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Development of soil chemical and microbial properties in reclaimed and unreclaimed grasslands in heaps after opencast lignite mining

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ABSTRACT

Understanding changes in soil chemical and microbial properties under different vegetation types on post-mining sites is an important step in developing management practices to enhance ecosystem functions. Changes in soil carbon (C), nitrogen (N) and phosphorus (P) stock, pH, bulk density and microbial properties (microbial biomass, respiration and ergosterol content) were studied in chronosequences on reclaimed and unreclaimed grasslands on heaps after lignite mining in the northwest of the Czech Republic. Reclaimed sites were established by applying topsoil and seeding cultural grasses and legumes. Unreclaimed sites were only levelled and spontaneously colonized by grassy vegetation dominated by bushgrass (*Calamagrostis epigejos* (L.) Roth). Topsoil application created more favourable conditions for organic matter accumulation in soil. The C and N contents in the soil of reclaimed sites increased with age, while no significant changes occurred in unreclaimed sites. The results indicated a high potential for C sequestration in reclaimed grasslands with topsoiling, estimated at up to 1.6 $t\,ha\,y^{-1}$. The P content did not change with age in either reclaimed or unreclaimed sites. Microbial biomass and respiration increased with chronosequence in both sites. However, respiration did not differ between reclaimed and unreclaimed sites, while microbial biomass was significantly higher in reclaimed sites.

1. Introduction

Opencast mining has a negative impact on the environment through large-scale land disturbance and landscape transformation (Macdonald et al., 2015). Overburden (or spoils) deposited in heaps become the parent material for developing mine soils (Pietrzykowski, 2014). In many cases, this soil differs substantially from natural soils (Bradshaw, 1983; Wick et al., 2013; Frouz, 2014). Reclamation is aimed to minimize these negative effects of opencast mining activities (Macdonald et al., 2015) and provides opportunities for creating new ecosystems in post-mining areas (Schulz and Wiegleb, 2000). Reclamation is a process of restoring the ecosystem and its functions. It may include technical measures such as modifying the terrain or applying topsoil and introducing vegetation (Bradshaw, 1983; Macdonald et al., 2015). Another alternative for restoring the natural values of post-mining areas is to leave it to natural succession (Wiegleb and Felinks, 2001; Frouz et al., 2008, 2015). In some site conditions, succession can be attractive because of the lower cost, higher biodiversity of communities and that these sites may offer habitats for rare and endangered species (Prach and Hobbs, 2008). Successional species are generally more adaptable to environmental stress conditions in unreclaimed sites than are introduced species in reclaimed areas.

Various reclamation treatments have been used to initiate ecosystem development and the soil forming process on post-mining sites (Pietrzykowski and Krzaklewski, 2007; Frouz, 2014). These usually include one or several of the following operations: terrain modification, topsoil application, introducing plants and applying fertilizers, soil organic amendments and other agrochemicals. These technical operations are intended to speed up vegetation establishment, soil formation and ecosystem development, as well as to improve the reclaimed sites (Frouz, 2014). Following the termination of mining, the soil and vegetation development on surface-mined sites may be studied through revegetation chronosequences. Thus, it is possible to compare various types of reclamation practices by studying the ecosystem development, including soil formation processes and vegetation succession with time, following various revegetation practices, with or without topsoil (Anderson, 1977; Pietch, 1996; Wali, 1999; Rumpel et al., 1999). Several previous studies focused on comparing reclaimed and unreclaimed sites to show the added value of reclamation measures and potential pitfalls these measures can bring (Pietrzykowski and Krzaklewski, 2007; Abakumov et al., 2013; Frouz, 2014; Frouz et al., 2015). These studies, conducted in temperate climate zones, were

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mostly focused on afforested sites. However, there is a lack of such studies in other types of ecosystems, such as grasslands. Restoration of grassland is a common way of restoring agricultural land in many post-mining soils. Spontaneous development of grassland may be quite common when soil is compacted, e.g. by levelling, and grassland commonly develops even on post-mining sites where levelling is part of the heaping process (Frouz et al., 2018).

An important part of ecosystem development is the soil formation process, which is connected to the accumulation of soil organic matter (SOM) (Bradshaw, 1997; Pietrzykowski and Daniels, 2014; Abakumov et al., 2013). SOM provides the material and energy necessary to sustain metabolism (Bendfeldt et al., 2001; Wick et al., 2013), enhances microbial activity and biomass and improves water retention. It is also an important source of nutrients, including deficient N and P (Frouz et al., 2006; Józefowska et al., 2017). SOM accumulation also involves changes in pH and bulk density (BD) in post-mining soils (Bradshaw, 1997). C sequestration in soil due to SOM accumulation is also important globally because it minimizes the greenhouse effect (Lal, 2004).

Ecosystems developed in post-mining areas have great potential to sequester C (Sperow, 2006; Pietrzykowski and Daniels, 2014) and the rate of C sequestration in these soils may be several times higher than, for example, in afforested arable land (Frouz and Vindušková, 2018). C sequestration in post-mining sites influences substrate properties, above- and belowground litter input, soil fauna and microbial activity, reclamation treatments and the types of introduced vegetation (Shrestha and Lal, 2006; Józefowska et al., 2017). Reclamation treatments can have a significant impact on the C sequestration rate in developed grassland ecosystems compared with unreclaimed grasslands, probably owing to the different species composition and, in some cases, in restoring plots for agriculture and topsoil application (Akala and Lal, 2001; Ussiri et al., 2006). Topsoiling often increases organic matter and nutrient contents in reclaimed mining soils (Borůvka et al., 2012). In some conditions, topsoiling also increases richness and diversity of the developed plant communities (Martínez-Ruiz and Fernández-Santos, 2005) but in other cases, increased nutrient availability may have opposite effects (Prach and Hobbs, 2008).

Topsoiling can influence the microbial community and activity. The microbial contribution to soil C storage is related to microbial community dynamics. A quantitative and qualitative improvement of SOM is observed in ecosystems favouring a fungal-dominated community (Six et al., 2006). Mentioned condition can be altered in post-mining soils because microbial communities must gradually develop from the "zero point".

The aim of this study was to assess soil C, N and P accumulation, pH, bulk density and microbial properties (respiration, microbial biomass and ergosterol content) in relation to site age on unreclaimed and reclaimed grasslands with added topsoil. We tested the following hypotheses: i) topsoil application per se will not increase organic matter content in soil but reclaimed grasslands will be characterized by greater C, N and P accumulation rates in soil compared with unreclaimed grasslands; ii) C sequestration in reclaimed grasslands will be similar compared with soil on afforested post-mining sites; iii) pH and BD will decrease with age; iv) microbial respiration and biomass will increase with age; and v) the ergosterol content in soils has an influence on C accumulation.

2. Material and methods

2.1. Study sites

The study was conducted on heaps produced by opencast lignite mining near the town of Sokolov in the Czech Republic (50°14′21″N, 12°39′24″E), with an altitude of 500–600 m a.s.l. The mean annual air temperature is 6.8 °C, and the mean annual precipitation is 650 mm (long term mean for second half of 20th century, source: Czech Hydrometeorological Institute). The spoil heaps consist of tertiary clay shale, and the pH of the substrate is alkaline in early successional forest ecosystems and gradually decreases with site age (Frouz et al., 2008, Bartuska and Frouz, 2015). Chronosequences of reclaimed and unreclaimed grasslands were used. The surfaces of both reclaimed and unreclaimed sites were levelled by earth-moving machinery 5–10 years after heaping. In both cases, the ages of the plots (point zero for ecosystem development) were calculated from this levelling event. After levelling, the unreclaimed sites developed without further intervention, and a plant community appeared with natural succession with dominant species, such as bushgrass (*Calamagrostis epigejos* (L.) Roth). The overall aboveground production in unreclaimed grassland reached approximately 0.9 t (DW) ha^{-1} y^{-1} (Frouz et al., 2008). A recent study conducted on the spoil heap in Sokolov showed that ungraded sites that were left without reclamation develop towards forest, while sites where the surface was levelled and then left without any other intervention developed towards grassland (Frouz et al., 2008). Consequently, only levelled sites were used in this study. In reclaimed sites, topsoiling (an approximately 30-cm layer) was performed by salvaging the uppermost soil layer from arable fields surrounding the forefield of the mine. Spreading typically occurred shortly after levelling, and a grass and legume mixture of *Dactylis glomerata* L., *Arrhenatherum elatius* (L.) P. Beauv. ex J. Presl & C. Presland and *Trifolium pratense* L. was applied. Biomass was periodically removed from the reclaimed grassland. During the initial period, the biomass was mulched and left at the site. During the period after the establishment (c. 5–10 years after reclamation), approximately half of the biomass was mulched, and half was removed and used as a hay or processed in a biogas station. The overall aboveground production in the established reclaimed meadow was 2.5 t (DW) ha^{-1} y^{-1} (based on the data of Sokolovská Uhelná, the mining company that operates the site).

2.2. Sampling and analysis

In total, 12 plots were studied: seven reclaimed grasslands with ages of 5, 10, 12, 20, 30, 50 and 52 years, and five unreclaimed grasslands, with ages of 10, 15, 22, 25 and 51 years. Each of the plots has an area of 5–10 ha. At each plot, composite samples were taken from three locations. At the locations, different composite samples were taken at least 100 m apart. Composite samples were taken in an area of about 10 × 10 m and consisted of five subsamples. In each location, three samples were collected by a corer with a diameter of 11.5 cm in three layers, 0–6 cm, 6–12 cm and 12–18 cm. Individual samples from matching layers in a given location were mixed into one composite sample. In each site, there were nine composite samples representing samples from three locations and three depth layers (108 composite samples in total).

Individual samples were sieved (2-mm mesh size) and weighed. Then, a 50-g sample was dried at 105 °C for 5 h and weighed. This weight was used to calculate the dry weight of the original sample, which was then divided by the volume of the three individual samples to obtain the BD of the fine fraction (< 2 mm). Next, samples were ground.

The dried samples were used to establish the total C, N and P contents and pH. Total C and N were analysed with an EA 1108 CHNS-O element analyser (Carlo Erba Instruments, Milan, Italy). The total P content of the soil was determined in composite samples by treatment with 70% perchloric acid (Sommers and Nelson, 1972), and orthophosphate ions were quantified by the ascorbic acid and ammonium molybdate method (Murphy and Rieley, 1962; Watanabe and Olsen, 1965). The pH was determined with a 1:5 (w:v) soil:water suspension using a WTW 526/538 pH meter (WTW, Weilheim, Germany) with a combination electrode.

The undried part of the sample from 0 to 6 cm horizons was passed through a 2-mm sieve and stored in the refrigerator at 4 °C for approximately 1 week until it was processed to measure the microbial respiration, biomass and ergosterol content. To assess microbial