), except in the case of 50 years old Antonín stand on plain terrain, where the MCC values were greater in C than in Bv horizon. Highest average water retention values were noticed in Antonín stand on the slope (52.95-56.87%). The greatest ranges in average values were noticed in Bohemia I on plain terrain and Antonín on plain terrain (6.93% and 6.63%, respectively), although Antonín exhibited greater variations between all samples, and bigger overal standard deviations. On the other side, both localities on the youngest site (Loketská) have shown quite narrow MCC ranges (2-3%). MCC values can be seen in Figure 5.

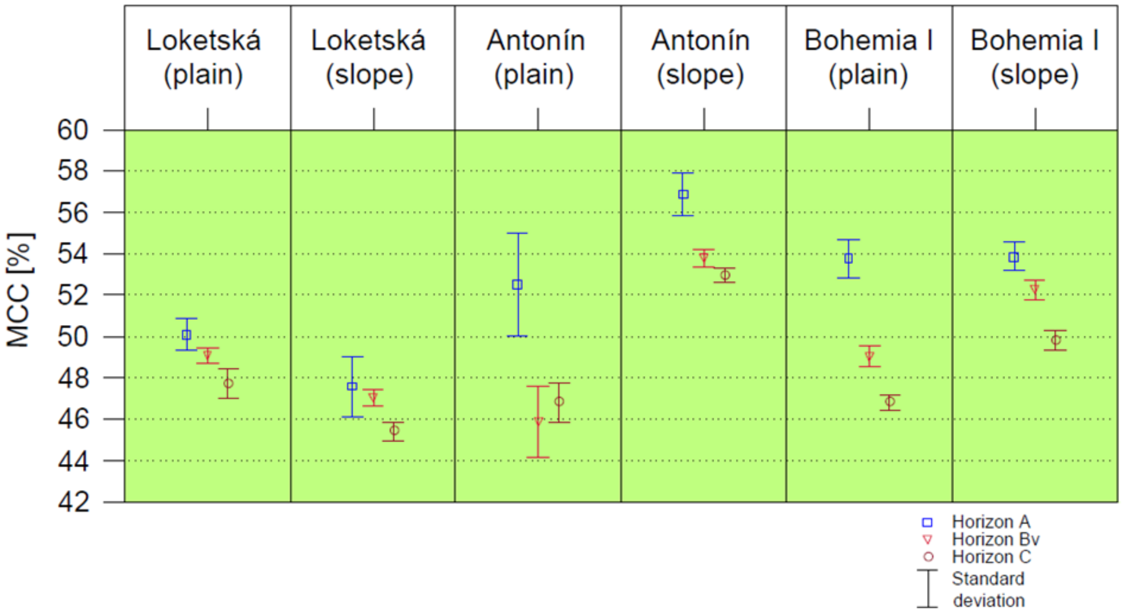

Figure 5. Maximum capillary capacity (MCC) values on Loketská, Antonín and Bohemia I sites on plain and slope terrain

Chemical analyses have shown that 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 A horizons (7.1-10.5%) of all stands, and usually dropped with depth, except in 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 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 [34], insufficient or low, whereas K, Ca and Mg 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 1.

Table 1. Average values of chemical soil properties from samples from all 6 soil profiles (with standard deviations)

Analysis	Horizon	Loketská plain	SD	Loketská slope	SD	Antonín plain	SD	Antonín slope	SD	Bohemia I plain	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
	>1m	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

	>1m	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
	>1m	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
	>1m	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	/
	>1m	ND	/	ND	/	ND	/	ND	/	ND	/	ND	/
$K_{available}$ [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
	>1m	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
	>1m	6678	26.2	17587	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
	>1m	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
	>1m	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
	>1m	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
	>1m	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 [35] 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's safe to assume that all of the tested PTEs were way under the limit where they would pose a threat. The classification criteria for macronutrients (P, Ca, K, Mg) and PTE (Al, Fe, Mn) according to Fiala et al. [35] and ÚKZÚZ (Central Institute for Supervising and Testing in Agriculture of the Czech Republic) are given in Tables 2 and

3. Other elements (Cd, Pb, Ni, Cu and Zn) have had 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 2. 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. [35]

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 3. 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. [35]

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	7901-11700	>11700
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 more or less developed organo-mineral and cambic horizon, which is in accordance with the statements that A horizon can develop after less than 20 years, and that formation of secondary minerals can be observed after around 40 years [9]. Formation of "cambic-like" horizons in 50 year old mine soils have been described by Feng et al. [36], along with various depths of A and B horizons. Having in mind that the clayey parent material of Sokolov region is not too severe for establishing vegetation, and the high quality litter provided by the broadleaved vegetation cover [24], these results are not surprising. Frouz et al. [13], [26] 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 organomineral horizons were present. Spasić et al. [12] have found that (with some exceptions) in most cases, similarly aged (~50 years old) conifers within Antonín forest arboretum in Sokolov formed horizon A thinner than 3 cm, whereas most broadleaves formed 4-6 cm thick A horizon. On a 28 year old site reclaimed by alders in Sokolov, 9.8 cm thick organomineral horizons were recorded [26]. Frouz et al. [25] have recorded A horizon depths of up to 6 cm in 41 year old spontaneous sucession 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 observing it as a 90 year old chronosequence. Hüttl & Weber [37] have highlighted the problem of finding reclamation plots older than 40 years. The development of A and Bv soil horizons which were, in case of plain terrain, noticed to be almost around 20 and 50 cm deep, respectively, proved to be deeper than what we've initially expected, and definitely highlighted the effect of time on 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. [38]. Disequilibria between parent material and natural environmental conditions, high pH promoting dissolution of silicates, good soil saturation properties, presence of salts or sulphates accelerating weathering are just some of the causes mentioned. Greater depths of horizons formed on mine Technosols compared to natural forest were also noted by Thomas et al. [39].

Our presumption about soil formation depth on plain vs. slope terrain proved to be correct in case of the oldest (Bohemia I stand). In Antonín, the horizon thickness did not vary that much. 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 might be too short for observing the soil formation proces through horizon formation with great certainty; secondly, local site varieties, 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 plain vs. 8.2-8.3 for slope), as well as the differences in slope steepnes (slope at Bohemia I was much steeper than slopes at Antonín and Loketská), could all be potential contributors of that result.

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 clearer and clearer. Such were, also, the horizon borders during the sampling. Although noticeable in all horizons (and following similar patterns), the differences in physical soil properties were, in particular, more pronounced between organomineral 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 of the soil cylinders used have a height of 5 cm, so in Loketská samples they've encompassed not only A, but the underlying Bv horizon, as well. Roberts et al. [40] 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 of soil physical properties' values were noticed in the two older stands on plain terrains compared to the ones on slopes, which further proves our hypothesis.

In most cases, pH decreased as new horizons have 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 & Frouz [18] have 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 have 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. Similar trend was also noticed in studies by various other authors [21], [22], [24], [25], where they've found that pH decreased with plot age.

Carbon and nitrogen accumulation in upper layers of reclaimed and successional forests on mining sites was expected and well documented in scientific literature [18], [22], [24], [25], [41], [42]. Reported levels of carbon 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 ones).

Due to 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 [42]. Fossil C correction methods have also been well described [41]. In some instances, it has been shown that no significant increase in C content was found in layers below the A horizon [21], [26].

According to Mládková et al. [43], 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. [44] have compared various methods for assessment of organic substances 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've hypothesized that quality would increase with the age of the stands. Bohemia I and Antonín stands have maple as the dominant vegetation type in common, whereas 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, mixed dominant tree species (maple and cherry) in Bohemia I could have resulted in greater humus quality, as Godefroid et al. [45] 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 Bohemia I stand (where the difference in slopes was the greatest), but OM quality was, surprisingly, greater on slope than on plain 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 results obtained by other authors on reclaimed mine sites [12], [46], [47]. Bartuska & Frouz [18] have found that total P levels were decreasing in reclaimed alder forests in Sokolov with site 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 & Frouz [18]), 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, 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 good range for availability of phosphorus availability to plants, whereas anything below or above this range limits P availability due to its fixation to Al, Fe or Ca [48]. Only one of the 6 samples from A horizon had the 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 aluminium 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. [49] have found higher P in 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 mentioned low phosphorus availability in clays due to their high pH. Frouz et al. [25] 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 Sokolov region [12], [47]. Plant available potentially toxic elements tested have had very low or low values, which are in accordance to the values obtained by Spasić et al. [12] and Frouz et al. [50]. Only zinc values in A and Bv horizon in Loketká on plain 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 [51]. Mehlich III method was found to extract higher amounts of Cu, Fe, Mn and Zn, especially in high pH [52], 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. [50] have shown that low pH was the most important factor for 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 observation of differences noticed in 6 soil profiles from 3 differently aged, broadleaved forest reclamation chronosequences 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 soil horizons showed the evolution of soil type to progress from an anthropogenic mine Technosol to a forest Cambisol in all 3 localities. The rate of development (and thickness) of the soil horizons increased with age, and the differences in physical and chemical soil properties were noticed to be greater as time passed. Physical properties have mostly shown wider ranges in pits located on plain 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. Quality of organic substances was noticeably higher in the oldest stand. The effect of soil pH and slope on soil development was observed. However, further, more comprehensive research needs to be carried out.

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7.1.6. Temporal changes of soil characteristics on Lítov spoil heap, Czech Republic

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Temporal changes of soil characteristics on Lítov spoil heap, Czech Republic

Enkhtuya Enkhtaivan[1], Oldřich Vacek[1,2], Petra Vokurková[1], Marko Spasić[1]*, Radim Vašát[1], Ondřej Drábek[1]

[1]*Department of Soil Science and Soil Protection, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129 - Suchdol, Prague 6, 165 00, Czech Republic*
[2]*Department of Landscape Architecture, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague, Kamýcká 129 - Suchdol, Prague 6, 165 00, Czech Republic*

**Corresponding author: spasic@af.czu.cz*

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Abstract: This study aimed to examine the changes in selected soil properties at Lítov spoil heap (Sokolov, Czech Republic) and compare the current situation with the situation described twenty years ago. A total of 110 soil samples were taken at Lítov at the same sites as in 1998. The analyses of basic soil characteristics involved: exchangeable soil pH (pH_{KCl}), organic carbon content (C_{ox}), quality of humic substances (A_{400}/A_{600}), exchangeable acidity (E_a), and two types of aluminum contents in the soil. Changes in all soil characteristics between 1998 and 2018 were statistically evaluated and compared, and visualized using Geographical Information Systems (GIS). We have observed an increase of pH_{KCl}, C_{ox} and a slight improvement in humus quality compared to the results from 1998. The temporal changes of soil characteristics were evident in the whole area, and the influence of reclamation methods was also pronounced. Soil development close to the regional common natural conditions was found in the area where agricultural reclamation measures (i.e., covering with topsoil) were carried out. Furthermore, afforestation - mainly by deciduous trees - supported the improvement of soil characteristics favourable for plant growth. High pyrite content and marshland were identified as the main causes that led to vegetation cover mortality.

Keywords: Mining; Reclamation; Anthropogenic soil; pH; Aluminium; Acidification;

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INTRODUCTION

Surface lignite mining has a massive negative impact on soil and leads to the destruction of soil properties. It impairs the aesthetic appearance of the landscape and the soil structure, and it removes local native vegetation and results in the disappearance of wildlife (Macdonald et al. 2015; Parrotta & Knowles 2001). As a result of mining, soil tends to have adverse physical properties and nutrient deficits, favor run-off and erosion, with significant environmental consequences, e.g., transported particles may bear toxic compounds such as potentially toxic elements (Echevarria & Morel 2015; Pająk & Krzaklewski 2007). In addition, surface mining significantly changes humus quality, organic carbon content, and concentrations of potentially toxic elements. Soil organic matter content is generally very low, thus limiting pedological processes of great importance (such as aggregation) and the supply of suitable physical properties and nutrients for plants (Echevarria & Morel 2015). Nowadays, an effort is made to restore the disturbed landscape as much as possible and keep nature healthy, fertile, and stable. In agreement with Czech legislation, that effort is concentrated on landscape reclamation and revitalization (Borůvka & Kozák 2001). Soil quality is among the most important parts of restoring a functional ecosystem after mining (Liu et al. 2017). Reclamation type is the key factor that determines anthropogenic soil formation rate (Hendrychová 2008). Apart from reclamation, unreclaimed sites left to spontaneous succession also exist.

Significant changes in pH concerning site age have been reported. Some researchers (Frouz et al. 2001; Šourková et al. 2005) have studied spoil heaps in the Sokolov mining basin afforested by alders (*Alnus glutinosa, Alnus incana*). They reported that pH had changed from alkaline on young sites to slightly acidic on older sites. pH dropped by 0.8 under deciduous trees but by 2.7 under coniferous monocultures over 28 years of development (Kabrna 2011). Similarly, during succession, pH (H_2O) in the topsoil layer has been shown to decrease from an initial value of 8 to about 6.5 (Frouz et al. 2008; Frouz & Nováková 2005).

We hypothesized that anthropogenic soils have significantly changed characteristics over a twenty-year period (dynamic evolution). Moreover, this development seems to be influenced by soil vegetation cover.

Our study aimed to investigate the changes of selected soil properties on Lítov spoil heap and compare the current situation with the situation twenty years ago. Another goal was to evaluate this spoil heap's temporal development and propose necessary measures leading to overall sustainable vegetation cover.

MATERIAL AND METHODS

Study area and sampling scheme

Lítov, a spoil heap created after extensive lignite mining operations had ended, was selected as a study site for this experiment. The location and sampling sites of the Lítov heap are presented in Figure 1. This site allows studying different soil characteristics and analyzing the temporal development of new anthropogenic soils. Lítov was created as an external dump of lignite mines Medard and Libík. The overburden (parent) material of the Sokolov area primarily consists of tertiary (cypress) clays and its pH usually ranges around 8-9 (Jačka et al., 2021).

In 1998, 110 soil samples were collected from the same study area (Figure 1) and analyzed (Borůvka et al. 1999, Borůvka & Kozák 2001). Inspired by their studies, in 2018, a total of 107 composite samples (three of the original sampling sites, № 23, 33, and 34 on Figure 1, are currently flooded) were collected from a 1.1 km^2 area. Samples were taken by soil auger from the top layer (which encompassed either organomineral (A) horizon developed on top of the mineral parent material (C), or just (C) if no organomineral (A) horizon has formed), 0 to 20 cm. The weight of each sample was approximately 1 kg. As already mentioned by Borůvka & Kozák (2001), the main components of Lítov spoil material were cypress clays, with an admixture of minerals of pyritic nature and brown coal particles.

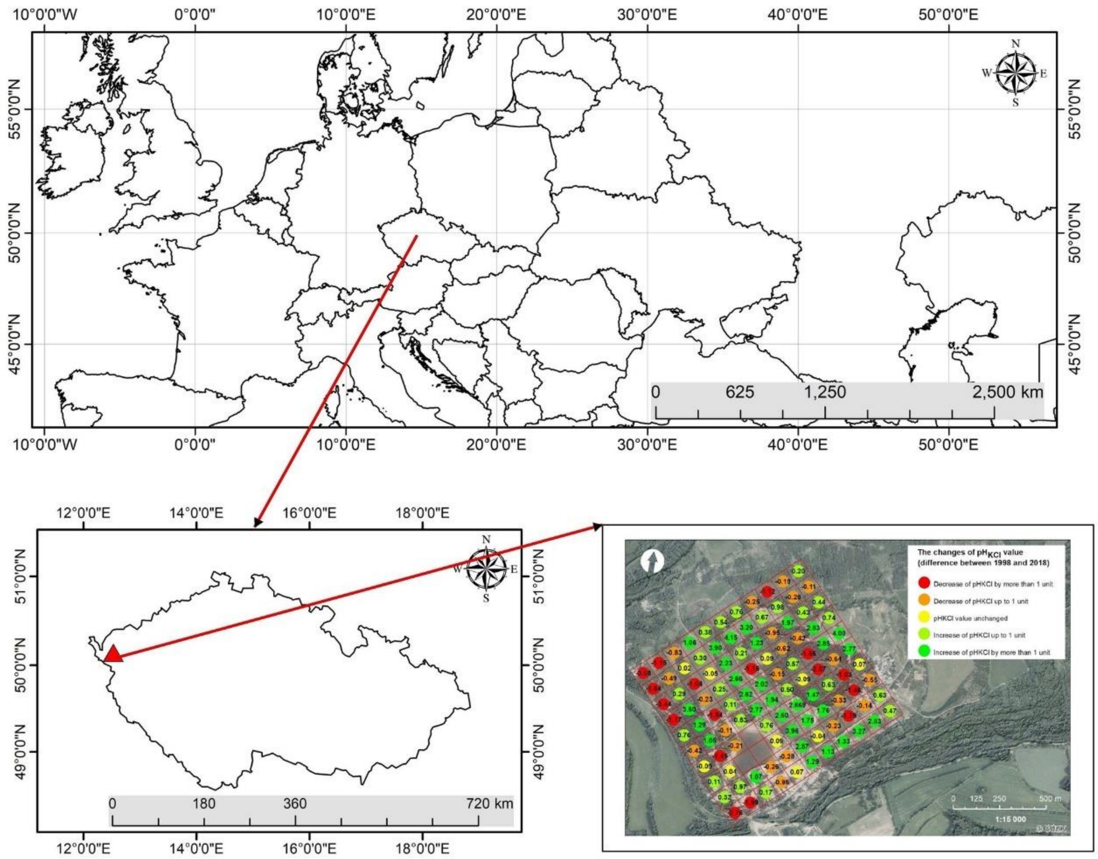

Figure 1. Sampled area. Lítov spoil heap in the northern Sokolov basin, Czech Republic

A map that shows the distribution of different reclamation measures of the study area was done by Bořůvka & Kozák (2001) and presented in Figure 2. Agricultural (topsoil covering) and forestry (afforestation with coniferous and deciduous trees) reclamation measures were completed. A certain part of the area was planted with trees, mainly pine (*Pinus sp.*) and alders (*Alnus sp.*), and a small area was turned into a lake whose banks are marshy depending on the season. Part of the area was mixed with natural topsoil, and a small part was covered with topsoil without mixing (Bořůvka & Kozák, 2001). The elevation of the terrain was initially 450 – 540 m, and after reclamation, it has increased to 570 m. The rest of the surface was left unchanged to spontaneous succession. The whole study area was characterized by extreme acidity because of the pyrite-containing geological substrate and water in the heap, which make the creation of sulphuric acid possible.

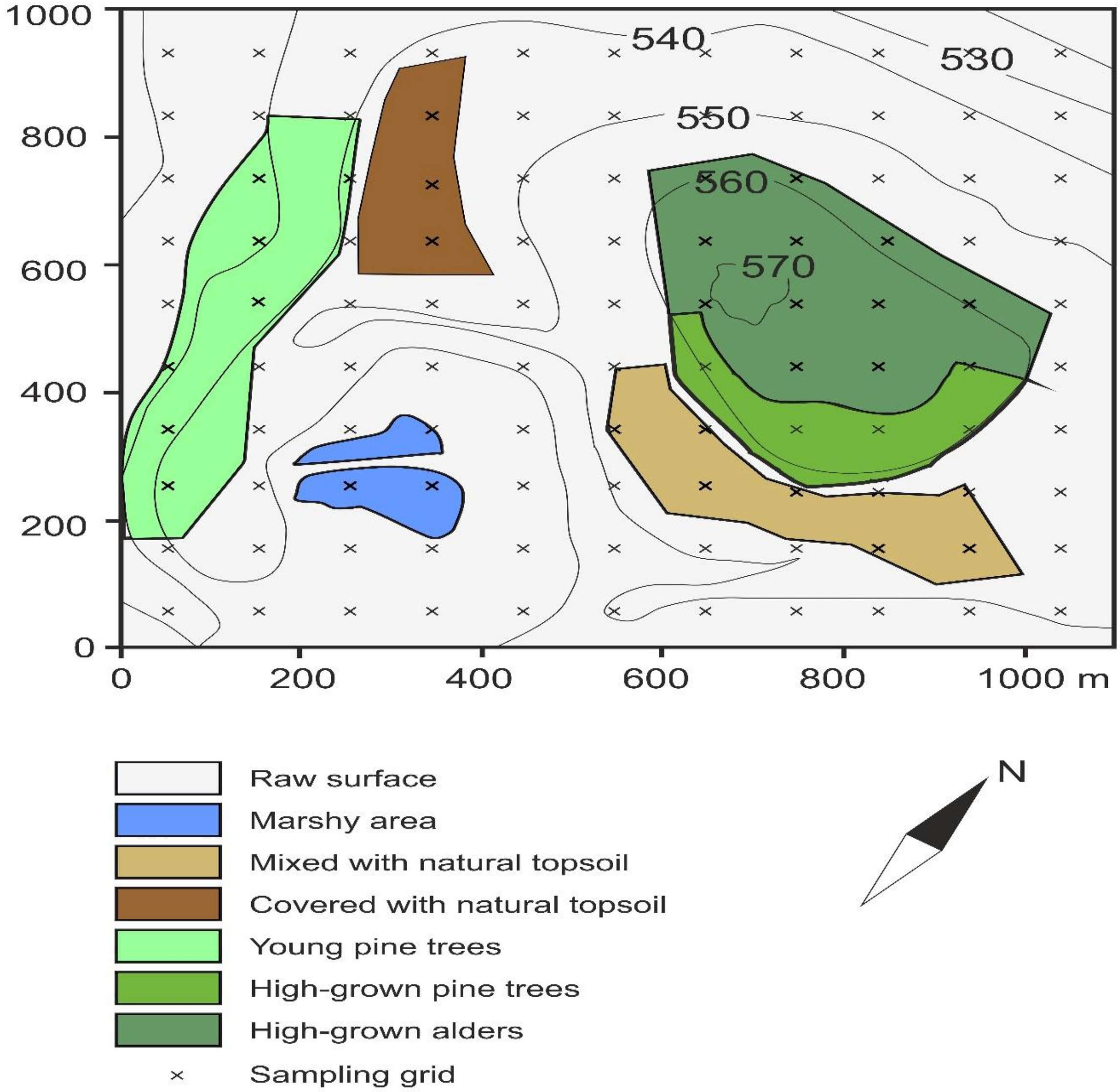

Figure 2. Distribution of vegetation cover and reclamation measures placed on the topographic map of the study area from Borůvka & Kozák (2001)

Analytical methods

All laboratory methods measuring selected soil properties, which are the exchangeable soil pH (pH_{KCl}), the quality of humus (A_{400}/A_{600}), the exchangeable acidity (E_a), organic carbon content (C_{ox}), and the content of aluminum in soil (mainly organically bound and so-called labile), were inspired by Borůvka & Kozák (2001) and repeated in our study in the same manner after 20 years. Data for this study were collected using the same methodology to compare with results from the study by Borůvka & Kozák (2001) and to assess the effect of time. All samples were air-dried and homogenized. After that, samples were sieved through a 2 mm sieve. pH_{KCl} and E_a were measured in 1 M KCl extract (1:2.5; w:v). The quality of organic matter was described by A_{400}/A_{600} ratio, i.e., the ratio of absorbances of soil in sodium pyrophosphate ($Na_4P_2O_7$) 0.05 M extract (20 mL per 1 g soil) at wavelengths 400 and 600 nm, by using an instrument spectrophotometer Hewlett Packard 8453 (Pospíšil 1981). Total organic carbon content was determined oxidimetrically by wet combustion using potassium dichromate (Pospíšil 1964). Labile exchangeable Al (Al_{lab}) was determined in 1 M KCl extract by the method proposed by James et al. (1983) when Al^{3+} is bound on eight hydroxyquinolines and determined spectrophotometrically using Hewlett Packard 8453 at a wavelength of 395 nm (Borůvka & Kozák 2001). The determination of mainly organically bound Al (Al_{org}) was done according to the methodology described by Drábek et al. (2003). In the solution, the total content of Al was measured by means of ICP-OES (iCap 7000; Thermo Scientific USA).

Data evaluation

All the statistical analyses were performed using Microsoft Office Excel 2019. Descriptive statistics were calculated for all soil characteristics. Data comparing and changes in soil characteristics between 1998 and 2018 were analyzed using a paired-sample t-test and correlation matrix. The output maps showing the differences of the measured values were processed using GIS (ArcMap Version 10. 5. – ESRI Inc.).

RESULTS AND DISCUSSION

Compared to the results from 1998 (Borůvka et al. 1999; Borůvka & Kozák 2001), some properties (pH_{KCl}, C_{ox}, E_a, A_{400}/A_{600} and Al_{org}) showed slight improvement (increase in pH_{KCl}, C_{ox}, Al_{org} content and a slight increase in humus quality). The basic statistical analyses of soil properties can be found in Table 1.

Table 1. Basic statistical analyses of soil characteristics

	pH_{KCl}		E_a (mmol/100g)		C_{ox} (%)		A_{400}/A_{600}		Al_{org} (mg·kg^{-1})		Al_{lab} (mg·kg^{-1})	
	1998	2018	1998	2018	1998	2018	1998	2018	1998	2018	1998	2018
mean	4.1	4.6	3.3	1.0	2.4	3.2	6.0	4.0	1496	3677	70.2	143.9
min.	1.6	2.3	0.1	0.1	0.3	0.5	4.7	2.3	282.0	3.9	0.1	0.1

max.	7.0	7.0	10.7	5.3	3.5	5.9	9.6	12.0	14476	13907	295.5	859.9
median	3.6	4.6	1.6	0.2	2.6	3.1	5.9	3.4	1036	2734	44.2	6.1
mode	2.8	5.1	0.2	0.1	3.1	4.3	-	-	744.0	3.9	-	1.2
Standard deviation	1.6	1.4	3.3	1.4	0.9	1.5	0.6	1.7	1796	2817	78.0	214.3
Coefficient of variation (%)	39.4	30.1	102.5	135.8	36.9	46.7	10.7	42.9	120.1	76.6	115.4	148.9

We applied a paired t-test on basic soil characteristics, and the results are shown in Table 2. In 2018, an increase in values of pH_{KCl}, C_{ox}, and in contents of two different forms of Al (Al_{org} and Al_{lab}) was observed.

Table 2. Paired t-test results of basic soil characteristics

	pH_{KCl}	E_a	C_{ox}	A_{400}/A_{600}	Al_{org}	Al_{lab}
P value	0.002**	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***

*, **, *** indicate a statistically significant difference at the P value < 0.05, 0.01, 0.001, respectively.

With the increase of time after reclamation, salt content, alkalinity, and particle size tend to decrease, while organic matter content tends to increase (Wang et al. 2014). Twenty years of development is a very short period of soil formation. However, the influence of this factor on this area is evident. In general, topsoil covering and afforestation have a predominantly positive effect on changes in reclaimed post-mining sites and gradually improve natural soil conditions. This fact can be found in previous studies, for example, Borůvka et al. (1999), Borůvka & Kozák (2001), and Shrestha & Lal (2011), which were dealing with soil development after reclamation measures in lignite spoil heaps.

In 2018, pH values ranged from very strongly acidic (2.3) to neutral (7.0) (Table 1). The most common pH was 5.1. 18 % of either grassland or afforested areas indicated neutral soil reaction. However, pH values mainly were very low, 45 % of the area was very acidic, and 22 % of the whole area showed acidic soil reaction. The lowest pH value was found at the southern border of the area of interest near the water reservoir.

A comparison of pH_{KCl} values frequency is displayed in bar graphs in Figure 3. A paired t-test was applied for pH_{KCl} values to analyze a significant difference between 1998 and 2018 in time effects. In 2018, pH_{KCl} values were significantly higher than in 1998. The difference was statistically significant ($P = 0.002$, $^{**}P < 0.01$) between these years.

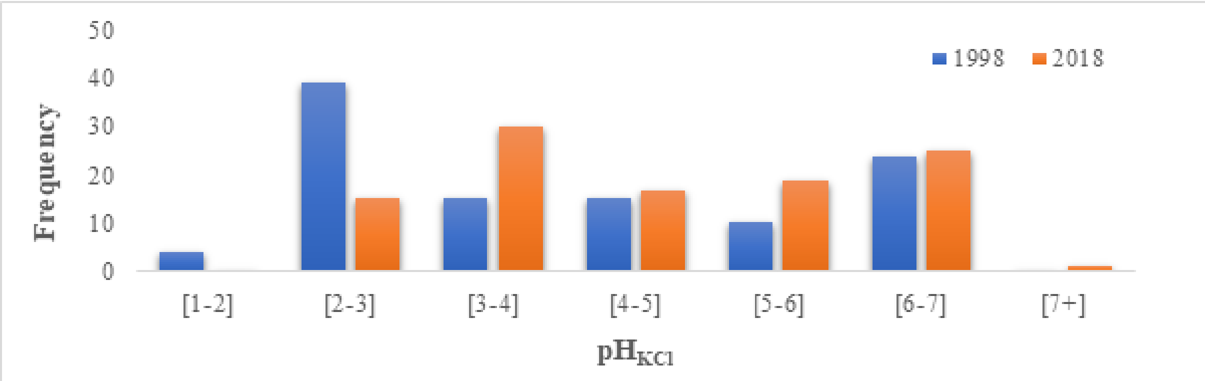

Figure 3. Comparison of pH_{KCl} values frequency between 1998 and 2018

Soil pH increased by 0.1 to 2 units on 36 % of the sampling area (Figure 4). However, almost the same percentage (33 %) of samples showed a decrease of 0.1 to 2 units (Figure 4). The average pH increased from 4.1 to 4.6. The increase in pH depended on vegetation, time, and climatic conditions, over the fact published by Borůvka et al. (1999). Asensio et al. (2013) also stated that tree planting (*Pinus pinaster* Aiton) significantly affects the increase in soil pH. These findings do not correspond to the data published by Čížková et al. (2018). These authors did not find any changes in pH values depending on time on neither reclaimed nor non-reclaimed spoil heaps (located in Sokolov coal basin, Czech Republic). In contrast, Shrestha & Lal (2011) mentioned the beneficial effect of reclamation measures (replacing overburden, covering with topsoil up to 30 cm) on increasing pH values. They stated that at a depth of 0-15 cm, the pH value increased by four units (from 4.9 to 8.1, i.e., by 31 %) on some reclaimed areas compared to the surrounding localities.

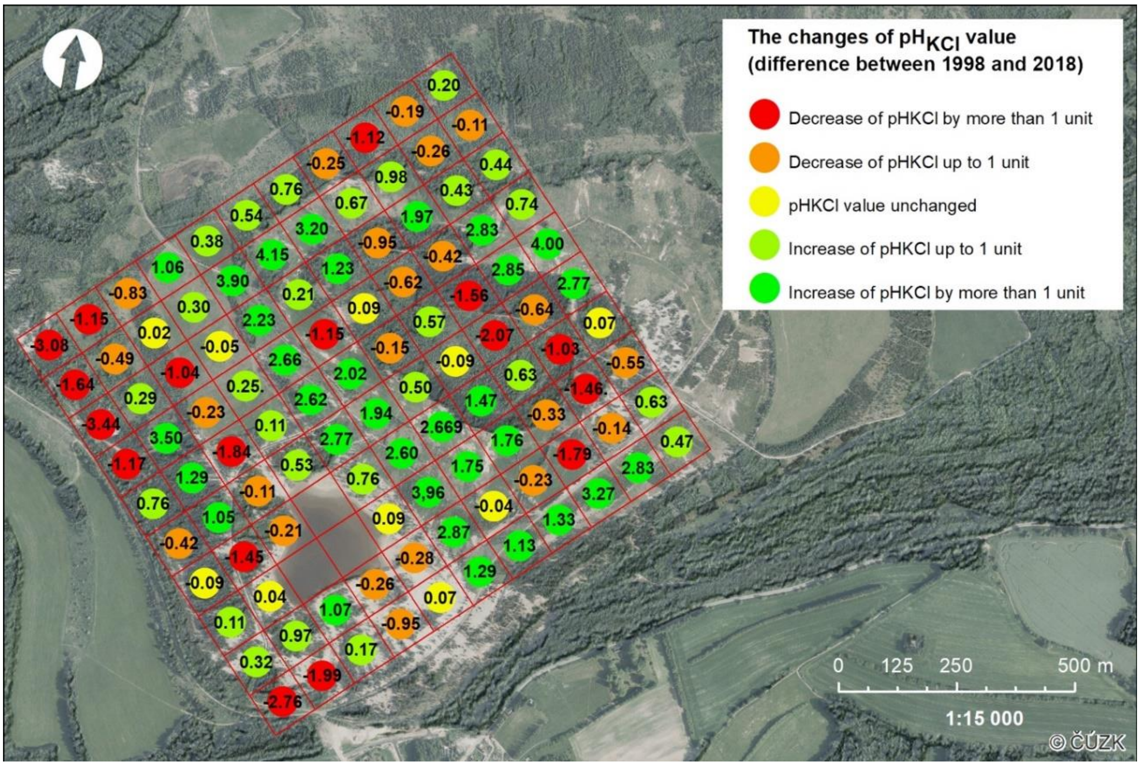

Figure 4. The changes of pH_{KCl} (difference between 1998 and 2018) on Lítov spoil heap

Most C_{ox} contents of soil samples were above 2.7 %. These samples are thus classified as soils with a very high content of oxidizable carbon. Sample number 79 (Figure 1), where there was no vegetation cover, had the lowest value of C_{ox} (0.5 %). The highest value of C_{ox} (5.9 %) was determined in sample number 104 (Figure 1), at the site covered with mature coniferous trees. However, a higher value of C_{ox} also can be an effect of brown coal residues. The values of organic carbon content showed a large variation. The organic carbon content could be described mostly as medium to high with an average C_{ox} content of 3.2 %. The lowest value of A_{400}/A_{600} was 2.3 in locality number 58 (Figure 1), where humus quality was the finest. Compared to the C_{ox} values from twenty years ago, 46 % of the total number of samples showed an increase in the C_{ox} content by more than 1 % (Figure 5), and 26 % of the measured values increased up to 1 % (Figure 5). The average C_{ox} was also increased from 2.7 % to 3.2 % (very high C_{ox} content).

The reduction of C_{ox} content by more than 1 % covered 16 % of the whole area (Figure 5). Shrestha & Lal (2011) also found a decrease in C_{ox} content in reclaimed spoil heaps. Borůvka et al. (1999) stated that the lower range of C_{ox} under alder could be explained by the high degree of mineralization due to increased microbial activity. In contrast, Čížková et al.

(2018) stated that C_{ox} increases with time and the degree of landfill reclamation. Furthermore, C_{ox} content increases significantly faster on reclaimed post-mining sites than non-reclaimed ones (Čížková et al. 2018). Bořůvka et al. (2012) also highlighted the increase in C_{ox} due to topsoil covering. This fact was observed on two spoil heaps from the Czech Republic (Libouš and Pokrok).

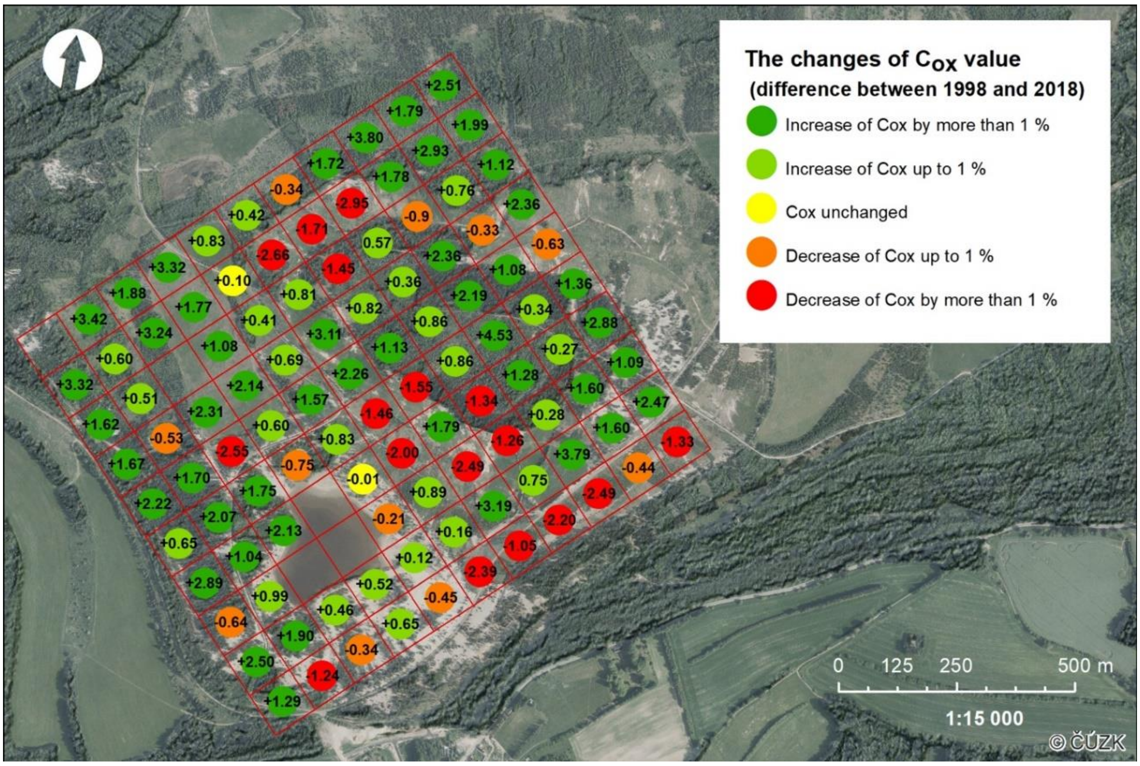

Figure 5: The organic carbon content changes (difference between 1998 and 2018) on Lítov spoil heap

According to the A_{400}/A_{600} coefficient, the humus quality was improved. 55 % of the whole area showed an improvement in humus quality by up to 3 A_{400}/A_{600} units (Figure 6), and 32 % of the samples showed an increase by more than 3 A_{400}/A_{600} units. The influence of vegetation on the C_{ox} content and humus quality was evident. Swab et al. (2017) found that the mix, which includes native plants, positively affected the stabilization of humus and potentially improved soil conditions. Bořůvka & Kozák (2001) also found that the humus quality was mainly influenced by afforestation (in the given study – afforestation of alders). According to Asensio et al. (2014), tree vegetation, especially eucalyptuses and pines, could significantly increase the mine soils' organic carbon content. The gradual formation of more complex soil organic matter led to a decrease of A_{400}/A_{600} values. According to a study by Frouz et al. (2001), deciduous trees create better conditions for edaphon than conifers. Borůvka et al. (2012) observed that the natural soil cover also affected an increase in C_{ox} and A_{400}/A_{600}.

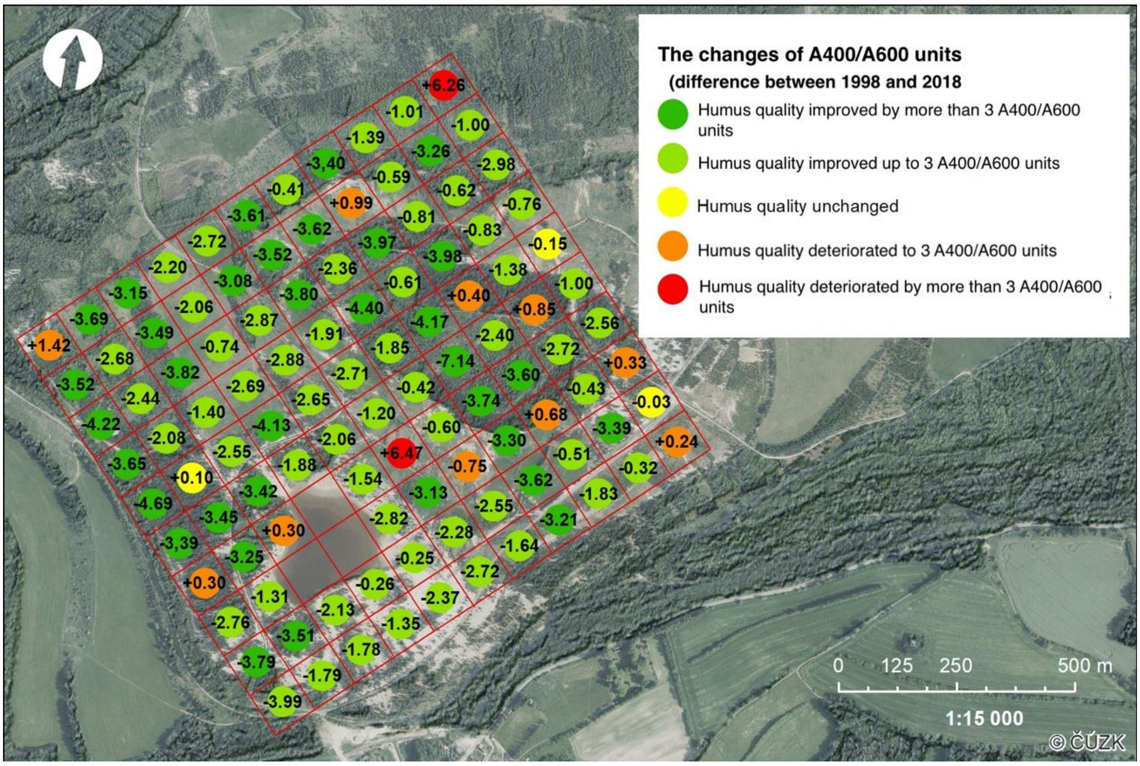

Figure 6: Humus quality coefficient changes (difference between 1998 and 2018) on Lítov spoil heap

Most of the area (68 %) had exchangeable acidity in a range from 0 to 1 mmol/100g; meanwhile, the rest of the area (32 %) represents very strong E_a (more than 1 mmol/100g). Locality with the highest E_a value (sample No. 25) was located next to the water reservoir (Figure 1), probably affected by naturally created sulfuric acid. The average E_a value decreased from 3.3 mmol/100g to 1 mmol/100g since 1998. 29 % of the whole area showed a high exchangeable acidity.

Most of the measured E_a values (46 %) showed a decrease by more than 1 mmol/100g (Figure 7), and 18 % indicated a reduction of E_a by less than 1 mmol/100g (Figure 7). One of the most serious problems on spoil heaps is water, which accelerates rock weathering, and as a result, the rocks disintegrate and release pyrite. This process was thoroughly described by Rimstidt and Vaughan (2003). Jelenová et al. (2018) also found high pyrite content in heaps near Kaňk (Czech Republic). Pyritic minerals tend to oxidize and form sulfuric acid (Sheoran et al. 2010). The formation of sulfuric acid in the soil environment causes an increase in exchangeable acidity, a decrease in pH value, and soil fertility. At the edge of dumpsites, water outflow, which probably contains a higher amount of sulfuric acid, was observed. Observed mortality of vegetation, including mature pines, was caused by this outflow.

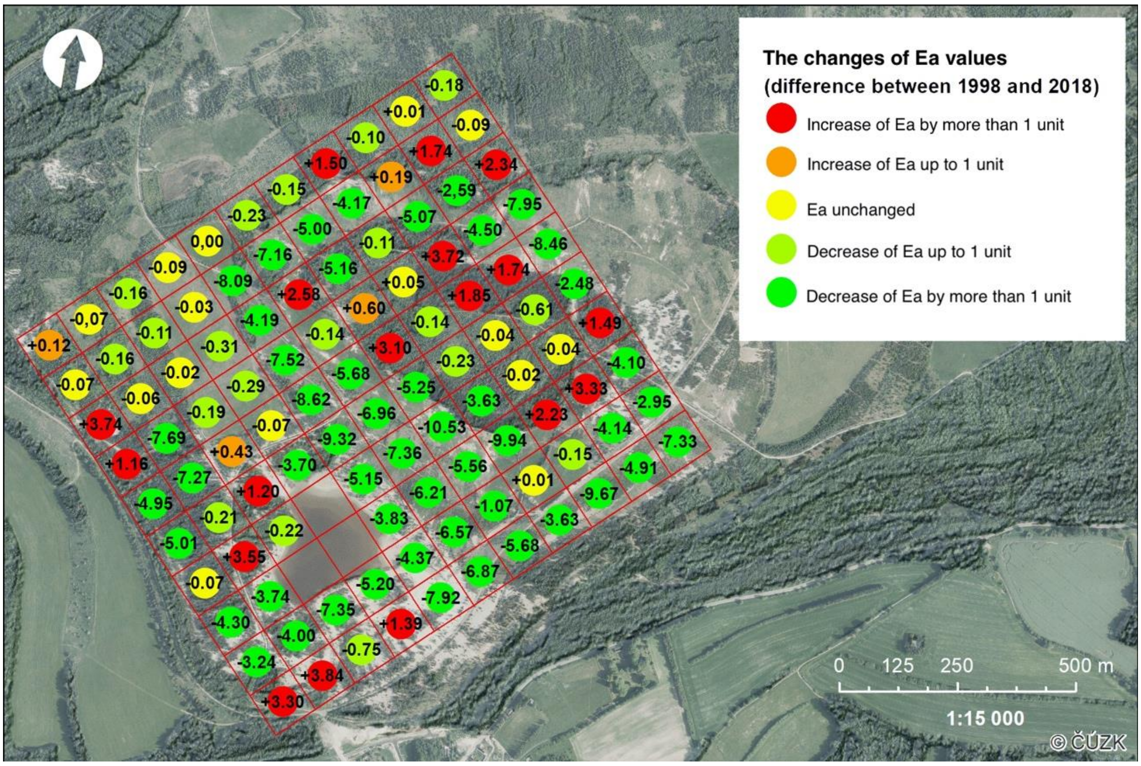

Figure 7: Exchangeable acidity value changes (difference between 1998 and 2018) on Lítov spoil heap

Different forms of Al have different characteristics of mobility, bioavailability, and toxicity in soil. Al is phytotoxic to most plants at soil pH below 5.5 (Schmitt et al. 2016), and a stronger relationship with soil pH was found in the organic horizon (Pavlů et al. 2019). In contrast, Al_{org} is reported as non-toxic and positively affects the monitored ecosystem (Drábek et al. 2003). Exchangeable and organically bound Al concentrations were higher in the anthropogenically acidified area (Pavlů et al. 2019). Also, Hagvall et al. (2015) and Dang et al. (2016) stated that the content of free Al in soil decreases in the presence of organic materials with a suitable soil reaction (neutral pH).

Both determined forms of Al showed a wide range, and their average values were doubled (Al_{org} 3677 mg·kg^{-1}, Al_{lab} 143.9 mg·kg^{-1}) since 1998 (Table 1). The correlation analyses of determining soil characteristics are shown in Table 3 and Table 4. According to the data from 2018, a closer inverse dependence was presented between the Al_{lab} content and pH_{KCl}

(r= -0.76) (Table 4) compared to data from 1998 (Table 3). In contrast, in 2018, correlation analysis of Al_{lab} showed weaker direct dependence with exchangeable acidity (r= 0.56) (Table 4) than in 1998 (Table 3). The weak relationships of Al_{org} to other soil characteristics (Al_{org} with pH_{KCl} r= -0.41, with E_a r= 0.22, and with C_{ox} r= 0.00) were indicated (Table 4) in 2018.

Table 3. Correlation matrix of soil characteristics in 1998

	pH_{KCl}_1998	**E_a_1998**	**C_{ox}_1998**	**A_{400}/A_{600}_1998**	**Al_{org}_1998**
E_a_1998	-0.87				
C_{ox}_1998	-0.40	0.54			
A_{400}/A_{600}_1998	-0.01	-0.07	-0.39		
Al_{org}_1998	-0.01	-0.11	-0.37	0.13	
Al_{lab}_1998	-0,65	0.70	0.41	-0.10	-0.12

Table 4. Correlation matrix of soil characteristics in 2018

	pH_{KCl}_2018	**E_a_2018**	**C_{ox}_2018**	**A_{400}/A_{600}_2018**	**Al_{org}_2018**
E_a_2018	-0.43				
C_{ox}_2018	0.06	0.09			
A_{400}/A_{600}_2018	-0.06	-0.07	-0.04		
Al_{org}_2018	-0.41	0.22	0.00	0.03	
Al_{lab}_2018	-0.76	0.56	0.11	0.03	0.40

0.0- ±0.2 Little correlation

±0.2 - ±0.4 Weak correlation

±0.4 - ±0.7 Correlated

±0.7 - ±0.9 Strong correlation

±0.9 - ±1.0 Very strong correlation

Al_{org} from 2104 to 4204 mg·kg-1 covered 36 % and 3.9 mg·kg-1 to 2104 mg·kg-1 in another 34 % of the whole area. Localities located in partially forested areas (samples No. 65, 84) had minimum values of Al_{org} (Figure 1). These localities also indicated strongly to very strongly acidic soil reactions. 49 % of measured Al_{org} values showed an increase up to 3000 mg·kg^{-1} (Figure 8), and 32 % of all samples showed an increase of more than 3000 mg·kg^{-1} (Figure 8). In general, the average value of Al_{org} was doubled after 20 years of soil development (Table 1).

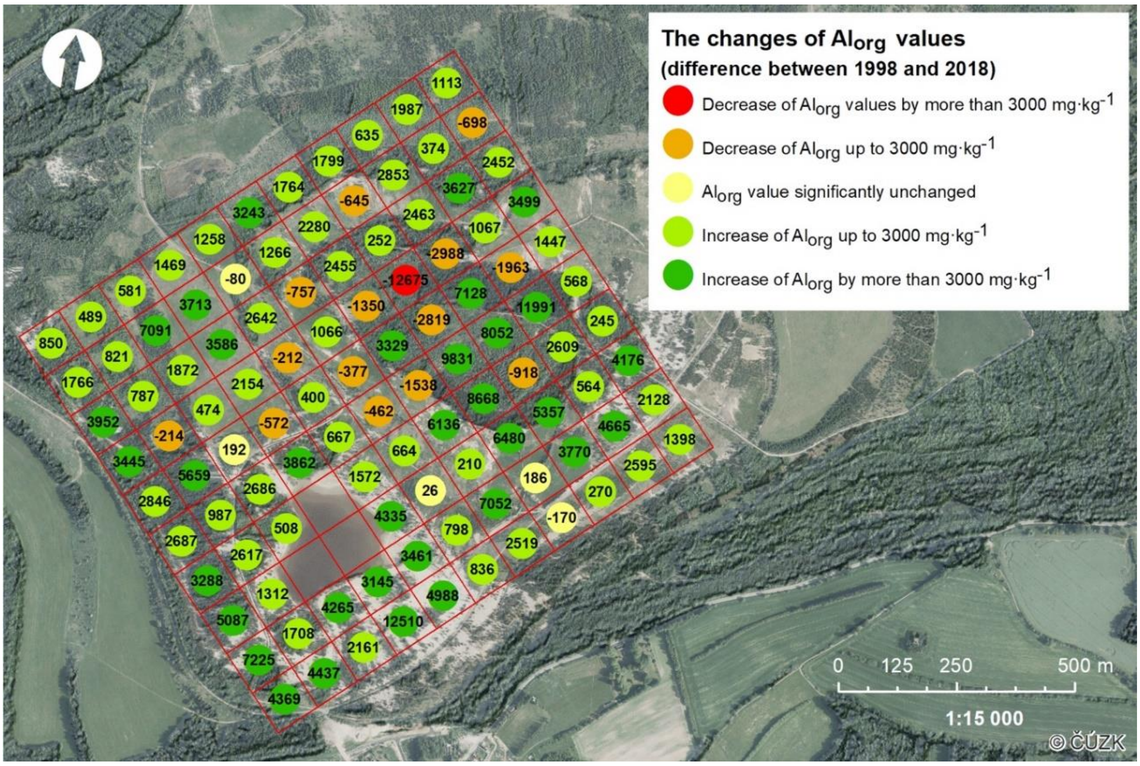

Figure 8: Al_{org} value changes (difference between 1998 and 2018) on Lítov spoil heap

68 % of the territory showed Al_{lab} values ranging from 0.1 to 155.3 mg.kg^{-1}. The lowest contents of Al_{lab} were determined in areas with a slightly acidic to neutral soil reaction. Bowman et al. (2008) stated that soil acidification accelerates the mobilization of potentially toxic elements (e.g., Al or Mn).

Al_{lab} values' increase was observed in 2018. The results indicated significant differences at levels P = 0.0005 (***P <0.001) between these years.

31 % of Al_{lab} measured values were reduced by 100 mg·kg^{-1} (Figure 9), and 27 % of the samples showed an increase greater than 100 mg·kg^{-1} (Figure 9). The average content of Al_{lab} was also doubled (143.9 mg·kg^{-1}) since 1998. The amount of Al_{lab} decreased with increasing pH values. This disturbing increase of Al_{lab} may be due to a strongly acidic soil reaction of the parent material, low C_{ox} content, and coniferous vegetation in certain parts of the study area. Álvarez et al. (2005) stated that aluminum toxicity varies considerably among different species and found the most significant risk of Al toxicity in soils under pine and the lowest under oak. Coniferous stands lead to soil acidification and thus to an increase in Al_{lab} content (Álvarez et al. 2005). Drábek et al. (2003) also found the highest amount of Al_{lab} in soils with the lowest pH_{KCl} and organic matter under forest cover.

According to Kotowski et al. (1994) and Merino et al. (1998), aluminum mobilization depends on acid concentrations and salts and differs between soil horizons. Merino et al. (1998) also found the highest mobilization of Al in the leachates from upper horizons.

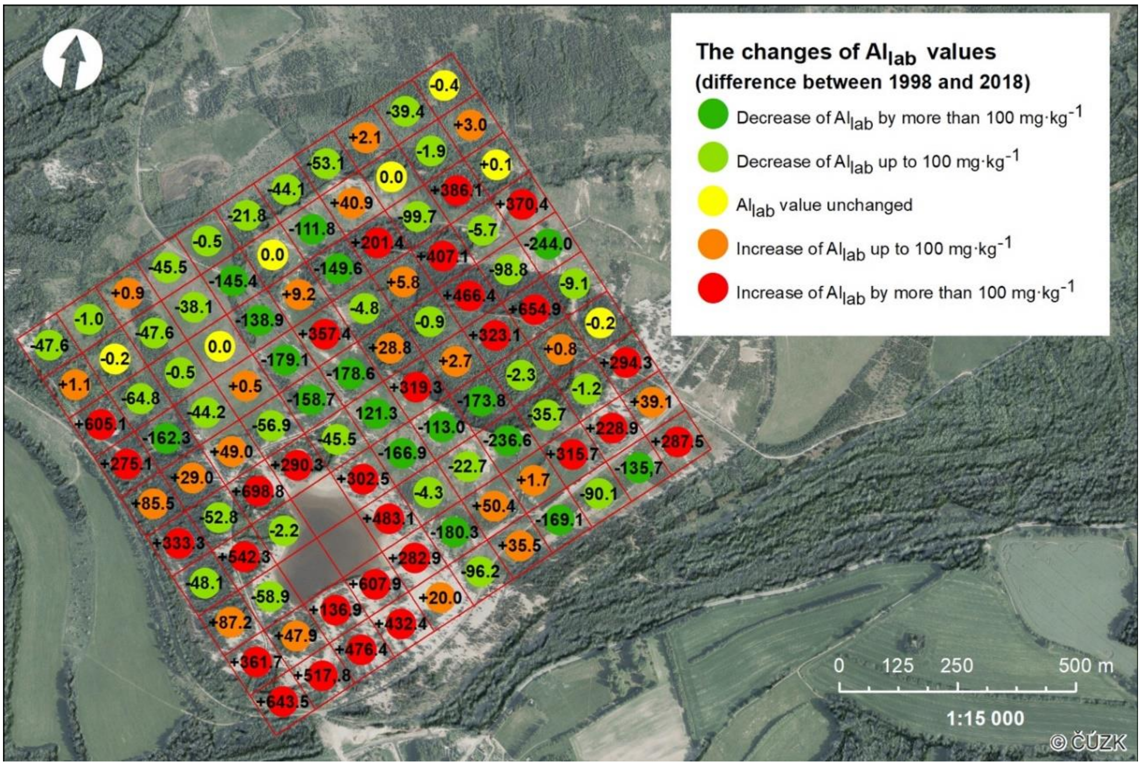

Figure 9: Al_{lab} values changes (difference between 1998 and 2018) on Lítov spoil heap

CONCLUSION

Humus of greater quality and higher content of organically bound (non-toxic) aluminum were found in areas that were covered by topsoil and afforested (mainly with deciduous trees). On the contrary, high labile (toxic) aluminum content was found under coniferous trees. We observed that in 2018, 45 % of the whole area showed a very acidic soil reaction. On these acidic parts of soils, it is possible to carry out liming or afforestation with deciduous trees and promote vegetation cover diversity. The organic carbon content also increased over time. Reclamation measures (e.g., topsoil covering) had affected this rate of increase. The most problematic part of the spoil heap is the marshland, which is located around the water reservoir. This part contains high amounts of pyrite, which produces sulfuric acid. Anthropogenically affected soils are affected by vegetation cover, and soil properties undergo dynamic evolution.

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7.2. Other publications

The works listed in this sub-chapter are publications in scientific journals with impact factor, but not included in the thesis, listed by publication year:

7.2.1. Influence of lime stabilization on shear strength parameters of silty clay soil

Spasić, M., Živanović, N., & Gajić, G. (2018). Influence of lime stabilization on shear strength parameters of silty clay soil. *Glasnik Šumarskog Fakulteta*, 117, 143–156. https://doi.org/10.2298/gsf1817143s

7.2.2. Understanding stable Tl isotopes in industrial processes and the environment: A review

Vejvodová, K., Vaněk, A., Drábek, O., & Spasić, M. (2022). Understanding stable Tl isotopes in industrial processes and the environment: A review. *Journal of Environmental Management*, 315. https://doi.org/10.1016/j.jenvman.2022.115151

7.2.3. Effect of peat organic matter on sulfide weathering and thallium reactivity: Implications for organic environments

Vejvodová, K., Vaněk, A., Spasić, M., Mihaljevič, M., Ettler, V., Vaňková, M., Drahota, P., Teper, L., Vokurková, P., Pavlů, L., Zádorová, T., & Drábek, O. (2022). Effect of peat organic matter on sulfide weathering and thallium reactivity: Implications for organic environments. *Chemosphere*, 299. https://doi.org/10.1016/j.chemosphere.2022.134380

7.2.4. Construction and calibration of a portable rain simulator designed for the in situ research of soil resistance to erosion

Živanović, N., Rončević, V., Spasić, M., Ćorluka, S., & Polovina, S. (2022). Construction and calibration of a portable rain simulator designed for the in situ research of soil resistance to erosion. *Soil and Water Research*, 17(3), 158–169. https://doi.org/10.17221/148/2021-SWR

7.2.5. Assessment of potential exposure to As, Cd, Pb and Zn in vegetable garden soils and vegetables in a mining region

Vejvodová, K., Ash, C., Dajčl, J., Tejnecký, V., Johanis, H., Spasić, M., Polák, F., Praus, L., Borůvka, L., & Drábek, O. (2022). Assessment of potential exposure to As, Cd, Pb and Zn in vegetable garden soils and vegetables in a mining region. *Scientific Reports*, 12(1). https://doi.org/10.1038/s41598-022-17461-z

7.2.6. Determination of physical properties of undisturbed soil samples according to V. Novák

Spasić, M., Vacek, O., Vejvodová, K., Tejnecký, V., Polák, F., Borůvka, L., & Drábek, O. (2023). Determination of physical properties of undisturbed soil samples according to V. Novák. *MethodsX*, 10, 102133. https://doi.org/10.1016/J.MEX.2023.102133