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RESEARCH ARTICLE

Evaluation of afforestation development and natural colonization on a reclaimed mine site

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Post-mining restoration sites often develop novel ecosystems as soil conditions are completely new and ecosystem assemblage can be spontaneous even on afforested sites. This study presents results from long-term monitoring and evaluation of an afforested oil-shale quarry in Estonia. The study is based on chronosequence data of soil and vegetation and comparisons are made to similar forest site-types used in forest management in Estonia. After site reclamation, soil development lowered pH and increased N, K, and organic C content in soil to levels similar to the common *Hepatica* forest site-type but P, total C, and pH were more similar to the *Calamagrostis* forest site-type. Vegetation of the restoration area differed from that on common forest sites; forest stand development was similar to the *Hepatica* forest-type. A variety of species were present that are representive of dry and wet sites, as well as infertile and fertile sites. It appears that novel ecosystems may be developing on post-mining reclaimed land in Northeast Estonia and may require adaptations to typical forest management regimes that have been based on site-types. Monitoring and evaluation gives an opportunity to plan further management activities on these areas.

Key words: ecosystem restoration, long-term monitoring plot, oil-shale, reclamation, Scots pine, silver birch

Implications for Practice

- Novel ecosystems developing on post-mining sites are dynamic, changing completely by disturbances or management activities, and their development is not easily predicted. Nevertheless, their functions and composition may serve restoration goals.
- Long-term monitoring and evaluation of restoration of post-mining sites should be linked with planning and implementation of further management activities on these areas.
- In certain cases, spontaneous succession should be considered in restoration of oil-shale post-mining sites as an alternative to common afforestation practice, especially if these sites are small, surrounded by natural vegetation, and there is no specific production goal or time limit for restoration.

Introduction

Classical ecological restoration actions follow the principle of moving an undesired ecosystem state toward the desired, pre-disturbance state that existed historically (Perring et al. 2013). In post-mining sites the challenge in ecological restoration goals is due to the radical difference in physiochemical and biological characteristics of these sites as compared with historical environments (Doley & Audet 2013). The degree of change caused by anthropogenic disturbance is often so severe, that novel ecosystems develop (Hobbs et al. 2006; Mascaro et al. 2013), where combinations of native or non-native species that have not previously occurred at a given site either arise or have been intentionally planted. Novel ecosystem development has multiple factors including invasive species, changes in soil fertility and physical condition, land degradation, environmental change or combinations of these that all interact to alter historical conditions (Hobbs et al. 2009). Novelty is not necessarily undesirable; however, species adapt to anthropogenic disturbances and set ecosystem recovery on a trajectory toward a more favorable end-state (Hallett et al. 2013).

Oil-shale mining has been carried out in Northeast Estonia since 1916 (Kaar et al. 1971). In opencast mining areas, the quaternary sediments and bedrock layers are removed to the depth of the oil-shale sediment layer, generally 5–35 m. After commercial extraction is exhausted, the area is abandoned from mining and a new artificial structure of rocks (waste heaps) and terrain is left behind (Toomik & Liblik 1998). The previous forest ecosystem is significantly destroyed and the surface and underground water regimes are left extensively altered. Afforestation of abandoned mine land has been initiated since 1960 on 13,000 ha sites dominated by calcareous detritus (Kaar 2010).

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Many ecological studies cover the initial stage of stand development on oil-shale quarry afforestation in Estonia (Ostonen et al. 2006; Kuznetsova et al. 2011), but there is lack of studies covering longer time-periods. Lack of monitoring and evaluation is a common challenge in restoration practice, generally limited by 5 years or less (Burton 2014; Mascia et al. 2014), and long-term research is needed to better understand the processes directing successional development of post-mining sites (Hüttl & Bradshaw 2001). Despite a lack of pre-mining data on such sites, it is possible to evaluate the success of restoration treatments by relying on a chronosequence of treated stands to examine developmental trends over time (Foster & Tilman 2000; Stem et al. 2005; Hutto & Belote 2013). Often pre-mining conditions are replaced with reference ecosystems as a baseline to guide restoration or to assess success (Anderson & Dugger 1998).

The objective of this study was to evaluate the restoration of former oil-shale mining sites in Northeast Estonia. Reclamation vegetation that began in the 1960s will be compared to native forest vegetation on similar sites. We examined stand composition and structure, ground flora diversity, and development of soil physical and chemical properties over time. Our first hypothesis is that planting does not always guarantee successful restoration, the second hypothesis is that the diversity of plants and other organisms increases with stand age and with stand heterogeneity after restoration, the third hypothesis is that in the short- and long-term a novel ecosystem has developed in these post-mining restoration sites.

Material and Methods

Study Area

The study was carried out on Aidu quarry (total area is 30 km^2) in Northeast Estonia in the hemiboreal vegetation zone (59°30′N; 27°07′E). The Estonian climate varies from maritime to continental. Average annual precipitation is 707 mm, recorded at the Jõhvi weather station close to the study area. Average annual temperature is 4.7°C (ranging from −6.5°C in February to 16.7°C in July) (Tarand et al. 2013). The pre-mining land use on this area was mainly commercial woodland (dominated by Scots pine, Norway spruce, and silver birch) but also wetland and small-scale agricultural land (Kaar 2010). The average thickness of soil in the woodland was 25 cm before the mining (Leedu 2010). The primary soils were *Eutro-Histic Gleysol* with peat thickness of 25 cm and pH 5.6 and a *Calcaric Luvisol* with soil thickness of 22–27 cm, pH 5.6–6.7, plant available phosphorus of 1.4 mg/100 g, and potassium 4.2 mg/100 g (Leedu 2010). The excavation of oil-shale in Aidu opencast quarry started in 1974 and was finished in 2012. The extent of the oil-shale sediment layer was 0.5–1.5 m, occurring at a depth of 5 m on the north of the mined area and dipping to 30 m in the south. After reclamation, including leveling of the waste materials, the elevation of the area is between 41 and 59 m above mean sea level. In most cases, topsoil was not brought back to the top layer of reclaimed forest sites. Since 1981, the area has been reclaimed with mostly (86%) Scots pine (*Pinus sylvestris* L.) that were planted at an initial density of 5,000–6,700 plants per hectare (Korjus et al. 2007; Kaar 2010).

Experimental Design

The study design used a chronosequence approach; plots were randomly located within stands. Sixty plots were established in 2011 in stands that were 12–33 years old (9 plots were between the ages of 12 and 15, 5 plots between 15 and 20, 18 plots between 20 and 25, 19 plots between 25 and 30, and nine plots between 30–33 years) to examine differences in characteristics at three levels: (1) forest stand at tree level (stand structure and species composition); (2) ground layer vegetation (moss, grass and shrub layer species, and their abundance); (3) soil (structure, texture, organic layer development, pH, and concentrations of K, P, N, organic C and total C). Although all monitoring plots were initially reclaimed using Scots pine, eight sample plots were replaced by silver birch (*Betula pendula* Roth.) that seeded in naturally. The other 52 monitoring plots are dominated by Scots pine. Three monitoring plots were established in every stand in order to estimate variation in the stand.

Sampling Methods

We used the methodology of the Estonian Forest Research Plots Network (Sims et al. 2009) for the design of the monitoring plots. Plots were circular with a radius of 15 m. On each plot the azimuth and distance from plot center to each tree (both live and dead) were recorded and damage on each tree was noted; diameter at breast height (1.3 m DBH) was measured on all stems (DBH > 4 cm) on 54 plots that had attained sufficient height (over 1.3 m). In young stands (six plots) there were many trees below 1.3 m in height and we measured height for every tree and DBH wherever possible. For every fifth tree in all plots, total height and height to crown base were also measured. We took tree cores from at least five trees in every stand to determine age of average trees.

Ground layer vegetation was sampled in subplots located within the monitoring plots, four subplots per site. Altogether 240 vegetation subplots were described. On these 1 × 1 m plots all woody plants, vascular plants, and mosses were recorded following the Braun-Blanquet scale. Nomenclature and designation by habitat preference as forest, meadow, or forest/meadow species groups follows Ingerpuu and Vellak (1998) for mosses and Leht (2010) for vascular plants. Understory plants were divided into four groups by degree of anthropogenic impact or hemeroby. We used Kukk and Kull (2005) classification defining the ability of a species to survive and develop on habitats with a specified level of tolerance to anthropogenic impact: anthropophytes tolerate severe disturbance, apophytes will tolerate a moderate level of disturbance, hemeradiaphores will be present after little disturbance, and hemerophobics are indicative of no anthropogenic impact.

In each plot, soil conditions were characterized. The depth to rock was measured by the re-bar method, where a metal rod was inserted at 13 points per plot, through the surface soil until impeded by the unconsolidated rock. Stoniness for each plot was calculated using a model developed by Laarmann et al. (2011). The depths of the organic layer and surface mineral soil were recorded at each point.

A composite mineral soil sample (to a depth of 10 cm) was taken from each plot, air dried, and analyzed. Total nitrogen and carbon content were determined by dry combustion method on a varioMaX CNS elemental analyzer (ELEMENTAR, Hessen, Germany). Soil organic carbon was determined with Tjurin's method (Vorobjova 1998), the pH values were determined by extraction using potassium chloride, the concentrations of available phosphorus was extracted in ammonium lactate and measured by flow injection analysis and available potassium was measured with a flame photometer (Ruzicka & Hansen 1981).

Data Analysis

Species richness and Shannon-Wiener diversity index were estimated for all plots using PC-ORD ver.6 software. Species richness was defined as number of different species per plot. Soil, stand, and understory data were ordinated using Detrended Correspondence Analysis (DCA). If the length of a variable's variation gradient was relatively short (<2 SD), then Principal Component Analysis (PCA) was used. Differences among the stands of the two main tree species (pine and birch) were tested using the Multi-Response Permutation Procedure (MRPP).

For ordination of understory data we used Non-Metric Multidimensional Scaling (NMS) for pine stands; there was insufficient age variation in the birch stands to examine understory development over time. NMS is an ordination technique based on ranked similarities of species composition suitable for community data that may not be normally distributed or fit assumptions of linear relationships among variables. We used the Sorensen distance measure with a log transformation on species abundances. We used the "autopilot" option on "slow and thorough" and a Monte Carlo randomization test was applied on the stress scores. Pearson correlations with ordination axes for all quantitative variables were calculated separately for each.

To verify the hypothesis of novel ecosystem development, we needed to compare soil variables and understory species and their composition in the research area to undisturbed forest site-types with similar bedrock conditions (alkaline) to the study area. These forest site-types functioned as generalized reference stands. The site-types that correspond to conditions in the study area were *Hepatica*, *Calamagrostis*, and *Arctostaphylos* according to the classification of Estonian forest site-types (Lõhmus 2006). *Hepatica* site-type is on the fresh fertile calcareous soils and dominated by nemoral mixed forests, *Calamagrostis* site-type is dryer and less fertile alvar forest type dominated by pure and mixed conifer forests, *Arctostaphylos* site-type is dry and poor alvar forest site type dominated by pure Scots pine forests. Indicator species of these three site-types were taken from the literature (Lõhmus 2006; Paal et al. 2009) and species did not belong were classified as "others." For comparing tree height and diameter of measured planted pine trees with data of regular forest types, we used forest inventory data from the database of the Estonian Forest Registry. From the database we selected a total of 2,140 managed Scots pine stands from *Hepatica* (1,111 stands), *Arctostaphylos* (973 stands), and *Calamagrostis* (64 stands) forest site-types (Lõhmus 2006), with stand mean age from 1 to 39 years.

A generalized additive model (GAM) estimation method was used for comparing measured plot data with forest inventory data (Hastie & Tibshirani 1990). On the basis of forest inventory data a diameter model was created:

$$D = s(A) + s(H) \tag{1}$$

where D is stand quadratic mean diameter, A is stand mean age, H is stand mean height, and $s(H)$ is a spline function in GAM.

The quadratic mean diameter for sample plots was estimated with the model and a paired t-test used to test for differences between measured and estimated diameters at a significance level of $p < 0.05$.

Results

Stands and Site Characteristics

Site development of spontaneously regenerated birch stands differed from afforested pine stands. The thickness of the surface mineral soil layer was significantly different and thicker under the birch stands ($p < 0.001$); the average soil depth in pine stands was 6.7 ± 0.6 cm and in birch stands it was 37.61 ± 3.0 cm (Table 1). According to the PCA, birch stands are clearly and significantly different from pine stands in the ordination plot (MRPP, $t = -11.75$, $p < 0.001$) (Fig. 1). The first ordination axis most closely represented a gradient of fine soil thickness, from a very thin soil layer on the left side of the diagram to a thicker layer on the right ($r = 0.92$, $p < 0.001$). The gradient was negatively correlated with the stoniness and pH level. The second ordination axis represented a gradient of stand age, with younger stands at the top of the diagram and older stands at the bottom ($r = -0.86$, $p < 0.001$).

The content of soil nitrogen (N) is significantly higher in older pine stands than in younger stands ($p < 0.001$) (Fig. 2), but still remains lower than the nitrogen level of birch stands (Table 1). The soil phosphorus (P) level is also lower in young stands and significantly higher in older stands ($p < 0.001$), reaching up to 40 mg/kg and the mean P level differed significantly between pine and birch stands ($p < 0.001$). Soil pH was higher in young pine stands and soil acidity increased with age ($p < 0.001$). We did not find significant differences between total carbon or potassium content among stands of different ages ($p = 0.317$, $p = 0.176$, respectively) (Fig. 2).

Vegetation

All together we found 98 herbaceous plants, 32 moss, and 11 woody species. Most of these herbaceous species are classified as apophytes. Two of the species sampled (*Tragopogon pratensis* and *Melilotus albus*) and are classified as anthropophytes according to Kukk and Kull (2005). There were two hemerophobic species *Orthilia secunda* and *Monotropa hypopitys*. We

Table 1. Summary of measured soil variables, vegetation community, and stand characteristics according to stand age and main species; mean values and standard errors (in parentheses) are presented (p values are for comparison between all pine and birch stands * 0.05, ** 0.01, *** 0.001).

Variable	*Pine stands (12–15 years)*	*Pine stands (22–26 years)*	*Birch stands (22–26 years)*	*Pine stands (30–33 years)*	p
Soil properties					
Fine soil thickness (cm)	5.3 (0.6)	6.2 (1.2)	38.5 (2.4)	6.4 (0.6)	***
Organic layer thickness (cm)	0.2 (0.1)	1.5 (0.2)	3.1 (0.3)	1.9 (0.2)	***
C total (%)	8.20 (0.91)	8.50 (0.82)	6.14 (0.73)	10.01 (0.9)	**
C organic (%)	4.37 (0.25)	4.38 (0.22)	5.96 (0.71)	5.18 (0.27)	**
N total (%)	0.07 (0.01)	0.10 (0.01)	0.22 (0.03)	0.15 (0.01)	***
K available (mg kg^{-1})	81.16 (6.44)	86.01 (5.44)	77.94 (5.17)	94.80 (6.18)	
P available (mg kg^{-1})	9.80 (1.29)	24.23 (4.58)	67.23 (11.8)	38.38 (4.44)	***
pH_{KCl}	7.68 (0.03)	7.58 (0.03)	7.02 (0.12)	7.43 (0.03)	***
Sand, 2–0.05 mm (%)	47 (3.5)	58 (2.3)	70 (2.2)	61 (2.2)	***
Silt, 0.05–0.002 mm (%)	38 (2.9)	29 (1.8)	20 (1.8)	26 (1.7)	***
Clay, <0.002 mm (%)	14 (0.8)	13 (0.7)	10 (0.6)	12 (0.7)	**
Stoniness (%)	70 (0.0)	69 (1.0)	34 (2.6)	68 (0.0)	***
Vegetation					
Herb richness	10 (0.7)	12 (0.9)	10 (0.7)	17 (2.2)	*
Mosses richness	3 (0.2)	4 (0.4)	2 (0.3)	6 (0.8)	**
Herb cover (%)	36 (3.9)	27 (3.2)	59 (6.0)	21 (5.2)	***
Moss cover (%)	26 (4.6)	39 (6.2)	9 (3.2)	61 (10.6)	**
Herb diversity by Shannon	0.67 (0.12)	0.71 (0.08)	1.00 (0.10)	1.04 (0.15)	
Moss diversity by Shannon	0.38 (0.05)	0.48 (0.07)	0.11 (0.06)	0.78 (0.11)	***
Stand characteristics					
Share of deciduous species (%)	5 (2.5)	9 (3.9)	99 (0.8)	10 (3.8)	***
Stand height (m)	3.6 (0.4)	7.1 (0.6)	15.3 (0.9)	10.4 (0.6)	***
Mean stand diameter (cm)	4.4 (0.6)	8.1 (0.8)	13.3 (0.8)	11.4 (0.8)	***
Basal area (m^2 ha^{-1})	3.6 (0.9)	12.5 (1.8)	16.6 (1.1)	17.7 (2.3)	
No. of trees (ha^{-1})	2210 (245)	2500 (182)	1350 (284)	1930 (336)	**
No. of dead trees (ha^{-1})	4 (3.5)	14 (7)	158 (35)	39 (28)	***

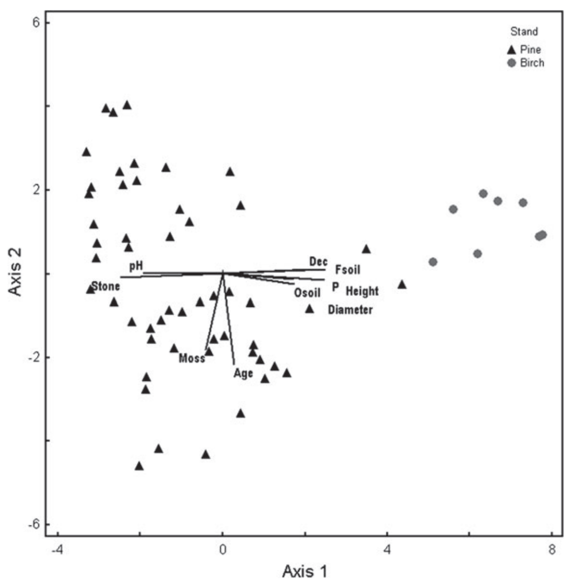

Figure 1. Ordination of plots by soil and stand variables. PC1 (37% of variance, $p = 0.001$) and PC2 (16% of variance, $p = 0.001$). The cut-off for vectors is R^2 of 0.5. Dec, share of deciduous trees in stand; Fsoil, fine soil layer thickness; P, content of soil phosphorus; Height, mean stand height; Diameter, mean stand diameter; Osoil, soil organic layer thickness; Age, stand age, Moss; mean richness of bryophytes; Stone, stoniness; pH, pH_{KCl}. Stands are represented by symbols: triangles, pine stands, circles, birch stands.

found three threatened herbaceous species: *Epipactis helleborine*, *Goodyera repens*, and *Dactylorhiza fuchsii*.

Our results showed that occurrence and cover of species increased with stand age. The average species richness of herbs on pine plots was 13 and 10 on the birch plots ($p = 0.05$). The highest species richness (32 species) occurred on a 32-year-old pine plot. Moss richness was almost three times higher on pine plots than on birch plots ($p = 0.001$). The average cover of herbs was significantly greater on birch plots (59%) than pine plots (27%) ($p < 0.001$). The moss cover showed an opposite result, with cover on pine plots four times higher than birch plots ($p = 0.001$). Pine and birch stands differed by herbaceous species composition (MRPP, $t = -17.71$, $p < 0.001$), but not by Shannon index ($p = 0.29$). Herbs species composition (Shannon index) was different by age on pine stands ($F = 14.88$, $p < 0.001$), but did not differ on birch stands ($p = 0.11$). Pine and birch stands differed by moss composition (MRPP, $t = -11.86$, $p < 0.001$) and by moss diversity index ($p < 0.001$); the average Shannon index on pine stands is 0.55 ± 0.10 and on birch stands 0.11 ± 0.02. The Shannon index differed by age on pine stands ($F = 10.34$, $p = 0.002$), but did not differ on birch stands ($p = 0.31$).

Comparing the species found on sample plots with the site-types indicator species based on similarity of bedrock condition, 68% of vascular species on the plots were not characteristic to the studied site-types (Fig. 3, Table S1, Supporting

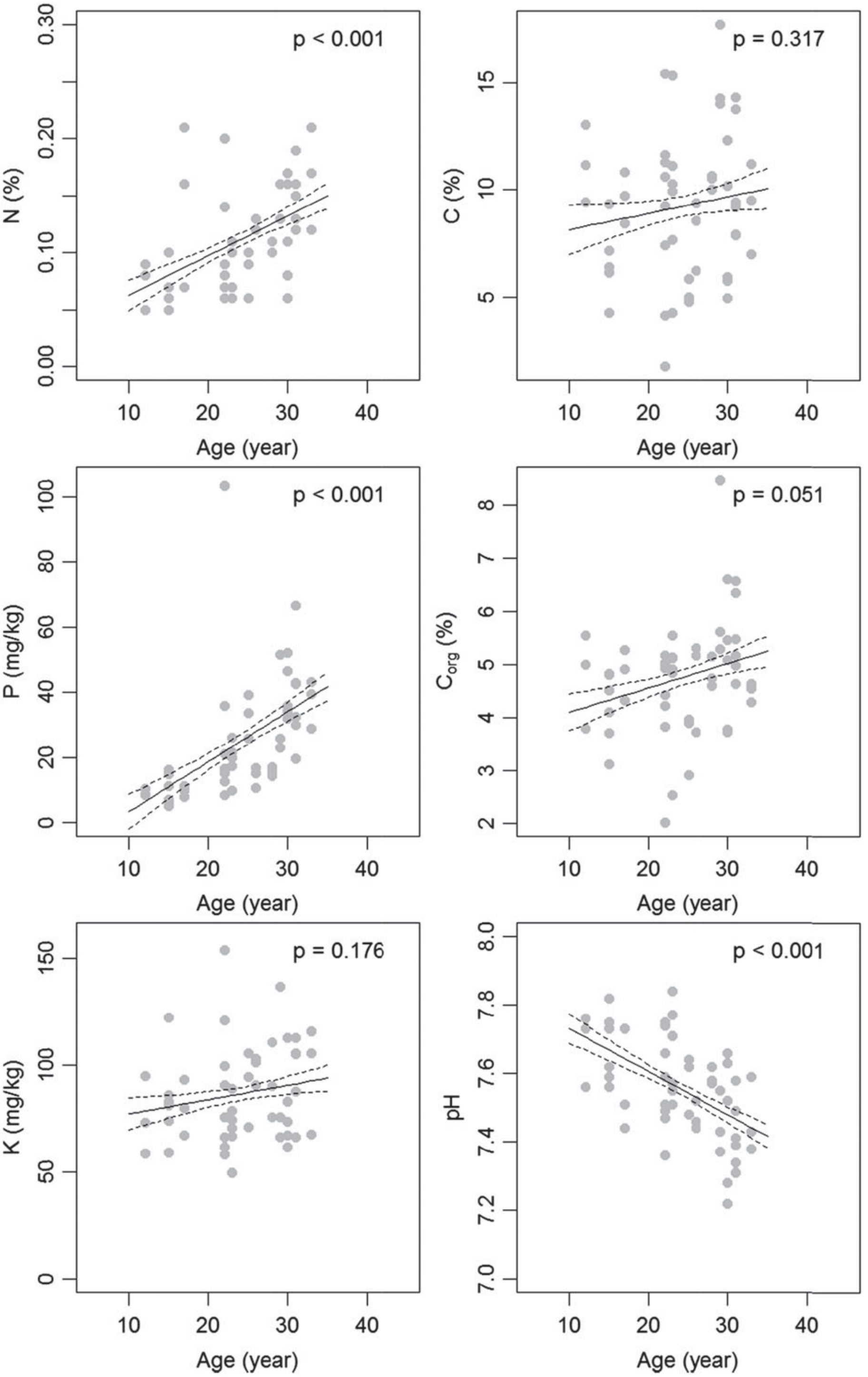

Figure 2. Changes in soil chemistry through time according to chronosequence data. Each dot represents one pine plot, mean value of pine plots is given by solid line and 95% confidence limits by the dashed lines.

Information). More species were indicators of the *Hepatica* site-type than the other types.

The best solution of NMS in the analysis of the composition of understory species in pine stands was 3-dimensional (final stress 15.9, number of iterations 92). Three axes described 78% of the variance (Axis 1, 23% and Axis 2, 35%). The variation of the data along the first axis is mainly determined by stand age ($r = 0.79$, $p < 0.001$); also significant were the relation with stand height (0.56, $p < 0.001$) and coverage of vascular plants ($r = -0.53$, $p < 0.001$). The gradient directed

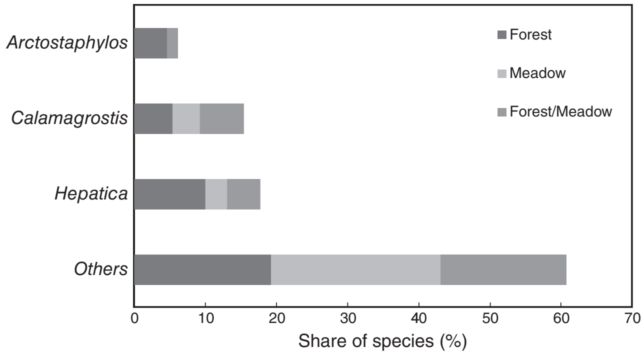

Figure 3. Distribution of all understory species according to forest site-type and habitat preference group.

along the second ordination axis was mainly related to stand basal area ($r = 0.64$, $p < 0.001$), soil organic layer ($r = 0.55$, $p < 0.001$), pH ($r = -0.46$, $p = 0.001$), Shannon index of moss ($r = -0.43$, $p = 0.002$), and stoniness ($r = -0.32$, $p = 0.02$). All species groups scattered along the first axis, whereas the positive side of Axis 2 represented more forest species and the bottom side contained more meadow species.

Species richness increased significantly with stand age (Fig. 4). The greatest increase was in the forest species group. Meadow species richness was higher than forest/meadow species richness. Height and diameter in pine stands showed strong relationships with stand age (Fig. 5). Data of tree height and diameter were not significantly different from the *Hepatica*-type forest ($t = -1.474$, $p = 0.146$) and was significantly different from the *Arctostaphylos* ($t = -3.10$, $p < 0.001$) and the *Calamagrostis* ($t = -6.70$, $p < 0.001$) site-types.

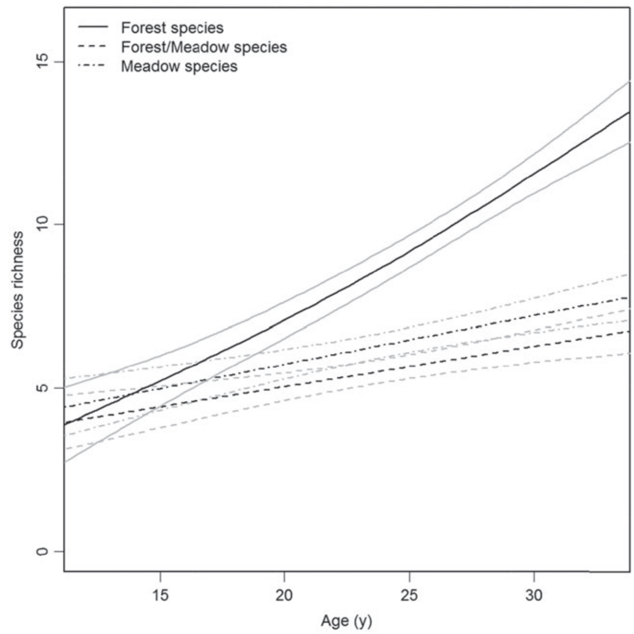

Figure 4. Relationship between stand age and species richness of understory vegetation in pine stands.

Discussion

A common outcome of post-mining restoration is a novel ecosystem that is characterized by new species combinations resulting from human intervention (Hobbs et al. 2006). Novel ecosystems may be more diverse than natural communities and may offer suitable habitat for threatened and protected species (Richardson et al. 2010). We evaluated whether the vegetation communities that develop on restored mined land in Northeast Estonia represent novel communities by comparing them to common forest conditions based on representative Scots pine site-types. The N, K, and organic carbon levels in soil are significantly similar to those found in soil of the *Hepatica* site-type, whereas P, total C, and pH levels in soil are more similar to the *Calamagrostis* site-type. Soil development and nutrient levels in reclaimed mined land differ from soils of common forest site-types and therefore formed unique conditions for vegetation development. The vegetation community is also distinctively different from vegetation on common forest site-types. Pine growth on the reclaimed sites is comparable to the *Hepatica* site-type (Fig. 5) and significantly different from the other site-types. Similarly, more understory species are indicators of the *Hepatica* site-type than the other types.

The goal of reclamation cannot be achieved if soil functionality is not restored (Chodak et al. 2009). Soil formation processes depend on initial conditions; commonly there is an extremely low organic matter component, which affects fertility, biological activity, and moisture relations and can suppress germination and growth of seedlings. This study used the chronosequence approach (Hutto & Belote 2013) and a quasi-experimental design lacking a true control (Anderson & Dugger 1998; Stem et al. 2005) to evaluate reclamation of oil-shale quarries in Northeast Estonia. Bodlák et al. (2012) pointed out that soil organic carbon provides information on the quality of the reclaimed post-mining area. In our study, soil organic carbon content significantly increased with stand age but total carbon had no correlation with stand age because of the mineral carbon content of the rocks and detritus. Weathering of oil-shale and calcareous detritus gradually releases nutrients and topsoil thickness increases with stand age (Kaar et al. 1971). Our results show strong relationships among stand age and soil properties (pH, nitrogen content, and phosphorus concentration), whereas pH decreased and P and N increased with stand age. Soil variables such as pH, organic carbon and phosphate levels, and water holding capacity influence species composition but it is not always clear how this influences vegetation colonization (Wiegleb & Felinks 2001). Broadleaf litter contains more nutrients and decomposes faster than conifer litter and this strongly influenced the nature of the ground vegetation.

There were differences in soil variables between birch and pine stands. Species composition of the canopy is known to influence soil variables as a result of litter type (Prescott 2002). Some differences could result from stand and soil development over time. Indeed, pH decreased in our stands in relation to age, from a pH of 8.0 in the initial post-mining stage

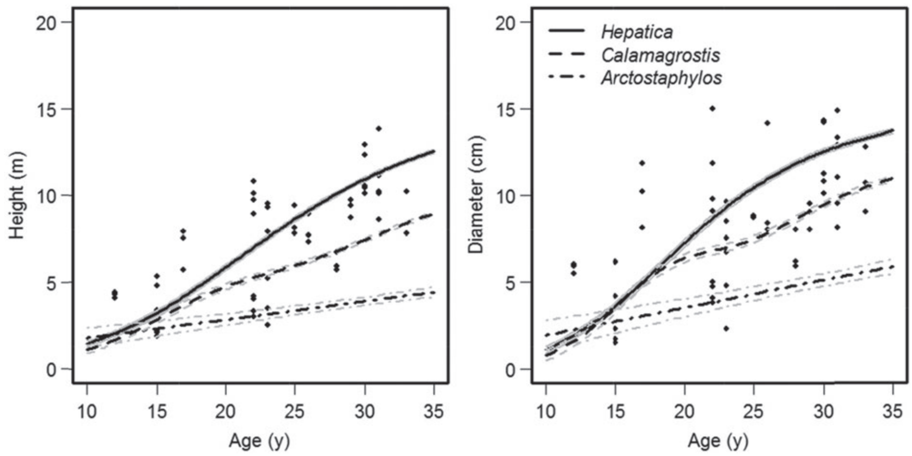

Figure 5. Relationship of stand height and diameter with stand age in pine stands. Dots are plots in the current study, lines show trends by forest site-type using the GAM model.

(Kuznetsova et al. 2011). To be sure, we compared pine and birch stands of similar age; we found large differences between pine and birch stands in terms of relatively slow-changing physical characteristics such as fine soil thickness, stoniness, and texture. More labile chemical characteristics closely related to organic matter inputs such as thickness of the organic layer, organic C percentage, and total N percentage also differed between the two overstory types, indicating that spontaneous succession (colonization by birch) and afforestation (planted pine) had different impacts on soil dynamics.

The reclamation approach that began in former Soviet times followed a simple revegetation paradigm (Stanturf et al. 2014) and focused on establishing a forest cover using *P. sylvestris*; this species was readily available, easy to establish in calcareous soils, and had economic value, which resulted in its extensive use (Kaar 2002). A question that arises is whether the cost of intervention (e.g. afforestation) is worthwhile, or does the natural revegetation process result in ecosystem recovery. For example, reliance on natural recolonization has been successful in some quarry reclamations (Prach & Pyšek 2001). One advantage of active restoration is usually there is a faster formation of continuous vegetation cover than a passive approach that relies on spontaneous succession (Prach & Hobbs 2008). If a goal is to restore productivity, as it was in the Soviet era when reclamation began, then afforestation is a preferred approach. Reclaimed mined land may present heterogeneous substrate conditions, however, and relying on a single planted species is risky if the planted species is not adapted to all site conditions. Risks include lower growth, higher mortality, and greater potential for disease or invasive species (Martinez-Ruiz et al. 2007). In some cases, spontaneous succession may be preferable; especially in smaller disturbed sites surrounded by natural vegetation that provides a seed source and if there is no specific species composition or productivity goal. Another advantage of the passive approach may be that spontaneous succession results in a more natural condition, which may be more important than future productivity of the disturbed site (Hodačovà & Prach 2003; Prach & Hobbs 2008).

An early failure of the reclamation treatment (planted pines died because of unknown reasons) and subsequent recolonization by *Betula* in one area provided an opportunity to examine whether we had a “counterfactual” treatment (Ferraro 2009), that is, a “no-treatment” or natural succession treatment (Prach & Pyšek 2001; Mascia et al. 2014). A counterfactual treatment would allow a comparison between active (afforestation) and passive (natural recolonization) approaches to reclamation. Our study lacked a true counterfactual treatment although early mortality of the planted Scots pine in some areas resulted in colonization by birch from natural populations nearby. The failure of the planted pine may have had some impact on the soil and site conditions so that the starting conditions of the substrate were not the same. And there may be also the issue of time and soil development, although the birch came to the site soon after afforestation. It is also possible that the planting did something positive (e.g. mycorrhizal inoculation) that allowed birch colonization. Just because the birch established successfully following pine mortality, there is no guarantee that the birch will achieve commercial size. The significant differences in soil physical characteristics between pine and birch stands argues that the sites are different; quite possibly another species, better adapted than birch to these site conditions, may have been planted that would have achieved both productivity and diversity restoration goals. Thus, we did not have a valid test of passive versus active approaches. Nonetheless, continuous cover was obtained and a diverse understory developed, different from that under pine; which may meet current goals of biodiversity restoration.

The goal for biodiversity restoration is never just increasing the total number of species (Prach & Hobbs 2008) as alien and ruderal species are often undesirable especially in long-term (they can change ecosystem structure and function) and forest and meadow species are more desirable in forest ecosystem restoration. We found a combination of meadow and forest species, but also ruderal species and pioneer species were represented. Dynamics of meadow, forest/meadow, and forest species are expected to shift in favor of forest species through time (Verheyen et al. 2003; Soo et al. 2009). We found that the share of forest species is increasing, as well as the number of meadow, forest/meadow, and forest species. This is surprising because meadow species should be declining with increasing stand age. The diversity of site conditions was apparent; when considering the preferences for dry and wet habitats, then species specific to both habitat types were present as well as species characteristic of both poor and fertile site types. Many sites offer unique environments for threatened and endangered species, and Prach et al. (2011) pointed out that sites exhibiting spontaneous succession may act as habitat for endangered species, while active restoration of reclaimed sites may favor common species with broad amplitudes over species with narrow habitat requirements. We found, however, three protected species in the actively restored pine stands, suggesting caution in generalizing that species with narrow amplitude are favored by passive approaches.

On balance, we suggest that indeed, novel ecosystems are developing on post-mining reclaimed land in Northeast Estonia and may require adaptations to typical forest management regimes that are based on site-types. Long-term monitoring of a novel ecosystem is important in order to study restoration pathways and determine if additional restoration measures are to be taken if the outcome is not desirable (e.g. low structural diversity on stand level, alien species invasion, etc.) (Laarmann et al. 2013). Long-term monitoring also provides feedback and information for better planning of restoration activities at new sites.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Species list. Common habitat type is designated as F-forest, M-meadow, and FM forest/meadow species; forest site type (by Lõhmus 2006) is shown as H-*Hepatica* type, A-*Arctostaphylos*, C-*Calamagrostis* site type; dynamics are indicated as A-ascending with stand age (cover and abundance increased), D-decreasing, S-same with age; stands are identified as P-pine, B-birch, PB-species occur in both stands; * – single occurrence.

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