Ecological Engineering 120 (2018) 504–512

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Reclaimed mine soil substrates and tree stands vs. successional forest floor vegetation: A case study of developing ecosystems on afforested mine sites

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ARTICLE INFO

Keywords:
Mining sites
Afforestation
Plant community
Diversity
Ecological indicator

ABSTRACT

This study presents an analysis of the relationships among tree species, the type of mine soil substrate vs. vegetation development and features of plant communities. The study was conducted on two types of afforested mine sites (open strip sulphur and sand pit mine) built from various parential rocks: mixed quaternary sands and Neogene clays (QsNc) and quaternary loams (Ql). The study plots were arranged in stands of Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver birch (*Betula pendula* Roth) and black alder (*Alnus glutinosa* Gaertn.) from 25 to 35 years old. Tree stand parameter measurements and analyses of soil substrate properties and vegetation characteristics based on phytosociological surveys were done. The diversity expressed as the number of species (S) and Shannon-Wiener index (H), the Simpson dominance index (C) and ecological indicator values of vascular plants (EIVP) were assayed. We hypothesised that in similar substrates (parent rock conditions) the influence of tree stand species in the early phase of reclaimed ecosystem development is significant. Based on the results, we concluded that forest floor vegetation under deciduous species had clearly more herb layer cover and less moss in comparison to vegetation under coniferous species, which confirmed a significant influence only on the level of the ecological group of trees and not at the level of individual tree species. In contrast, the diversity of plant communities was influenced mainly by tree stand species. The highest diversity indexes (H) of communities were under birch and larch, and the lowest H was noted under alder. This phenomenon may be explained by the impact of the alder on soil nitrogen content, which led to the domination of communities by highly competitive species such as *Aegopodium podagraria* L. and *Geranium robertianum* L. on QsNc and *Calamagrostis epigejos* (L.) Roth on Ql. Only EIVP values depended more strongly on soil substrate than tree stand species, and these were only slightly affected by tree stand species composition. Among the tree species, alder significantly increased the value of trophy indicators.

1. Introduction

The reclamation of post-industrial sites is dependent on restoration of their ecological functions. This can be achieved by spontaneous succession or reclamation, e.g., afforestation (Bradshaw, 1997). Studying the floristic differentiation of herb layers under tree stands of woody plant species relates to the habitat-shaping roles of tree species, which are foundational elements of forest ecosystems that determine light availability, microclimate and matter cycling. In this way, the diversity of the dominant tree species in an area determines the biological diversity of understory plant species (Augusto et al., 2003; Barbier et al., 2008; Dölle and Schmidt, 2009; Tinya et al., 2009). The amount of light reaching the forest floor is conditioned by canopy density, which in turn is connected with tree stocking and species features, including the spatial distribution of leaves as well as their size and shape (Barbier et al., 2008). The canopy shape determines not only the amount of light but also the microclimate of the forest interior, especially the humidity and air temperature, thus impacting the conditions for the development of plant communities (Prescott, 2002; Barbier et al., 2008). Tree stands have an impact on the soil-water circulation system by determining the amount of water reaching the forest floor under the canopy and varying the intensity of evapotranspiration (Barbier et al., 2008). Tree species also have different nutrient requirements and compete for them with the forest floor vegetation (Barbier et al., 2008). Another important factor that impacts the characteristics of plant communities emerging under the tree canopy are modifications of pH and the chemical properties of surface horizons, mainly through the changing size and quality of litterfall

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https://doi.org/10.1016/j.ecoleng.2018.07.010
Received 15 May 2017; Received in revised form 5 July 2018; Accepted 9 July 2018

Table 1
Mine site and basic substrate variant characteristics.

	Szczakowa sand quarry	Piaseczno external slope
Latitude	50° 14.394 N	50° 33.622 N
Longitude	19° 25.140 E	21° 34.185 E
Mean annual precipitation (mm; period 2000–2012; mean ± SD; source: https://en.tutiempo.net)	731 ± 121	565 ± 103
Mean annual temperature (°C; period 2000–2012; mean ± SD; source: https://en.tutiempo.net)	8.6 ± 0.6	8.8 ± 0.6
Parent material (substrate variant)	**Ql** Fluvioglacial Quaternary loamy sands and loams	**QsNc** Mixture of Quaternary sands and Neogene Krakowiec Bed formation clays, mudstones from Pecten Bed horizons
Reclamation treatments	Organic amendment addition (300 m^3 ha^{-1} organic horizons from forest soil, approx. From 0.3 to 1.0% organic carbon content); liming (1.5 Mg ha^{-1}); NPK fertilisation (140 kg ha^{-1} N, 130 kg ha^{-1} P, 150 kg ha^{-1} K); 2-years lupine (*Lupinus luteus* L.) cultivation (sowing 240 kg ha^{-1}); planting of tree seedlings (0.7 × 1.5 m spacing; in 1987–88 yr): Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver birch (*Betula pendula* Roth), black alder (*Alnus glutinosa* Gaertn.)	NPK fertilisation (80 kg ha^{-1} N, 50 kg ha^{-1} P, 60 kg ha^{-1} K); 2-year papilionaceous (*Papilionaceae*) plants and grasses cultivation: *Medicago sativa* L., *Lotus corniculatus* L., *Melilotus albus* Medik., *Lupinus polyphyllus* L., *Festuca rubra* L., *Lolium multiflorum* Lam., *Phleum pratense* L.; planting of tree seedlings (0.7 × 1.5 m spacing; in 1977 yr): Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), silver birch (*Betula pendula* Roth), black alder (*Alnus glutinosa* Gaertn.)

(Xiong and Nilsson, 1999; Augusto et al., 2003; Barbier et al., 2008). Sub-canopy precipitation also affects the thickness and properties of litter under the tree stands, which mechanically impedes the development of plant communities (Xiong and Nilsson, 1999; Augusto et al., 2003; Barbier et al., 2008). Additionally, tree species have a biochemical impact on the development of the forest floor vegetation by alleopatic substances released during their decomposition, which inhibits the germination and root development of plants (Souto et al., 2001; Barbier et al., 2008; Mudrák and Frouz, 2012).

In post-mining sites where overburden rocks (bare geological substrates) have been uncovered and deposited at spoil heaps, primary succession occurs and is modified by reclamation treatments and afforestation. Emerging communities of vascular plants grow on soil substrates of different origins and physicochemical properties in the absence of soil organic matter (Bradshaw, 1997; Hüttl, 1998; Schaaf, 2001; Knoche et al., 2002; Brevik, 2013; Pietrzykowski, 2014). In the initial stages of succession at post-mining sites, the main factor modifying the species composition of the plant communities are the soil substrate properties such as pH, organic carbon, nitrogen and phosphate content, and water capacities (Wiegleb and Felinks, 2001). In afforestation, a significant factor modifying the characteristics of plant communities is the tree species composition. During afforestation, climax species for a given zone (such as e.g., oak) may be introduced immediately, omitting earlier stages of succession, or else a larger share of pioneering species (such as Scots pine or birch) may be included (Pietrzykowski, 2014). An afforestation strategy with the introduction of a larger share of alders as a nitrogen-fixing species may also be implemented (Krzaklewski et al., 2012; Pietrzykowski et al., 2015).

Despite the diversity of ecosystems emerging at former mining sites and an opportunity to examine the development processes of plant communities in new areas with no prior history, it has not been demonstrated to what extent the type of soil substrate, the tree species and their interactions impact the features of plant communities in emerging ecosystems on reclaimed mining sites. In studies of vegetation on post-mining sites to date, the focus has mainly been on changes in the community features in the early stages of the succession process (e.g., Prach et al., 2001; Wiegleb and Felinks, 2001; Pietrzykowski, 2008; Prach et al., 2013). There are also comparative studies of communities emerging on reclaimed sites as well as communities where spontaneous succession occurs (e.g., Pietrzykowski, 2008; Mudrák et al., 2010). Pioneering research on the impact of tree species on the characteristics of plant communities was conducted by Mudrák et al. (2010) and Mudrák and Frouz (2012) on a lignite spoil heap in the Sokolov region (the Czech Republic). The authors compared the characteristics of plant communities emerging under birch (*Betula pendula* Roth), larch (*Larix decidua* Mill.), spruce (*Picea omorica* (Pančić) Purk. and *Picea pungens* Engelm.), pine (*Pinus contorta* Dougl. ex Loud. and *Pinus nigra* Arn.), oak (*Quercus robur* L.) and linden (*Tilia cordata* Mill.) stands with communities under birch and great sallow from natural succession on unreclaimed stands (Mudrák et al., 2010). In this previous work, the authors investigated the allelopathic impact of *Salix caprea* L. on the germination and biomass of 3 forest floor species: *Arrhenatherum elatius* (L.) P. Beauv. ex J. & C. Presl, *Plantago lanceolata* L. and *Lotus corniculatus* L. (Mudrák and Frouz, 2012).

The aim of our study was to analyse the relationships between tree species and the type of mine soil substrate with vegetation development and the features of plant communities. We tested the following hypotheses: i) forest floors under coniferous species will display less cover in the herb layer and more mosses than under deciduous tree stands; ii) diversity, species richness and dominance will depend on the dominant tree species; iii) communities under coniferous species will display lower richness and diversity compared to communities under deciduous tree species; iv) the values of vascular plant ecological indicators will depend more on the soil substrate than on tree species; and v) black alder will have the greatest influence on an increase in the trophic indicators compared to other tree species

2. Study sites and methods

2.1. Experimental design

The study was conducted on reclaimed and afforested sites located in southern Poland, i.e.: the spoil heap of the former open strip sulphur mine Piaseczno and sand pit mine excavation Szczakowa (Table 1). According to the Köppen–Geiger climate classification system, the climate of Piaseczno and Szczakowa region is cold without a dry season and with a warm summer (Dfb; Peel et al., 2007). The Piaseczno mine is located near the Wisła River (N 50 33.622 E 21 34.185). In this region, the average annual air temperature is 8.8 °C, and precipitation is 565 mm $year^{-1}$. The Szczakowa sand mine is located in the Upper Silesia Region (N 50 14.394 E 15 25.140). In this region, the mean annual air temperature is 8.6 °C, and precipitation is 731 mm $year^{-1}$ (Table 1).

The research areas were determined using geographic information systems tools (ArcView 10, ESRI Poland). The Piaseczno sulphur mine spoil heap was covered by a regular 50 × 50-m grid of squares. Due to its large size (more than 3000 ha), the Szczakowa sand mine pit grid squares were arranged only on selected parts of the mine excavation within Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua*