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The spontaneous development of understory vegetation on reclaimed and afforested post-mine excavation filled with fly ash

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ABSTRACT

We studied the spontaneous development of understory vegetation in a reclaimed fly ash landfill. Plots were reclaimed 11 years earlier with sewage sludge, and boulder clay mixed with fly ash, and then afforested. Additionally, fertilisation with different doses of NPK was used. The treatments resulted in differences in the success of afforestation and in the spontaneous development of understory vegetation. Fifty-five understory species were found in total across all treatments. Nearly half of these species consisted of synanthropic vegetation, 20% represented meadow species, and 20% forest species. Sparse vegetation developed on raw fly ash without fertilisation and on plots shaded by tall trees. The most abundant understory vegetation was linked with the presence of two expansive grasses. *Calamagrostis epigejos* invaded plots with NPK-fertilised fly ash. *Elymus repens*, in part growing together with *Galium aparine*, developed dense stands in plots with fly ash covered with sewage sludge. The abundant growth of both grasses caused a significant reduction in understory species diversity. Canonical correspondence analysis (CCA) showed that the addition of sewage sludge and boulder clay had a stronger influence on understory species composition than fertilisation or shade from the tree canopy. The results of this study indicate that spontaneous succession combined with the technical reclamation measures and afforestation may be advantageous for the development of dense and relatively species-rich vegetation on fly ash landfills.

1. Introduction

Opencast mining of lignite is closely linked with the functioning of electric power plants, which use this material as an energy source. Carbon dioxide is the best-known greenhouse gas emitted from electric power plants; however, another source of environmental problems associated with coal-based energetics is the production of large amounts of fly ash. Power plants generate 70–75% of the residues derived from the combustion of coal, and only approximately 30% of this amount is utilised (Haynes, 2009). The rest is stored in landfills or used as infilling for excavations, usually located close to the power plants. The disposal and use of vast and growing amounts of fly ash has become a serious environmental problem on a global scale (Ahmaruzzaman, 2010). Fly ash storage sites must be promptly covered with vegetation to prevent water and wind erosion and to achieve other goals of restoration, including increasing the ecological value of a disturbed site, such as providing a suitable wildlife habitat, and enhancing the aesthetics of the reclaimed environments (Haynes, 2009; Pandey and Singh, 2012; Prach and Hobbs, 2008).

Fly ash creates a very difficult habitat for plant succession; it has unfavourable physical and chemical properties combined with often extreme microclimatic conditions (Pavlović et al., 2004). Fly ash is poor in nitrogen and available phosphorous (Gupta et al., 2002). Its high pH reduces the solubility of, and causes plant deficiency in Fe, Mn, Cu, and Zn. Simultaneously, high concentrations of soluble salts and toxic levels of boron might occur, as well as low microbial activity (Haynes, 2009). Gupta and Sinha (2008) found naturally growing plant species that are suitable both for revegetation and for decontamination of fly ash dykes.

Introduction of plants onto raw fly ash landfills is a difficult task; it might require physical improvement of the fly ash surface (Bradshaw, 2000) and, reduction in toxicity and salinity in some cases (Chu, 2008). To improve site conditions, farmyard manure and other organic matter supplements are used, together with bacterial and mycorrhizal inoculation and the introduction of legumes (Haynes, 2009; Juwarkar and Jambhulkar, 2008). Plant species to be introduced on fly ash deposits must be carefully chosen because they should be well adapted to that particular habitat (Bradshaw, 2000; Haynes, 2009).

Post-mining sites, including fly ash landfills, can be successfully covered by vegetation intentionally introduced by man following various

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technical reclamation treatments, but many studies also emphasise the role of spontaneous succession as an advantageous natural process that stimulates the colonisation and development of plant communities (Bradshaw, 1997, 2000; Mudrák et al., 2010; Pandey and Singh, 2012; Pavlović et al., 2004; Prach and Hobbs, 2008; Rebele and Lehmann, 2002; Tropek et al., 2010; Wiegleb and Felinks, 2001).

Spontaneous succession can lead to the development of refuges for biodiversity by creating various habitats for different plants and animals, including rare species, even without any active restoration measures (Kirmer et al., 2008; Tropek et al., 2010). Pandey et al. (2012) found that *Saccharum munja*, a species of grass which spontaneously occurs in fly ash lagoons in India, is useful in reclamation and can be used to convert fly ash deposits into productive habitats without any soil amendments or maintenance. Pandey and Singh (2012) recommended the rehabilitation of fly ash basins by promoting the natural succession of native species followed by planting of tolerant tree species; this process would be likely to result in productive and diverse ecosystems that are able to provide a variety of services. In the Czech Republic, Čermák (2008) found that *Robinia pseudoacacia* and native Central European tree species belonging to such genera as *Salix*, *Populus*, and *Pinus* were suitable for fly ash reclamation, and performed well in the early stages of primary succession. In an experiment conducted in Poland by Krzaklewski et al. (2012) in a power-plant fly ash landfill, the tree species alder (*Alnus glutinosa* and *Alnus incana*) exhibited a high rate of survival following substrate enhancement with lignite culm.

Revegetation and erosion prevention are the main goals of management of fly ash landfills and other post-industrial wastes. However, the diversity of natural vegetation may become an equally important goal because vegetation in post-mining areas can contribute to the maintenance of high local and regional biodiversity and to the aesthetics of the area. Scientific literature addressing problems of plant succession in fly ash landfills is still sparse. We expand this understanding by focusing on an 11-year-old experiment on a reclamation site, and presenting results of research on vegetation responses to amendments of the soil substrate. The first part of the research, dealing with properties of the soil substrate is published in this issue (Weber et al., 2015). The objective of our study was to determine which reclamation measures allow for the development of spontaneous understory vegetation and which, in turn, promote the establishment of species-diverse plant communities. In particular we wanted to know which factors determine (i) the amount of above-ground plant biomass, (ii) plant species composition of the spontaneously-developing vegetation, and (iii) plant species richness and diversity.

2. Materials and methods

2.1. Reclamation design

We studied the spontaneous development of understory vegetation in plots established on the reclaimed part of the fly ash landfill of the Adamów Power Plant, located near the town of Turek, central Poland. This 600-MW power plant is fuelled with lignite containing 8–15% ash. The fly ash is mixed with the bottom ash originating from the furnaces, and then transported from the power plant as ash–water slurry and deposited in an artificial water reservoir created in the nearby excavation remaining from the former open-cast mine. The outer part of the filled-in and dried-up water reservoir has been turned into waste land; lack of vegetation is due to the crusting of fly ash, strong alkaline reaction (pH in 1 M KCl 8.3–11.2), and high salinity (EC ranged from 4 to 5 dS m^{-1}). Our studies were carried out 11 years after the reclamation conducted by the power plant in 1999 (Wróbel et al., 2006).

The reclaimed part of the landfill was divided into several areas (reclamation plots) of 60 m × 16 m, separated by 2-m borders. Plots were reclaimed with different treatments, including fly ash covered with a 0.25-m thick layer of sewage sludge (3000 t ha^{-1}), and 0.25 m or 0.5 m layer of boulder clay (4000 t ha^{-1} and 8000 t ha^{-1}) (Table 1); the materials received deep (1 m) crushing and mixing of the substrate with the use of a special mining machine provided by the mine and operated by the power station personnel. Two additional plots were also established; here, pits were dug into the raw fly ash (for later tree and shrub planting) and were filled with sewage sludge or boulder clay. A plot with raw fly ash was used as reference. Properties of the sewage sludge were as follows: contents of dry matter: 350 g kg^{-1}; organic matter: 380 g kg^{-1} d.m.; nitrogen: 26.5 g kg^{-1} d.m.; phosphorous: 30 g kg^{-1} d.m.; and pH = 7.3. Properties of boulder clay were as follows: pH = 7.7; contents of organic carbon: 6.24 g kg^{-1}; nitrogen: 0.49 g kg^{-1}; and available phosphorous: 56.4 mg kg^{-1}. Subsequently, some of the reclaimed plots were fertilised with different doses of NPK for five years, while the other ones were not fertilised (for details see Table 1).

The surface 0–25 cm layer of the soil substrate (reclaimed material) had a loamy texture (clay 4%, silt 5%, sand 91%), and exhibited the following properties: pH (KCl) of 7.4–7.6 (material mixed with sewage sludge or boulder clay), and 8.5–8.8 (raw fly ash); salinity from 0.61 dS m^{-1} (material mixed with sewage sludge or boulder clay) to 1.02 dS m^{-1} (raw fly ash), and plant-available phosphorous from 5.0 mg kg^{-1} (raw fly ash) to 30.4 mg kg^{-1} (material mixed with sewage sludge or boulder clay). Both raw fly ash and mixed material indicated a variable organic carbon content (7.4–21.2 g kg^{-1}), and were rich in plant-available potassium (138–254 mg kg^{-1}) and magnesium (159–174 mg kg^{-1}). Available forms of phosphorus and potassium were determined with the Egner–Riehm method, and the available form of magnesium — with the Schachtschabel method. Porosity of substrate ranged from 40 to 70%, and field water capacity ranged from 22 to 44%. Detailed information on the properties of the fly ash and soil substrate amended with sewage sludge and clay is given in the paper published in the same issue (Weber et al., 2015).

Seven non-native and one native tree and shrub species were planted on all reclaimed plots in a random pattern: black locust, *Robinia pseudoacacia*; green ash, *Fraxinus pennsylvanica*; box elder maple, *Acer negundo*; sycamore maple, *Acer platanoides* (a native species for Poland); silver berry, *Elaeagnus angustifolia*; caragana (Siberian peashrub), *Caragana arborescens*; common dogwood, *Cornus sanguinea* and common sea-buckthorn, *Hippophaë rhamnoides*. Unfortunately a few plots of the original experiment have been devastated before our investigation and therefore they were omitted in our study. A total of twelve reclamation plots consisting of the different reclamation designs were used in this study (Table 1). The applied treatments resulted in differences in the success of afforestation and in the spontaneous development of understory vegetation.

2.2. Field research

Field observations were performed 11 years after reclamation. A systematic sampling design was used; three square study subplots (5 m on a side) were established in the central part of each reclamation plot in a regular grid separated by 10 m between subplot sides, and vegetation data and above-ground biomass samples of the understory vegetation were collected. Plant aerial biomass was cut using a 25 × 25 cm frame from a randomly chosen location within each quarter of the plot and the four subsamples were pooled. Measurements of light penetration were taken using a lux meter at heights of 1 m and at ground level in the same locations as the above-ground biomass samples were collected. Light penetration was measured at the time of vegetation sampling. Measurements were simultaneously taken in the study subplots and in an open area next to the reclamation plots. Measurements were carried out on cloudless days. Height of trees < 5 m was measured with a height pole measuring device, while a laser distance meter was used for trees taller than 5 m. Field research was carried out in the first week of July 2010. Samples of plant biomass were dried at 80 °C to a constant weight. Above-ground biomass production was expressed as g dw m^{-2}.