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*

Citation: Spasić M., Borůvka L., Vacek O., Drábek O., Tejnecký V. (2021): Pedogenesis problems on reclaimed coal mining sites. Soil and Water Res., 16: 137–150.

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

Supported by the Project "Centre for the investigation of synthesis and transformation of nutritional substances in the food chain in interaction with potentially harmful substances of anthropogenic origin: comprehensive assessment of soil contamination risks for the quality of agricultural products" of the European Structural and Investment Funds Operational Programme Research, Development and Education of the European Union and the Ministry of Education, Youth and Sports of the Czech Republic, No. CZ.02.1.01/0.0/0.0/16_019/0000845.

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.

https://doi.org/10.17221/163/2020-SWR

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

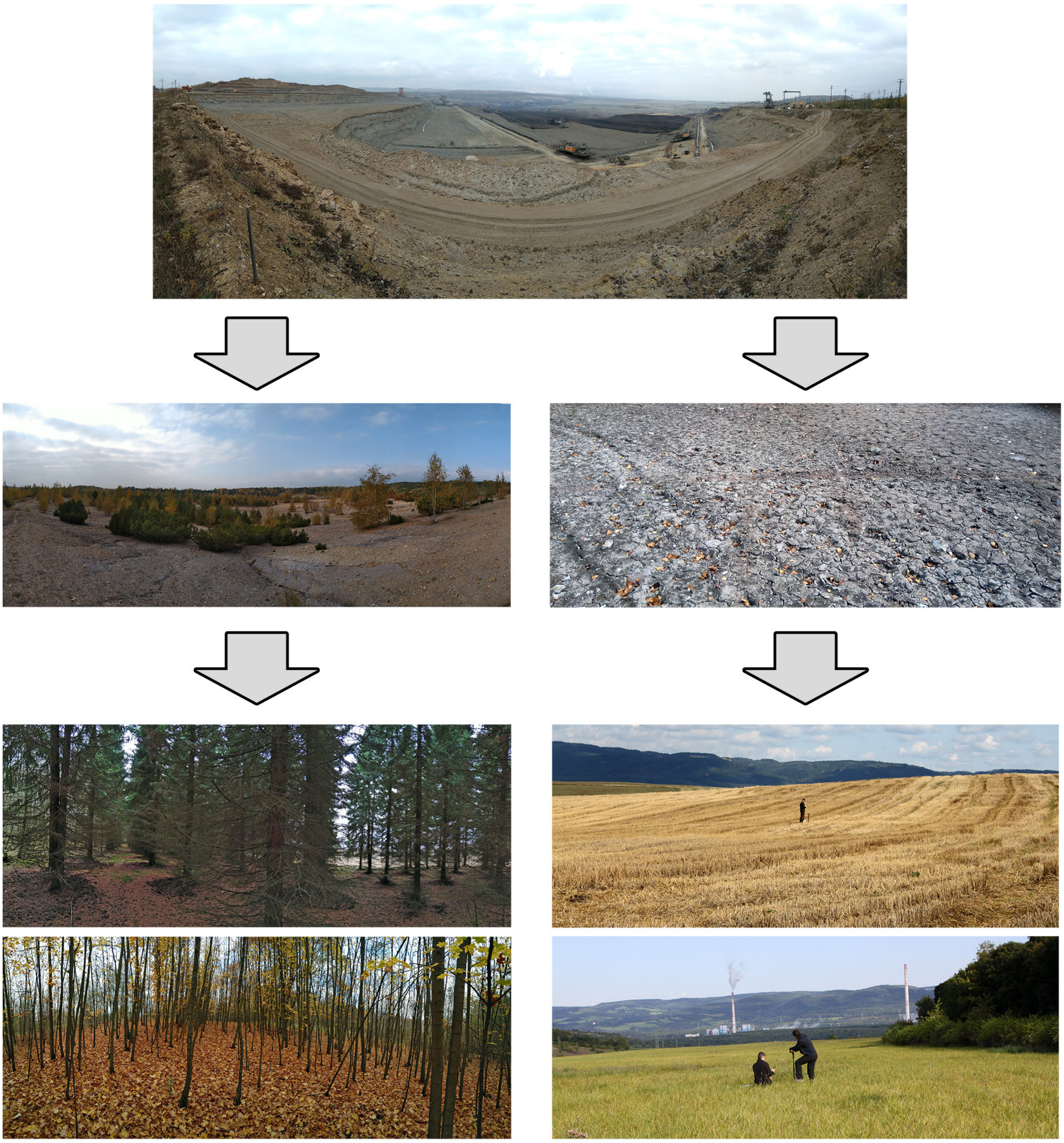

Figure 1. Evolution of forest (left) and agriculturally (right) reclaimed landscapes in the Czech Republic (source: authors, courtesy of J. Kozák)

https://doi.org/10.17221/163/2020-SWR

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

https://doi.org/10.17221/163/2020-SWR

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

https://doi.org/10.17221/163/2020-SWR

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)

https://doi.org/10.17221/163/2020-SWR

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

https://doi.org/10.17221/163/2020-SWR

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.

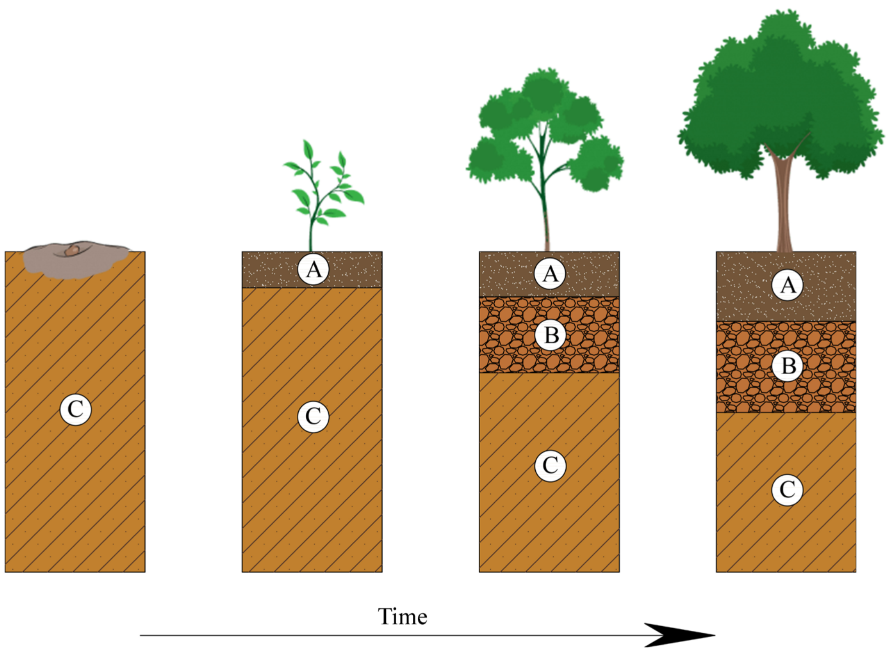

Figure 2. Presumed evolution of an afforested mine Technosol on clayey parent materials of central European region

https://doi.org/10.17221/163/2020-SWR

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.

Acknowledgements: The authors would like to thank prof. Ing. J. Kozák, DrSc., dr.h.c. for providing the photographs and his overall contribution to the paper.

REFERENCES

Ahirwal J., Kumar A., Pietrzykowski M., Maiti S.K. (2018): Reclamation of coal mine spoil and its effect on Technosol quality and carbon sequestration: a case study from India. Environmental Science and Pollution Research, 25: 27992–28003.

Alday J.G., Marrs R.H., Martínez Ruiz C. (2011): Vegetation succession on reclaimed coal wastes in Spain: The influence of soil and environmental factors. Applied Vegetation Science, 14: 84–94.

Anderson J.D., Ingram L.J., Stahl P.D. (2008): Influence of reclamation management practices on microbial biomass carbon and soil organic carbon accumulation in semiarid mined lands of Wyoming. Applied Soil Ecology, 40: 387–397.

Baldrian P., Trögl J., Frouz J., Šnajdr J., Valášková V., Merhautová V., Cajthaml T., Herinková J. (2008): Enzyme activities and microbial biomass in topsoil layer during spontaneous succession in spoil heaps after brown coal mining. Soil Biology and Biochemistry, 40: 2107–2115.

Bandyopadhyay S., Rana V., Maiti S.K. (2018): Chronological variation of metals in reclaimed coal mine soil and tissues of *Eucalyptus* hybrid tree after 25 years of reclamation, Jharia coal field (India). Bulletin of Environmental Contamination and Toxicology, 101: 604–610.

Banning N.C., Grant C.D., Jones D.L., Murphy D.V. (2008): Recovery of soil organic matter, organic matter turnover and nitrogen cycling in a post-mining forest rehabilitation chronosequence. Soil Biology and Biochemistry, 40: 2021–2031.

Barry Phelps L., Holland L. (1987): Soil compaction in topsoil replacement during mining reclamation. Environmental Geochemistry and Health, 9: 8–11.

Bell L.C. (2001): Establishment of native ecosystems after mining – Australian experience across diverse biogeographic zones. Ecological Engineering, 17: 179–186.

Bendfeldt E.S., Burger J.A., Daniels W.L. (2001): Quality of amended mine soils after sixteen years. Soil Science Society of America Journal, 65: 1736–1744.

Bodlák L., Křováková K., Kobesová M., Brom J., Šťastný J., Pecharová E. (2012): SOC content – An appropriate tool for evaluating the soil quality in a reclaimed post-mining landscape. Ecological Engineering, 43: 53–59.

Boels D., Havinga L. (1982): Physical soil degradation in the Netherlands. In: Proc. Land Use Seminar on Soil Degradation, Wageningen, Oct 13–15, 1980: 1–29.

Borůvka L., Kozák J. (2001a): Interpretation of soil variability on a reclaimed dumpsite. In: Soil Science: Past, Present and Future: Proc. of the Joint Meeting of the Czech Society of Soil Science and the Soil Science Society of America and International Conference of the Czech Society of Soil Science, Prague, Czech Republic, Sept 16–20, 2001: 17–19.

Borůvka L., Kozák J. (2001b): Geostatistical investigation of a reclaimed dumpsite soil with emphasis on aluminum. Soil and Tillage Research, 59: 115–126.

Borůvka L., Kozák J., Drábek O. (1999): Influence of some soil properties on the content of selected Al forms in the soil of the dumpsite Lítov. Rostlinná Výroba, 45: 9–15.

Bradshaw A. (1997): Restoration of mined lands – Using natural processes. Ecological Engineering, 8: 255–269.

Bradshaw A.D., Hüttl R.F. (2001): Future minesite restoration involves a broader approach. Ecological Engineering, 17: 87–90.

Bragina P.S., Tsibart A.S., Zavadskaya M.P. (2014): Soils on overburden dumps in the forest-steppe and mountain taiga zones of the Kuzbass. Eurasian Soil Science, 47: 723–733.

Brenner F.J. (1979): Soil and plant characteristics as determining factors in site selection for surface coal mine reclamation. Minerals and the Environment, 1: 39–44.

Brenner F.J., Werner M., Pike J. (1984): Ecosystem development and natural succession in surface coal mine reclamation. Minerals and the Environment, 6: 10–22.

Brom J., Nedbal V., Procházka J., Pecharová E. (2012): Changes in vegetation cover, moisture properties and surface temperature of a brown coal dump from 1984 to 2009 using satellite data analysis. Ecological Engineering, 43: 45–52.

Chaulya S.K., Singh R.S., Chakraborty M.K., Tewary B.K. (2000): Bioreclamation of coal mine overburden dumps in India. Land Contamination and Reclamation, 8: 189–199.

Chodak M., Niklińska M. (2010): The effect of different tree species on the chemical and microbial properties of reclaimed mine soils. Biology and Fertility of Soils, 46: 555–566.

Chuman T. (2015): Restoration practices used on post mining sites and industrial deposits in the Czech Republic with an example of natural restoration of granodiorite quarries and spoil heaps. Journal of Landscape Ecology, 8: 29–46.

Claassens S., Jansen Van Rensburg P.J., Maboeta M.S., Van Rensburg L. (2008): Soil microbial community function and structure in a post-mining chronosequence. Water, Air, and Soil Pollution, 194: 315–329.

Coppin N.J., Bradshaw A.D. (1982): Quarry Reclamation: The Establishment of Vegetation in Quarries and Open Pit Non-metal Mines. London, Mining Journal Books.

Dick D.P., Knicker H., Ávila L.G., Inda A.V., Giasson E., Bissani C.A. (2006): Organic matter in constructed soils from a coal mining area in southern Brazil. Organic Geochemistry, 37: 1537–1545.

Doll E.C., Wollenhaupt N.C., Halvorson G.A., Schroeder S.A. (1984): Planning and evaluating cropland reclamation after stripmining in North Dakota. Minerals and the Environment, 6: 121–126.

Domínguez-Haydar Y., Castañeda C., Rodríguez-Ochoa R., Jiménez J.J. (2018): Assessment of soil fauna footprints at a rehabilitated coal mine using micromorphology and near infrared spectroscopy (NIRS). Geoderma, 313: 135–145.

Dutta R.K., Agrawal M. (2003): Restoration of opencast coal mine spoil by planting exotic tree species: A case study in dry tropical region. Ecological Engineering, 21: 143–151.

Echevarria G., Morel J.L. (2015): Technosols of mining areas. Tópicos Ci. Solo, 9: 1–20.

FAO (2015): Soil is a Non-renewable Resource. Rome, FAO. Available at http://www.fao.org/3/a-i4373e.pdf (accessed Feb 15, 2021)

Fettweis U., Bens O., Hüttl R.F. (2005): Accumulation and properties of soil organic carbon at reclaimed sites in the Lusatian lignite mining district afforested with *Pinus* sp. Geoderma, 129: 81–91.

Filcheva E., Noustorova M., Gentcheva-Kostadinova S., Haigh M.J. (2000): Organic accumulation and microbial action in surface coal-mine spoils, Pernik, Bulgaria. Ecological Engineering, 15: 1–15.

Filip Z. (2002): International approach to assessing soil quality by ecologically-related biological parameters. Agriculture, Ecosystems & Environment, 88: 169–174.

Free G.R., Lamb J., Carleton E.A. (1947): Compactibility of certain soils as related to organic matter and erosion. Agronomy Journal, 39: 1068–1076.

Frouz J. (1999): Restoration of soil micoroganisms population in soils of forestry reclamated brown coal dumpsites and their significance for soil formation. Ochrana Přírody, 5: 157–159. (in Czech)

Frouz J., Nováková A. (2005): Development of soil microbial properties in topsoil layer during spontaneous succession in heaps after brown coal mining in relation to humus microstructure development. Geoderma, 129: 54–64.

Frouz J., Keplin B., Pižl V., Tajovský K., Starý J., Lukešová A., Nováková A., Balík V., Háněl L., Materna J., Düker C., Chalupský J., Rusek J., Heinkele T. (2001): Soil biota and upper soil layer development in two contrasting post-mining chronosequences. Ecological Engineering, 17: 275–284.

Frouz J., Elhottová D., Pižl V., Tajovský K., Šourková M., Picek T., Malý S. (2007a): The effect of litter quality and soil faunal composition on organic matter dynamics in

https://doi.org/10.17221/163/2020-SWR

post-mining soil: A laboratory study. Applied Soil Ecology, 37: 72–80.

Frouz J., Pižl V., Tajovský K. (2007b): The effect of earthworms and other saprophagous macrofauna on soil microstructure in reclaimed and un-reclaimed post-mining sites in Central Europe. European Journal of Soil Biology, 43 (Supplement 1): S184–S189.

Frouz J., Livečková M., Albrechtová J., Chroňáková A., Cajthaml T., Pižl V., Háněl L., Starý J., Baldrian P., Lhotáková Z., Šimáčková H., Cepáková Š. (2013): Is the effect of trees on soil properties mediated by soil fauna? A case study from post-mining sites. Forest Ecology and Management, 309: 87–89.

Gast M., Schaaf W., Scherzer J., Wilden R., Schneider B.U., Hüttl R.F. (2001): Element budgets of pine stands on lignite and pyrite containing mine soils. Journal of Geochemical Exploration, 73: 63–74.

Gerke H.H., Hangen E., Schaaf W., Hüttl R.F. (2001): Spatial variability of potential water repellency in a lignitic mine soil afforested with *Pinus nigra*. Geoderma, 102: 255–274.

Ghose M. (2001): Management of topsoil for geo-environmental reclamation of coal mining areas. Environmental Geology, 40: 1405–1410.

Ghose M.K., Majee S.R. (2007): Characteristics of hazardous airborne dust around an Indian surface coal mining area. Environmental Monitoring and Assessment, 130: 17–25.

Ghosh A.B., Bajaj J.C., Hassan R., Singh D. (1983): Soil and Water Testing Methods – A Laboratory Manual. New Delhi, IARI: 31–36.

Giri D.D., Shukla P.N., Ritu S., Kumar A., Pandey K.D. (2013): Substrate utilization of stress tolerant methylotrophs isolated from revegetated heavy metal polluted coalmine spoil. World Journal of Microbiology and Biotechnology, 29: 635–643.

Haigh M.J., Gentcheva-Kostadinova S.V. (2002): Ecological erosion control on coal-spoil banks: An evaluation. Ecological Engineering, 18: 371–377.

Hamidović S., Cvijović G.G., Waisi H., Životić Lj., Janković Šoja S., Raičević V., Lalević B. (2020): Response of microbial community composition in soils affected by coal mine exploitation. Environmental Monitoring and Assessment, 192: 364.

Hartmann R., Schneider B.U., Gast C., Keplin B., Hüttl R.F. (1999): Effects of N-enriched rock powder on soil chemistry, organic matter formation and plant nutrition in lignite-poor sandy mine spoil in the forest reclamation practice. Plant and Soil, 213: 99–115.

Heděnec P., Vindušková O., Kukla J., Šnajdr J., Baldrian P., Frouz J. (2017): Enzyme activity of topsoil layer on reclaimed and unreclaimed post-mining sites. Biological Communications, 62: 19–25.

Helingerová M., Frouz J., Šantrůčková H. (2010): Microbial activity in reclaimed and unreclaimed post-mining sites near Sokolov (Czech Republic). Ecological Engineering, 36: 768–776.

Hendrychová M. (2008): Reclamation success in post-mining landscapes in th e Czech Republic: A review of pedological and biological studies. Journal of Landscape Studies, 1: 63–78.

Hodačová D., Prach K. (2003): Spoil heaps from brown coal mining: technical reclamation versus spontaneous revegetation. Restoration Ecology, 11: 385–391.

Hoth N., Feldmann H., Rinker A., Glombitza F., Häfner F. (2005): Reductive processes within lignite dumps – Chance of a long-term natural attenuation process. Geoderma, 129: 19–31.

Huggett R.J. (1998): Soil chronosequences, soil development, and soil evolution: a critical review. Catena, 32: 155–172.

Huot H., Simonnot M., Marion P., Yvon J., Donato P. De (2013): Characteristics and potential pedogenetic processes of a Technosol developing on iron industry deposits*.* Journal of Soils and Sediments, 13: 555–568.

Hüttl R.F., Weber E. (2001): Forest ecosystem development in post-mining landscapes: A case study of the Lusatian lignite district. Naturwissenschaften, 88: 322–329.

Hüttl R.F., Gerwin W. (2005): Landscape and ecosystem development after disturbance by mining. Ecological Engineering, 24: 1–3.

Jambhulkar H.P., Kumar M.S. (2019): Eco-restoration approach for mine spoil overburden dump through biotechnological route. Environmental Monitoring and Assessment, 191: 772.

Jenny H. (1941): Factors of Soil Formation: A System of Quantitative Pedology. New York, Dover Publications.

Jenny H. (1980): The Soil Resource: Origins and Behavior. New York, Springer-Verlag.

Kalabić D., Dražić G., Dražić N., Ikanović J. (2019): Production of agri-energy crop *Miscanthus giganteus* on land degraded by power industry: SWOT analysis. Polish Journal of Environmental Studies, 28: 3243–3251.

Kaufmann M., Tobias S., Schulin R. (2009): Quality evaluation of restored soils with a fuzzy logic expert system. Geoderma, 151: 290–302.

Keplin B., Hüttl R. (2001): Decomposition of root litter in *Pinus sylvestris* L. and *Pinus nigra* stands on carboniferous substrates in the Lusatian lignite mining district. Ecological Engineering, 17: 285–296.

Kim S., Mortimer P., Ostermann A. (2018): Tree species and recovery time drives soil restoration after mining: A chronosequence study. Land Degradation and Development, 29: 1738–1747.

https://doi.org/10.17221/163/2020-SWR

Kříbek B., Strnad M., Boháček Z., Sýkorová I., Čejka J., Sobalík Z. (1998): Geochemistry of Miocene lacustrine sediments from the Sokolov Coal Basin (Czech Republic). International Journal of Coal Geology, 37: 207–233.

Kuter N. (2013): Reclamation of Degraded Landscapes due to Opencast Mining. Advances in Landscape Architecture, IntechOpen: 823–858.

Lal R. (2001): Soil degradation by erosion. Land Degradation and Development, 12: 519–539.

Lanham J., Sencindiver J., Skousen J. (2015): Characterization of soil developing in reclaimed Upper Freeport Coal surface mines. Southeastern Naturalist, 14: 58–64.

Lavelle P., Spain A.V. (2001): Soil Ecology. New York, Kluwer Academic Publishers.

Ličina V., Fotirić Akšić M., Tomić Z., Trajković I., Antić Mladenović S., Marjanović M., Rinklebe J. (2017): Bioassessment of heavy metals in the surface soil layer of an opencast mine aimed for its rehabilitation. Journal of Environmental Management, 186: 240–252.

Lima A.T., Mitchell K., O'Connell D.W., Verhoeven J., Van Cappellen P. (2016): The legacy of surface mining: Remediation, restoration, reclamation and rehabilitation. Environmental Science & Policy, 66: 227–233.

Lindemann W.C, Lindsey D.L., Fresquez P.R. (1984): Amendment of mine spoil to increase the number and activity of microorganisms. Soil Science Society of America Journal, 48: 574–578.

Lipiec J., Hatano R. (2003): Quantification of compaction effects on soil physical properties and crop growth. Geoderma, 116: 107–136.

Lorenz K., Lal R. (2007): Stabilization of organic carbon in chemically separated pools in reclaimed coal mine soils in Ohio. Geoderma, 141: 294–301.

Maiti S.K. (2007): Bioreclamation of coalmine overburden dumps – with special empasis on micronutrients and heavy metals accumulation in tree species. Environmental Monitoring and Assessment, 125: 111–122.

Marshall T.J., Holmes J.W., Rose C.W. (1996): Soil Physics. 3rd Ed. Cambridge, Cambridge University Press.

McCormack D.E. (1984): Legislating soil reconstruction on surface-mined land in the United States. Minerals and the Environment, 6: 154–156.

Mikanová O., Usťak S., Czakó A. (2009): Utilization of microbial inoculation and compost for revitalization of soils. Soil and Water Research, 4: 126–130.

Mohr D., Simon M., Topp W. (2005): Stand composition affects soil quality in oak stands on reclaimed and natural sites. Geoderma, 129: 45–53.

Moreno-de las Heras M. (2009): Development of soil physical structure and biological functionality in mining spoils affected by soil erosion in a Mediterranean-Continental environment. Geoderma, 149: 249–256.

Moreno-de las Heras M., Merino-Martín L., Nicolau J. M. (2009): Effect of vegetation cover on the hydrology of reclaimed mining soils under Mediterranean-Continental climate. Catena, 77: 39–47.

Mummey D.L., Stahl P.D., Buyer J.S. (2002a): Microbial biomarkers as an indicator of ecosystem recovery following surface mine reclamation. Applied Soil Ecology, 21: 251–259.

Mummey D.L., Stahl P.D., Buyer J.S. (2002b): Soil microbiological properties 20 years after surface mine reclamation: Spatial analysis of reclaimed and undisturbed sites. Soil Biology and Biochemistry, 34: 1717–1725.

Naprasnikova E.V. (2008): Biological properties of soils on mine tips. Eurasian Soil Science, 41: 1314–1320.

Pająk M., Krzaklewski W. (2007): Selected physical properties of initial soils on the outside spoil bank of the Bełchatów brown coal mine. Journal of Forest Science, 53: 308–313.

Paradelo R., Barral M.T. (2013): Influence of organic matter and texture on the compactability of Technosols. Catena, 110: 95–99.

Pietrzykowski M., Krzaklewski W. (2007): An assessment of energy efficiency in reclamation to forest. Ecological Engineering, 30: 341–348.

Raj D. (2019): Bioaccumulation of mercury, arsenic, cadmium, and lead in plants grown on coal mine soil. Human and Ecological Risk Assessment: An International Journal, 25: 659–671.

Řehounková K., Řehounek J., Prach K. (2011): Near-natural Restoration vs. Technical Reclamation of Mining Sites in the Czech Republic. České Budějovice, University of South Bohemia in České Budějovice.

Remeš J., Šíša R. (2007): Biological activity of anthropogenic soils after spoil-bank forest reclamation. Journal of Forest Science, 53: 299–307.

Rimstidt D.D., Vaughan D.J. (2003): Pyrite oxidation: A state-of-the-art assessment of the reaction mechanism. Geochimica et Cosmochimica Acta, 67: 873–880.

Rincón A., Ruíz-Díez B., Fernández-Pascual M., Probanza A., Pozuelo J.M., Felipe M.R. de (2006): Afforestation of degraded soils with *Pinus halepensis* Mill.: Effects of inoculation with selected microorganisms and soil amendment on plant growth, rhizospheric microbial activity and ectomycorrhizal formation. Applied Soil Ecology, 34: 42–51.

Rumpel C., Knicker H., Kögel-Knabner I., Skjemstad J.O., Hüttl R.F. (1998): Types and chemical composition of organic matter in reforested lignite-rich mine soils. Geoderma, 86: 123–142.

https://doi.org/10.17221/163/2020-SWR

Rumpel C., Kögel-Knabner I., Hüttl R. (1999): Organic matter composition and degree of humification in lignite-rich mine soils under a chronosequence of pine. Plant and Soil, 213: 161–168.

Rumpel C., Kögel-Knabner I., Knicker H., Hüttl R.F. (2000): Composition and distribution of organic matter in physical fractions of a rehabilitated mine soil rich in lignite-derived carbon. Geoderma, 98: 177–192.

Santini T.C., Fey M.V. (2016): Assessment of Technosol formation and in situ remediation in capped alkaline tailings. Catena, 136: 17–29.

Sarah P. (2005): Soil aggregation response to long- and short-term differences in rainfall amount under arid and Mediterranean climate conditions. Geomorphology, 70: 1–11.

Schaaf W. (2001): What can element budgets of false-time series tell us about ecosystem development on post-lignite mining sites? Ecological Engineering, 17: 241–252.

Schaaf W. (2003): Leaching induced changes in substrate and solution chemistry of mine soil microcosms. Water, Air and Soil Pollution: Focus, 3: 139–152.

Schaaf W., Hüttl R.F. (2006): Direct and indirect effects of soil pollution by lignite mining. Water, Air, and Soil Pollution: Focus, 6: 353–364.

Schaaf W., Gast M., Wilden R. (1999): Temporal and spatial development of soil solution chemistry and element budgets in different mine soils of the Lusatian lignite mining area. Plant and Soil, 213: 169–179.

Schnitzer M., Khan S.U. (1975): Soil Organic Matter. Amsterdam, Elsevier Science.

Sexstone A.J., Revsbech N.P., Parkin T.B., Tiedje J.M. (1985): Direct measurement of oxygen profiles and denitrification rates in soil aggregates. Soil Science Society of America Journal, 49: 645–651.

Sheoran A., Sheoran V., Poonia P. (2008): Rehabilitation of mine degraded land by metallophytes. Mining Engineers Journal, 10: 11–16.

Sheoran V., Sheoran A.S., Poonia P. (2010): Soil reclamation of abandoned mine land by revegetation: A Review. International Journal of Soil, Sediment and Water, 3: 13.

Shrestha R.K., Lal R. (2008): Land use impacts on physical properties of 28 years old reclaimed mine soils in Ohio. Plant and Soil, 306: 249–260.

Sinha S., Masto R.E., Ram L.C., Selvi V.A., Srivastava N.K., Tripathi R.C., George J. (2009): Rhizosphere soil microbial index of tree species in a coal mining ecosystem. Soil Biology and Biochemistry, 41: 1824–1832.

Šourková M., Frouz J., Fettweis U., Bens O., Hüttl R.F., Šantrůčková H. (2005a): Soil development and properties of microbial biomass succession in reclaimed post mining sites near Sokolov (Czech Republic) and near Cottbus (Germany). Geoderma, 129: 73–80.

Šourková M., Frouz J., Šantrůčková H. (2005b): Accumulation of carbon, nitrogen and phosphorus during soil formation on alder spoil heaps after brown-coal mining, near Sokolov (Czech Republic). Geoderma, 124: 203–214.

Spasić M., Drábek O., Tejnecký V., Vacek O., Borůvka L. (2020): Physico-chemical properties of lignite mine reclaimed soil formed under 19 different tree species in Sokolov, Czech Republic. Mechanization in Agriculture & Conserving of the Resources, 66: 134–135.

Štrudl M., Borůvka L., Dimitrovský K., Kozák J. (2006): Contents of potentially risk elements in natural and reclaimed soils of the Sokolov region. Soil and Water Research, 1: 99–107.

Tang Q., Li L., Zhang S., Zheng L., Miao C. (2018): Characterization of heavy metals in coal gangue-reclaimed soils from a coal mining area. Journal of Geochemical Exploration, 186: 1–11.

Topp W., Simon M., Kautz G., Dworschak U., Nicolini F., Prückner S. (2001): Soil fauna of a reclaimed lignite opencast mine of the Rhineland: Improvement of soil quality by surface pattern. Ecological Engineering, 17: 307–322.

Tropek R., Kadlec T., Hejda M., Kocarek P., Skuhrovec J., Malenovsky I., Vodka S., Spitzer L., Banar P., Konvicka M. (2012): Technical reclamations are wasting the conservation potential of post-mining sites. A case study of black coal spoil dumps. Ecological Engineering, 43: 13–18.

Ussiri D.A.N., Jacinthe P.A., Lal R. (2014): Methods for determination of coal carbon in reclaimed minesoils: A review. Geoderma, 214–215: 155–167.

Uzarowicz L., Skiba S. (2011): Technogenic soils developed on mine spoils containing iron sulphides: Mineral transformations as an indicator of pedogenesis. Geoderma, 163: 95–108.

Valla M., Kozák J., Ondráček V. (2000): Vulnerability of aggregates separated from selected anthrosols developed on reclaimed dumpsites. Rostlinná Výroba, 46: 563–568.

Vega F.A., Covelo E.F., Andrade M.L., Marcet P. (2004): Relationships between heavy metals content and soil properties in minesoils. Analytica Chimica Acta, 524: 141–150.

Vetterlein D., Hüttl R.F. (1999): Can applied organic matter fulfil similar functions as soil organic matter? Risk-benefit analysis for organic matter application as a potential strategy for rehabilitation of disturbed ecosystems. Plant and Soil, 213: 1–10.

Vetterlein D., Bergmann C., Hüttl R.F. (1999): Phosphorus availability in different types of open-cast mine spoil and the potential impact of organic matter application. Water, 1991: 189–194.

https://doi.org/10.17221/163/2020-SWR

Vindušková O., Frouz J. (2013): Soil carbon accumulation after open-cast coal and oil shale mining in Northern Hemisphere: A quantitative review. Environmental Earth Sciences, 69: 1685–1698.

Vitousek P.M., Reiners W. (1975): Ecosystem succession and nutrient retention: A hypothesis. Bioscience, 25: 376–381.

Wali M.K. (1999): Ecological succession and the rehabilitation of disturbed terrestrial ecosystems. Plant and Soil, 213: 195–220.

Wang X., Yost R.S., Linquist B.A. (2001): Soil aggregate size affects phosphorus desorption from highly weathered soils and plant growth. Soil Science Society of America Journal, 65: 139–146.

Wanner M., Dunger W. (2001): Biological activity of soils from reclaimed open-cast coal mining areas in Upper Lusatia using testate amoebae (protists) as indicators. Ecological Engineering, 17: 323–330.

Waschkies C., Hüttl R.F. (1999): Microbial degradation of geogenic organic C and N in mine spoils. Plant and Soil, 213: 221–230.

Wiegleb G., Felinks B. (2001): Primary succession in post-mining landscapes of Lower Lusatia – Chance or necessity. Ecological Engineering, 17: 199–217.

Wilden R., Schaaf W., Hüttl R.F. (1999): Soil solution chemistry of two reclamation sites in the Lusatian lignite mining district as influenced by organic matter application. Plant and Soil, 213: 231–240.

Wilden R., Schaaf W., Hüttl R.F. (2001): Element budgets of two afforested mine sites after application of fertilizer and organic residues. Ecological Engineering, 17: 253–273.

Wu L., Vomocil J.A., Childs S.W. (1990): Pore size, particle size, aggregate size, and water retention. Soil Science Society of America Journal, 54: 952–956.

Zellmer S.D., Wilkey M.L. (1979): A reclamation demonstration project at an abandoned deep mine. Minerals and the Environment, 1: 57–63.

Zharikova E.A., Kostenkov N.M. (2014): Physicochemical properties and potassium state of the soils developed on dump rocks of coal mines. Eurasian Soil Science, 47: 26–34.

Zier N., Schiene R., Koch H., Fischer K. (1999): Agricultural reclamation of disturbed soils in a lignite mining area using municipal and coal wastes: the humus situation at the beginning of reclamation. Plant and Soil, 213: 241–250.

Received: November 18, 2020
Accepted: April 15, 2021
Published online: May 11, 2021