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Development of canopy cover and woody vegetation biomass on reclaimed and unreclaimed post-mining sites

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ABSTRACT

On an open-cast coal mining heap in the northwestern Czech Republic, development of the canopy cover of woody vegetation was studied using historical aerial photographs of unreclaimed sites overgrown by natural succession and of sites reclaimed by the planting of alder. A comparison of sites by general linear models revealed that canopy cover did not differ significantly between reclaimed sites and unreclaimed sites. Dominant species on unreclaimed sites (*Salix caprea* and *Populus tremula*) and reclaimed sites (*Alnus glutinosa*) sites were destructively sampled to generate site-specific allometric equations. Trees and shrubs were counted and measured on 5-, 19-, 15-, and 45-year-old reclaimed and unreclaimed sites. When sites were 5 years old, tree density was much higher on reclaimed sites (7575 trunks ha^{-1}) than on unreclaimed sites (1215 trunks ha^{-1}). On reclaimed sites, tree density gradually decreased with site age and was equivalent to that on unreclaimed sites when sites were 45 years old (1675 trunks ha^{-1}). Woody biomass did not significantly differ between reclaimed and unreclaimed sites when measured across all ages but did significantly differ when measured at specific ages: thus, woody biomass was greater on reclaimed sites than on unreclaimed sites at age 5 years but was greater on unreclaimed sites than on reclaimed sites at age 25 years.

1. Introduction

Open-cast coal mining causes massive disturbance to ecosystems, which are either removed by excavation or buried by the large amount of substrate located above the coal layers (the "overburden"), which is excavated and deposited in soil heaps before coal is extracted (Frouz et al., 2001; Helingerová and Frouz, 2010). Ecosystem restoration of soil heaps is essential for their socioeconomic recovery (Bradshaw, 1997). Converting post-mining land to forest has been assumed to be a sensible way of restoration (Zeleznik and Skousen, 1996). Forest reclamation has been frequently performed as part of restoration in the Czech Republic and elsewhere in Europe (Frouz et al., 2001, 2013a,b; Pietrzykowski and Krzaklewski, 2007; Pietrzykowski, 2014). During restoration, the site is usually leveled by earthmoving machinery, and trees are then planted. In some cases, topsoil is also added, and herbaceous species are established (Frouz et al., 2001, 2013a; Zeleznik and Skousen, 1996). In many places, however, spontaneous re-growth of forest vegetation has occurred on post-mining land (Frouz et al., 2007; Frouz et al., 2008; Mudrák et al., 2010; Pietrzykowski, 2008; Skousen et al., 1994). Although several studies have compared have compared invertebrate and herb species diversity or soil development on reclaimed sites (with planted trees) and unreclaimed sites (with spontaneous establishment and succession of vegetation) (Frouz et al., 2008; Hendrychová et al., 2012; Holec and Frouz, 2005; Mudrák et al., 2010; Pietrzykowski, 2008; Skousen et al., 1994), few studies have compared woody biomass and woody biomass production on reclaimed and unreclaimed sites (Poland and Gorman et al., 2001; Pietrzykowski and Krzaklewski, 2007).

Woody biomass is important from an economic perspective (the wood is eventually harvested and sold) but also from an environmental perspective in that the forests that produce wood provide many ecosystem services including carbon sequestration, which is correlated with tree biomass (Barford et al., 2001; Fahey et al., 2010; Frouz et al., 2013a). The goal of reclamation is to establish plant cover and associated ecosystem services (e.g., reduced soil erosion and improved soil development) more quickly. Although

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it is generally expected that the acceleration of tree establishment leads to higher biomass and higher wood production (Prach and Hobbs, 2008), empirical evidence to support this expectation is scarce. Several reports have discussed the potential use of spontaneous woody regrowth on agriculture land for bioenergy (Bose et al., 2009), but there is a shortage of similar information on post-mining land (Pietrzykowski, 2008).

The major aim of this study was to compare the biomass of reclaimed and unreclaimed forest stands. Several tree species are used for reclamation in the Sokolov post-mining area, and here we focused on sites planted with alder. We focused on alder because alder is the most commonly used tree species in this post-mining area and because (i) a comparison of forest stands by Frouz et al. (2009) showed that alder provided the second largest production of aboveground woody biomass of the studied tree species. The only tree species with larger biomass production was larch, but larch occurs in very few stands, which precluded extensive comparison. Although reclamation practices are highly variable, we compared unassisted, spontaneous regrowth with a very basic form of forest restoration involving grading and tree planting.

Using a set of historical aerial photographs, we first compared canopy cover development in reclaimed and unreclaimed sites. We then compared woody biomass (both above and belowground) in reclaimed and unreclaimed sites of different ages.

2. Materials and methods

2.1. Study sites

This study was conducted on a single coal-mine heap (2.5 km wide and 10 km long) near the town of Sokolov in the Czech Republic (50°1404400 N, 12°410400 E, 450–520 m a.s.l.). The mean annual precipitation in this area is 650 mm, and the mean annual temperature is 6.8 °C (Frouz et al., 2001). The heap was formed from the 1960s until 2002 by the dumping of overburden produced by brown coal mining. The overburden consists of tertiary clay material and has a pH near 8 (Helingerová and Frouz, 2010).

The heap was covered by a mosaic of patches (hereafter referred to as "sites") that were overgrown by different types of vegetation of various ages. Our study included sites that had been reclaimed (afforested) by the planting of alder (a mixture of *Alnus incana* and *Alnus glutinosa*) at 10,000 seedlings per ha. In contrast to the reclaimed sites, the unreclaimed sites had not been planted and were covered by spontaneous woody vegetation dominated by willow (*Salix caprea*), aspen (*Populus tremula*), and birch (*Betula pendula*). No topsoil had been spread on the surface of the reclaimed or the unreclaimed sites. The substrate in both types of sites was formed by the same clay overburden. The surface of the reclaimed sites had been leveled before the trees were planted. No leveling had been conducted at the unreclaimed sites, where the surface consisted of longitudinally oriented 1 m high ridges and depressions.

2.2. Mapping of canopy cover using historical photographs

To map the development of vegetation, we used aerial photographs of the study sites that were taken in 1990, 1993, 1998, 2005, 2008, 2010, and 2012, and that were provided by the Military Geographical Service of the Armed Forces of the Czech Republic. The photographs were orthorectified using pre-rectified photographs from 2005 provided by the Czech Geodetic Institute. In these photographs, we identified three polygons covered by spontaneous-succession vegetation and eight polygons reclaimed by the planting of alder.

Unreclaimed sites were larger in area than reclaimed sites, but their area decreased over time, because they were partly leveled by earthmoving machinery and converted into roads and other infrastructure or they were reclaimed. Hence, the undisturbed area that had a wavy surface was mapped for each plot in each available year, and this area was assumed as the total available unreclaimed area that could possibly have woody canopy cover. In reclaimed sites, the boundary on each site was simply projected onto the aerial photograph and used to estimate canopy cover. Because photographs were in black and white before 2005 but were in color after 2005, and because the light aspect of older photographs varied among years, we did not use an automatic image analyzer but instead we visually estimated the area covered by canopy. For this estimate, the area covered by woody canopy was manually plotted in ArcGIS. The canopy cover was assumed as continuous if there was a group of trees (minimum group size was three trees or shrubs) with interconnected canopy or if the space between two neighboring trees or shrubs did not exceed two diameters of a tree.

The age of unreclaimed sites was set equal to the "time since heaping". The age of reclaimed sites was set equal to the "time since tree planting", because tree planting and soil leveling were considered to have reset the system. Because reclaimed sites were typically leveled and planted until 5–10 years after heaping had ceased, the reclaimed sites would be considered older than indicated if time since heaping was used to estimate age for both kinds of sites. For reclaimed sites, information about tree planting was obtained from the Sokolovska uhelná mining company. For unreclaimed sites, data about heaping were taken from aerial photographs; in some cases, heaping machinery was visible in the photographs; in other cases, a heap was not evident in an older photograph but became evident in a more recent photograph, and we assumed that the heap was created in the middle of the interval between the time when the two photographs were taken.

To compare canopy cover development between reclaimed and unreclaimed sites, we used general linear models (GLMs) with percentage of canopy cover as the dependent variable, site type (unreclaimed vs. reclaimed) as a categorical predictor, and plot age as a continual predictor. Because the site area varied between reclaimed and unreclaimed sites, we used canopy cover data that were either unweighted or weighted by site area. Weighted data were weighted by factor representing relative size of each area (size of the area divided by mean size of all areas). Computations were done in Statistica 10.0.

2.3. Destructive sampling of trees and development of allometric equations

To estimate total woody biomass on individual sites, we sampled the dominant woody species, which were aspen (*P. tremula*) and willow (*S. caprea*) for unreclaimed sites and alder (*A. glutinosa*) for reclaimed sites. Seven aspen trees, six willow trees and six alder trees were sampled. Height and DBH (diameter at breast height) of selected, standing trees or shrubs were measured. In shrubs with multiple trunks, all trunks with DBH > 2 cm were measured. DBH was measured to the nearest millimeter with a caliper at 130 cm height, and tree height was measured to the nearest centimeter with a laser rangefinder (Nikon 8381 Forestry Pro). Individual trees or shrubs were then cut down, and all roots with diameter >0.5 cm were carefully excavated with a JCB 8030 excavator and manually. The entire tree was then divided into trunk, branches (including leaves), and roots; these parts were separately weighed to the nearest gram. Samples of branches representing at least 20% of the total weight or 1 kg of branches were separated into leaves and branches, and these were separately weighed to the nearest gram. This enabled us to calculate fresh weight of roots, trunk, branches, and leaves. Leaves were then mixed, and a random sample of leaves