

**PLANTATIONS OF NATIVE AND INTRODUCED
TREE SPECIES IN THE RECLAMATION
OF OIL SHALE POST-MINING AREAS**

**KODUMAISTE JA VÕÕRLIIGILISTE PUISTUTE KASV
PÕLEVKIVIKARJÄÄRIDE TASANDATUD PUISTANGUTEL**

TATJANA KUZNETSOVA

A Thesis
for applying for the degree of Doctor of Philosophy in Forestry

Väitekirj
filosoofiadoktori kraadi taotlemiseks metsanduse erialal

EESTI MAAÜLIKOOL
ESTONIAN UNIVERSITY OF LIFE SCIENCES

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following papers, referred to by their Roman numerals in the text.

- I** **Kuznetsova, T.**, Rosenvald, K., Ostonen, I., Helmisaari, H.-S., Mandre, M., Lõhmus, K. 2010. Survival of black alder (*Alnus glutinosa* L.), silver birch (*Betula pendula* Roth.) and Scots pine (*Pinus sylvestris* L.) seedlings in a reclaimed oil shale mining area. *Ecological Engineering*, 36(4), 495–502.
- II** Lõhmus, K., Truu, J., Truu, M., Kaar, E., Ostonen, I., Alama, S., **Kuznetsova, T.**, Rosenvald, K., Vares, A., Uri, V., Mander, Ü. 2006. Black alder as a promising deciduous species for the reclaiming of oil shale mining areas. In: Brebbia, C.A., Mander, Ü. (Eds.). *Brownfields III. Prevention, Assessment, Rehabilitation and Development of Brownfield Sites*. WIT Transactions on Ecology and the Environment, Vol. 94. Southampton, Boston: Wessex Institute of Technology Press, pp. 87–97.
- III** **Kuznetsova, T.**, Lukjanova, A., Mandre, M., Lõhmus, K. 2010. Aboveground biomass and nutrient accumulation dynamics in young black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas in Estonia. *Forest Ecology and Management*. doi:10.1016/j.foreco.2010.09.030.
- IV** **Kuznetsova, T.**, Mandre, M. 2006. Chemical and morphological indication of the state of lodgepole pine and Scots pine in restored oil shale opencast mining areas in Estonia. *Oil Shale*, 23(4), 366–384.
- V** **Kuznetsova, T.**, Tilk, M., Pärn, H., Mandre, M. Growth, aboveground biomass and nutrient concentration of young Scots pine and lodgepole pine in oil shale post-mining landscapes in Estonia (submitted to *Environmental Monitoring and Assessment*).
- VI** **Kuznetsova, T.**, Mandre, M., Klõšeiko, J., Pärn, H. 2010. A comparison of the growth of Scots pine (*Pinus sylvestris* L.) in a reclaimed oil shale post-mining area and in a *Calluna* site in Estonia. *Environmental Monitoring and Assessment*, 166(1-4), 257–265.

- VII Kuznetsova, T.**, Tilk, M., Ots, K., Lukjanova, A., Pärn, H. 2009. The growth of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in a reclaimed oil shale mining area, abandoned agricultural land and forestland. *Baltic Forestry*, 15(2), 186–194.

The contribution of the authors to the papers was as follows:

	I	II	III	IV	V	VI	VII
Original idea	TK, MM, KL	KL	All	All	TK, MT, HP	TK, JK	TK
Study design	TK, MM, KL	KL	All	All	TK, MT	TK, JK	TK
Data collection	TK, KR, KL	All	TK, AL, KL	TK	TK, MT	TK, JK, HP	All
Data analysis	All	All	All	TK	TK, MT	All	TK
Manuscript preparation	All	KL	All	All	All	All	All

AL – Aljona Lukjanova; HP – Henn Pärn; JK – Jaan Klõšeiko; KL – Krista Lõhmus; KR – Katrin Rosenvald; MM – Malle Mandre; MT – Mari Tilk; TK – Tatjana Kuznetsova; All – all authors of the paper

ABBREVIATIONS

B	Aboveground biomass
CAP	Current annual production
DBH	Diameter of the stem at breast height
D	Diameter at root collar
D_{SR}	Short root diameter
H	Height of trees
RR	Root ratio
FR/R	Fine root ratio
L/FR	Foliage/fine root ratio
SRL	Specific root length
SRA	Specific root area
RTD	Root tissue density
L	Short root length
W	Short root mass
NUE	N use efficiency
PUE	P use efficiency

1. INTRODUCTION

Mining activities, especially opencast mining, create significant areas of degraded land that need restoration. The goal of restoration is usually to develop a long-term sustainable ecosystem native to the area where mining occurred (Chambers *et al.*, 1994). The restoration of post-industrial landscapes is often a challenge regarding multifunctional land use issues (Haines-Young *et al.*, 2006). On the other hand, restoration provides several opportunities for the optimal use of landscape functions (de Groot, 2006). By the year 2006 the area damaged by oil shale opencast mining in Northeast Estonia was 13,098 ha, of which 10,347 ha had been afforested (Kaar and Tomberg, 2006). The opencast oil shale mine sites are characterized by unfavourable conditions: heterogeneity, stoniness up to 100%, limited moisture, low nitrogen and organic content of mining spoil, and inhibited phosphorus uptake due to high pH (~8). Since agricultural use of post-mining landscapes is made difficult by the heterogeneity of the soil and by poor moisture conditions, their afforestation is more suitable (Kaar, 2002; Lõhmus *et al.*, 2006; **II**). Afforestation is a sustainable reclamation option for post-mining landscapes (Parrotta *et al.*, 1997; Filcheva *et al.*, 2000; Singh *et al.*, 2002; Dutta and Agrawal, 2003; Lõhmus *et al.*, 2006; Pietrzykowski and Krzaklewski, 2007) to reduce CO₂ emission and to create renewable energy sources. For a long time Estonian oil shale mining areas have been “research laboratories”, where large-scale investigations have been conducted to find out most suitable tree species for restoration (Kaar *et al.*, 1971). Results of previous research (Kaar, 2002) of restoration of post-mining areas in Estonia showed that new stands are of better quality than the stands that grew there before mining. A total of 52 indigenous and introduced species have been used for restoration. Various introduced larch species (*Larix europaea*, *L. sibirica*, *L. kurilensis*) have shown the best growth among coniferous trees, and the native deciduous species of silver birch (*Betula pendula* Roth.) and black alder (*Alnus glutinosa* (L.) Gaertn.) have been the most productive deciduous trees (Kaar, 2002; Kuznetsova and Pärn, 2004; Lõhmus *et al.*, 2007). Despite successful restoration, it should be noted that so far a disproportionately large proportion of Scots pine (*Pinus sylvestris* L.) (86% of the afforested area) has been planted (Kaar, 2002; **II**). Moreover, the opencast mining in Northeast Estonia has been moving toward areas with deeper excavation (Kaar, 2002; Korjus *et al.*, 2007) and the quality of the substrate has declined and its stoniness has

increased due to the thickening overburden in new mining areas. These harsh growing conditions might limit the growth and survival of different tree species at different rates, and hence the reasonable choice of tree species for the reclamation of levelled opencast mines will be even more important in the future.

To reduce the large proportion of Scots pine monocultures and in the interests of biodiversity, a possible species for restoration could be lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), which is known as rather tolerant to high soil pH and nutrient deficit in soil (Weetman *et al.*, 1985). Native species are successful in plantations on post-mining areas (Shepherd, 1994; Butterfield, 1996), but still fast-growing exotic species are often preferred (Ang, 1994; Shepherd, 1994). Fast-growing exotic species are reported to show faster growth than native species on degraded land during the initial couple of years of establishment (Parrotta, 1999). Dutta and Agrawal (2003) concluded that exotic species may be recommended for primary rehabilitation on coal mine spoil due to their fast growth and development. The results from Lusatian lignite mining region in Germany indicate that black pine (*Pinus nigra* Arn.) may be a better choice for reforestation of post-mining landscapes than Scots pine (Baumann *et al.*, 2006). Investigations in Sweden showed that the fast growth rate of lodgepole pine makes it capable of suppressing slower growing species such as Scots pine and Norway spruce (Despain, 2001).

For successful forestation and stability of plantations, the proportion of deciduous trees in the new stands should rise to 40–60%. Deciduous species have a number of advantages: increased N and P availability in the soil, faster growth at young age and higher resistance to pests, diseases and fires in comparison with conifer monocultures (Kaar, 2002; Vares *et al.*, 2004; II). Although Scots pine is mostly a stress-tolerator (Grime, 1979) broadleaf species seem to yield better results than conifers (Parrotta *et al.*, 1997). Black alder could be considered to be a “biological fertilizer”, which improves soil nitrogen status, fixing N₂ in symbiosis with *Frankia* in its root nodules and increases phosphorus availability in soil by the activity of its roots and associated microbial communities (Giardina *et al.*, 1995; Uri *et al.*, 2002). However, the potential of different tree species for the reclamation of exhausted opencast oil shale mines in relation to biomass production, nutrient accumulation and use efficiency and fine-root adaptations in opencast oil shale mining areas is still poorly investigated. The morphology of trees is used in monitoring to evaluate the state of

trees in areas under human impact (Озолинчюс, 1996). Needle analysis has often been used as a diagnostic method of describing the nutritional status of trees (Brække, 1996) as well as biomass increment and growth conditions of trees (Niinemets *et al.*, 2002). The success of the restoration of damaged areas has been assessed by evaluating the growth and biomass production of various plants (Kumar *et al.*, 1995; Singh and Singh, 1999). Fine root adaptations are among the key factors determining the growth rate and performance of species. Morphological plasticity of fine roots has been proposed as a mechanism by which plants respond to variation in soil nutrient supply (Lõhmus *et al.*, 1989; Ostonen *et al.*, 1999; Hodge, 2004). Alterations in fine-root morphological traits reflect exploitation of water and nutrients in the soil (Fitter, 1996) as well as the cost/benefit ratio of the fine-root system (Ostonen *et al.*, 2007). Previously it has been found that the higher growth rate of black alder corresponds to the higher activity of microbial communities in its rhizosphere and to the higher specific root area of short roots compared to conifers (Vares *et al.*, 2004; Lõhmus *et al.*, 2006; Ostonen *et al.*, 2006). Moreover, Vares *et al.* (2004) found the aboveground productivity in a 21-year-old black alder plantation on reclaimed oil shale mining area to be comparable with that of the stands of the same age growing on fertile mineral soils.

This doctoral thesis presents the results from the investigation of plantations of native black alder, silver birch and Scots pine and of introduced lodgepole pine on reclaimed oil shale mining areas. The survival, growth, biomass, nutrient accumulation and fine root adaptations were investigated to assess the suitability of the studied species for the reclamation of post-mining areas. Species having higher growth rates and biomass production and increasing soil fertility faster are considered to be more suitable for speedy restoration of degraded lands. Our findings are important for a better understanding of the development of stands and allow giving recommendations concerning the species suitable for the reclamation of exhausted oil shale mining areas taking into account ecological and economic factors. The approaches of this study can be used for other regions where alkaline wastelands require reclamation.

2. REVIEW OF THE LITERATURE

2.1. Reclamation of post-mining landscapes

Vast areas of land all over the world have been rendered unproductive by human activities. Post-mining landscapes following opencast mining are examples of large-scale land transformation (Pietrzykowski and Krzaklewski, 2007). Strip-mining destroys vegetation, causes extensive soil damage and destruction and alters microbial communities (Reintam and Kaar, 2002; Dutta and Agrawal, 2003). As the utilization of natural resources continues and opportunities to restore ecosystems damaged by human activities become more common, restoration is playing an increasingly important role in environmental protection (Prach *et al.*, 2001). The Society for Ecological Restoration (SER) defined ecological restoration as the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (Society for Ecological..., 2004). The term *reclamation* is used to describe efforts that aim to improve the quality of the land by restoring some pre-disturbance functions (Bradshaw, 1984).

According to most international laws, all surface-mined lands must receive reclamation and a large part of these areas are reclaimed for forestry (Pietrzykowski and Krzaklewski, 2007). In the case of post-mining reclaimed sites the key question is what criteria are used to evaluate the efficiency of reclamation (Bradshaw and Hüttl, 2001). Therefore it is important from the point of view of reclamation by forestation to determine the rates of soil formation and nutrient and biomass accumulation (Bradshaw, 1983; Schaaf, 2001; Pietrzykowski and Krzaklewski, 2007). A complex assessment of the reclamation processes should take into consideration both ecological and economic factors. Evaluation of biological and economic feasibility of forest restoration on reclaimed post-mining sites is possible by measuring wood production, carbon sequestration and multiple benefits and values provided by forests (Rodrigue *et al.*, 2002).

The goal of restoration is usually to develop a long-term sustainable ecosystem native to the area where mining had occurred (Chambers *et al.*, 1994). Thus, one of the solutions to problems based in damaged mining areas is economically feasible establishment of sustainable plant cover on post-mining areas. Soil formation and the development of the whole ecosystem in levelled spoil of post-mining areas can be considered as a primary succession, which can be accelerated by planting trees. In comparison

with unplanted sites, tree plantations have a marked catalytic effect on forest and soil development in severely degraded sites (Parrotta *et al.*, 1997; Filcheva *et al.*, 2000; Pietrzykowski and Krzaklewski, 2007; Wang *et al.*, 2007). Forest trees, which are dominant plants, act as an environmental filter that controls the availability of resources and the composition of understorey vegetation (Pensa *et al.*, 2008). Tree plantations can be used as a tool for mine spoil restoration as they have an ability to restore soil fertility and ameliorate microclimatic conditions (Singh *et al.*, 2002). Trees can potentially improve soils through numerous processes including maintenance or increase of soil organic matter, biological nitrogen fixation, uptake of nutrients from below the reach of roots of understorey herbaceous vegetation, increase water infiltration and storage, reduce loss of nutrients by erosion and leaching, improve soil physical properties and soil biological activity (Filcheva *et al.*, 2000). Some plantation species exhibit high nutrient use efficiency and may be more effective nutrient sink than other species (Lugo, 1992). Hence, the choice of tree species is a decisive factor in the success of mine reclamation. A suitable species for afforestation of quarry spoils should be able to grow on poor and dry soil, develop the vegetation cover as quickly as possible, prevent erosion and nutrient leaching and improve the soil organic matter status and microbial biomass. In addition, if possible, the species should be also of economic importance (Singh *et al.*, 2002). Landscape engineers and foresters often establish a low-diversity plant cover or use monospecific plantations of exotic species (Hunter *et al.*, 1998). Investigations conducted in recent years have suggested that monocultures may in long-term perspective give negative results in the restoration of vegetation (Holl, 2002). The questions that are raised against the use of tree plantations in rehabilitation usually centre on the negative effects of monoculture such a low stability, low resource use efficiency and low level of biodiversity (Lugo, 1997).

Introduced species. Native species are successful in plantations on post-mining areas (Shepherd, 1994; Butterfield, 1996), but still fast-growing exotic species are often preferred (Ang, 1994; Shepherd, 1994). Introduced non-native tree species can enrich the biodiversity and improve the productivity of low-diversity forests (Andersson and Rosvall, 1999). But non-native introductions may potentially spread uncontrollably, suppress indigenous species, and carry virulent pathogens or insect parasites of an indigenous species (Andersson and Rosvall, 1999; Engelmark *et al.*, 2001), also alter the ecosystem structure and functions, suppress or change mycorrhizae and other microflora and microfauna, and alter pH, cation exchange capacity,

and nutrient cycling (Ehrenfeld *et al.*, 2001; Crooks, 2002; Chornesky and Randall, 2003). Fast-growing exotic species are reported to show faster growth than native species on degraded land during initial couple of years of establishment (Parrotta, 1999). Dutta and Agrawal (2003) concluded that exotic species may be recommended for primary rehabilitation on coal mine spoil due to their fast growth and establishment. It is known that exotic coniferous species have frequently higher productivity than *Pinus sylvestris* or native broad-leaved trees (Peterken, 2001). Baumann *et al.* (2006) found that black pine grows better in the post-mining substrate than Scots pine. Many mine reclamation efforts focus on establishing rapid-growing non-native species that control erosion but may compete with later-successional, native species (Holl, 2002). A number of authors have suggested that intensive reclamation efforts may inhibit long-term ecosystem recovery (Chambers *et al.*, 1994; Holl and Cairns, 1994). The Surface Mining Control & Reclamation Act (SMCRA) of 1977 states that mining operations shall establish a diverse, effective, and permanent vegetative cover of the same seasonal variety and native to the area and capable of self-regeneration and plant succession (Holl, 2002).

Lodgepole pine. Lodgepole pine (*Pinus contorta*) is a native in western North America that has a wide ecological range (Elfving *et al.*, 2001). Lodgepole pine occurs as four subspecies, each of which has different morphological characteristics and a different geographical distribution. The subspecies *Pinus contorta* var. *latifolia* was used for reclamation of post-mining landscapes in Estonia and was under investigation in the present study. The habitat of the subspecies *latifolia* extends from northern New Mexico and the USA to Yukon Territory in Canada (Despain, 2001). Lodgepole pine has been found to grow well on the nutritionally poor soils (Weetman *et al.*, 1985), where it has advantages over other species (Despain, 2001). Tigerstedt (1986) notes that in Mustila (Finland) lodgepole pine has especially great advantages over Scots pine on heavy clay soils. Also, lodgepole pine is adaptive to soil pH variability (Koch, 1996). Commonly, the roots of this species are deeply distributed in the sandy nutritionally poor soils (Laas, 1987; Cohen *et al.*, 1990). Young lodgepole pines survive well, grow fast and tolerate well severe climate conditions, therefore in Northern Europe it is cultivated for forestry purposes more widely than other nonindigenous pine species (Laas, 2004). Favourable characteristics of lodgepole pine include immunity to the needle cast fungus and relatively high shade, drought and frost tolerance (Krajina *et al.*, 1982; Lotan and Critchfield, 1990). Lodgepole pines

grow rapidly when young, they form a slender crown and may grow in a dense stand (Kasesalu, 2000), the crown shape and biomass partitioning in the crown vary depending on the type of stand (Pearson *et al.*, 1984; Landsberg, 1986).

Due to its wide range of environmental tolerance, lodgepole pine has been introduced as an exotic for a variety of purposes in both northern and southern hemispheres. Lodgepole pine has been used in forest plantations in different climate zones and on different types of soil. It has been reported that lodgepole pine has been planted on climatically harsh, exposed, nutrient-poor peat soils in Scotland (Lines, 1996) and Ireland (Gallagher *et al.*, 1987); on poor, dry, out-washed sand-fields in Denmark (Larsen, 1980); and on subalpine or cold climate sites in New Zealand (Ledgard, 2001). Lodgepole pine has also been used in plantations in Finland (Ruotsalainen and Velling, 1993), Sweden (Rosvall *et al.*, 1998, Knight *et al.*, 2001) and Iceland (Sigurgeirsson, 1988).

From research in Sweden it is known that lodgepole pine could become more abundant on some sites than Scots pine because of its higher growth rate (Elfving *et al.*, 2001). In general, lodgepole pine is considered more competitive than Scots pine when the two species occur together (Norgren, 1996; Elfving *et al.*, 2001). The growth period seems to be equal for both of the species (Norgren, 1996); thus, the total growth may be affected more by differences in the growth rates than by differences in the growth period. However, lodgepole pine exposes its new shoots and needles earlier in the season, has a faster leaf area growth over the years, reaches crown closure earlier, has a higher needle longevity, and has a larger maximum leaf area index than Scots pine (Leverenz and Hinckley, 1990). The most significant ecological effects of lodgepole pine compared to Scots pine are the greater light absorption and higher nitrogen productivity (Elfving *et al.*, 2001). It is known that lodgepole pine litter has higher lignin and lower nitrogen concentrations than Scots pine, indicating slower decomposition (Engelmark *et al.*, 2001). Hence Ågren and Knecht (2001) reported that no significant effects on soil carbon can be attributed at this time to planting lodgepole pine instead of Scots pine. Both lodgepole pine and Scots pine plantations are relatively poor habitats for both plant and animal species in Sweden; however, a more homogeneous flora is found in stands of lodgepole pine compared to stands of Scots pine, suggesting lower understorey species richness at the landscape scale (Nilsson *et al.*, 2008).

Deciduous species. While most species appear to act as catalysts for ecosystem rehabilitation, broadleaf species seem to give better results than conifers (Parrotta *et al.*, 1997). The presence of different tree species in a productive system can result in a better structure and increased nutrient availability of soil (Montagnini and Sancho, 1990). Stanturf and Madsen (2002) reported that where funding is limited, simple wood production plantations may be the only feasible way to begin to restore agricultural or degraded lands, and over the longer term, simple plantations can be converted into complex plantations and natural forest. Deciduous trees have a number of advantages: the increased N and P availability in the soil, faster growth at a young age and higher resistance to pests, diseases and fires in comparison with conifer monocultures (Kaar, 2002; Löhmus *et al.*, 2007). The results from the Lusatian lignite mining region in Germany indicate that the cultivation of fast-growing poplars, their hybrids (including hybrid aspen) and willows in short-rotation plantations is an adequate tool for establishing sustainable land use systems in the post-mining landscapes (Bungart and Hüttel, 2001). Hybrid poplars have been found to have a good potential for reforestation of reclaimed surface-mined lands also in the Appalachian coal producing region in the USA (Casselman *et al.*, 2006). Afforestation of post-mining areas in Germany used to be limited to dumps with extremely unfavourable site conditions, and it was preferably carried out with fast-growing Scots pine (Häge, 1996). However, a natural-like and efficient forest structure should be achieved by establishing a multi-species forest, and trees such as oak and beech should be utilized as well as soil-improving (N-fixing) species like alder and black locust and pioneer trees like birch (Häge, 1996). The results in reclaimed post-mining sites near Sokolov (Czech Republic) showed the best adaptation to clay substrates of black alder and maple (Kupka and Dimitrovský, 2006).

Spontaneous succession. Although plantations can play a key role in restoring forest ecosystems (Singh *et al.*, 2002), spontaneous vegetation succession, or natural recovery, as an alternative approach to restoration or reclamation has gained increasing attention (Prach and Pyšek, 2001; Prach *et al.*, 2001). Considering that natural succession on degraded lands also takes longer (Wali, 1987; Bradshaw, 1997; Reintam and Kaar, 2002), it has been claimed that spontaneous succession can be more efficient than human efforts at returning degraded lands to their original state and reestablishing the self-regularity of ecosystems (Prach *et al.*, 2001). Plantations may produce high-quality timber and may positively influence

the economic status as well as the environment of degraded sites in the short period (Singh *et al.*, 2002), but their long-term effects on biological diversity have only recently been studied. For example, in the United States Holl (2002) found that spontaneous succession can create diverse plant communities on an abandoned coal opencast. In the Czech Republic Hodačová and Prach (2003) found that the development of vegetation by means of natural succession may have advantages in terms of species richness as compared with the engineered reclamation of brown coal opencasts after 45 years of development. Several researches (Hodačová and Prach, 2003; Pensa *et al.*, 2004; Karu *et al.*, 2005) claim that spontaneous succession enhances establishment of diverse vegetation.

2.2. Reclamation of disturbed landscapes in the Northeast Estonian oil shale mining area

Every year, opencast mining in the Northeast Estonian oil shale field – the largest commercially exploited oil shale deposit in the world (total amount of resources: 7×10^9 tonnes) (Bauert and Kattai, 1997) – creates substantial areas of wasteland. The Estonian oil shale (kukersite) basin was formed in the Middle Ordovician and is covered by Ordovician and Devonian carbonaceous rocks and Quaternary deposits. Presently, two underground mines and two opencast mines are in operation. In this area the overburden ranges from 0 to 70 m due to the gentle southward dipping of the Ordovician strata. Opencast mining began to spread intensively in 1959. Pits are preferred in places covered by forests and bogs, in digging to a depth of 30 m. Opencast mining is preferred for economic and social reasons, e.g., relatively cheaper and quicker preparations for production; introduction of highly productive machinery and the resulting improvement in efficiency; safer and healthier working conditions than in mines. Nowadays around 50% of oil shale is mined in pits. Opencast oil shale mining creates alkaline wasteland that requires reclamation. Following opencast mining, the relief is rugged and the soil heterogeneous and extremely stony; the N and organic content of oil shale mining spoil is low (Kaar *et al.*, 1971; Löhmus *et al.*, 2007). Reintam (2004) reported that spoil is alkaline and highly skeletal, containing 40%–75% limestone. Over time, the thickness of the overburden in the Narva opencast has increased (Valgma, 2000) and opencast mining has become deeper, the proportion of hard Ordovician carbonate rocks will increase in the dump (Kaar, 2002). The substrate of exhausted oil shale opencasts is very unfa-

vourable for reoccupation by plants, especially due to its uttermost dryness and the extreme temperatures of its surface (Laasimer, 1973). Easily acquirable water for plants is basically absent in the top layers of opencast spoil, or appears in small quantities only in spring and autumn (Raid, 1972). Plants growing on spoil may occasionally suffer from drought, but the moisture regime in the top layers of levelled spoil is tolerable for most tree species (Raid, 1972). Since the spoil of opencast oil shale mining is extremely coarse and depleted in nutrients and organic matter, afforestation is considered the most suitable reclamation option for these areas (Vaus, 1970; Lõhmus *et al.*, 2007).

Extensive afforestation of exhausted opencast oil-shale mines in Northeast Estonia began in 1960, and as of 2006 the area damaged by oil shale opencast mining was 13,098 ha, of which 10,347 ha has been afforested (Kaar and Tomberg, 2006). Mostly Scots pine has been used for reclamation, and pine plantations cover 86% of the afforested land (Kaar, 2002). The wide use of Scots pine for afforestation of abandoned oil shale opencast sites is due to its successful establishment and adaptation under harsh conditions (Kaar, 2002). In addition some other local tree species such as silver birch and black alder and a number of exotic species (mainly *Picea*, *Pinus*, *Larix*, also *Populus* spp.) have been used. Birch, alder and larch plantations made up only 7%, 0.1% and 2% of the afforested areas in 2002, respectively. The afforestation of post-mining areas with deciduous species has been hampered by the lack of planting stock (Kaar, 2002). Species of *Larix* have shown the best growth among coniferous trees, and the native deciduous species silver birch and black alder have been the most successful deciduous trees (Kaar, 2002; Kuznetsova and Pärn, 2004; Vares *et al.*, 2004; Korjus *et al.*, 2007; Lõhmus *et al.*, 2007). Good results have been obtained with lodgepole pine grown from local seeds on clay substrates on Narva opencast mine (Kaar, 2002; Kuznetsova and Pärn, 2004). Lodgepole pine areas make up 11% of the levelled Narva opencast (Kaar, 2002). Various other exotic *Pinus* and *Picea* species were not adapted to post-mining substrates (Kaar, 2002; Kuznetsova and Pärn, 2004). Research into the suitability of hybrid aspen (*Populus × wettsteinii* Hämet-Ahti) for afforestation of degraded landscapes (Tullus *et al.*, 2008) showed that this species is able to grow on a post-mining area, although its growth is faster on a post-mining area covered with the former soil. Research results showed that new stands are of better quality than the stands that grew there before mining (Kaar, 2002). Moreover, Korjus *et al.* (2007) found that the mean height, diameter and volume development

on Scots pine and silver birch plantations are showing similar growth rate as average of stands on the best forest site types in Estonia. Productive forests with moder-type forest floor and Calcaric Regosols and Calcaric Arenosols develop on mine spoil within 20–30 years after afforestation (Reintam and Kaar, 2002; Reintam *et al.*, 2002; Reintam, 2004). The planted stands have better growth compared to naturally developed stands (Reintam and Kaar, 2002; Luud and Pensa, 2004). In plantations tree species affect the succession and diversity of vegetation on reclaimed mining areas (Chambers *et al.*, 1994; Singh *et al.*, 2002; Pensa *et al.*, 2004, 2008). Pensa *et al.* (2008) recorded the greatest number of herbaceous species in naturally developed mixed stands, also broadleaved trees tend to enhance the growth of herbaceous species, whereas conifers suppress it. *Alnus glutinosa* promoted the growth of most ground vegetation and the diversity of vegetation was lowest in *Pinus sylvestris* plots (Pensa *et al.*, 2004).

Considering also other important ecological issues, such as biodiversity and soil development, it was suggested that a larger proportion of oil shale spoils should be afforested with birch and alder instead of establishing Scots pine monocultures (Kaar, 2002; Vares *et al.*, 2004). Pensa *et al.* (2008) suggested planting mixed stands with different tree species as a prerequisite for the development of a diverse herb layer.

In Estonia, the economic importance of deciduous trees started to increase markedly only 10–15 years ago as the priority for Estonian forestry policy before the 1990s was towards coniferous species (Uri *et al.*, 2007). The proportion of pine, birch and alder stands in Estonian forests is 35%, 30.2% and 3%, respectively (Yearbook Forest 2008, 2009). Birches are native throughout Europe, and partially in Asia, they have a very wide climatic tolerance (Evans, 1984; Atkinson, 1992). Silver birch is found mainly on dry, sandy mineral soils. Birch is known to have a high regeneration capacity and a high growth rate, even on poor soils (Walle *et al.*, 2007). Fertilisation experiments showed that production of birch is increased by N fertilisation (Saarsalmi, 1995). Birch has a reputation as a soil improving species (Bradley and Fyles, 1995). Priha *et al.* (1998) reported that soil microbial biomass and activity are stimulated by the roots of silver birch and Scots pine seedlings, while seedlings of Norway spruce have no effect. Bradley and Fyles (1995) found in soil under paper birch more C available and higher rates of N mineralisation compared to other species.

Black alder is distributed throughout the Nordic countries as well as in middle and southern Europe, partially in Asia and North Africa (McVean, 1953). The species can survive under very wet soil conditions during the dormant season (Johansson, 2000), tolerates late spring and early autumn frosts and grows at a wide pH range (Evans, 1984). Owing to the ability to fix N₂ by the symbiosis of actinomycetes *Frankia* in alder root nodules, the soil under alders is enriched in nitrogen. Due to the low nitrogen retranslocation from senescing leaves, alder leaf litter is extremely rich in nitrogen and mineralizes easily (Vares, 1999). Alders have a high requirement for P (Giardina *et al.*, 1995), which is usually the most limiting nutrient for them. Also in fertilisation experiments P has been found to be the most important mineral nutrient that increase the growth of alders (Hytönen *et al.*, 1995). Alders increase phosphorus availability in the soil through the activity of their roots and associated microbial communities (Giardina *et al.*, 1995; Uri *et al.*, 2002). The majority of alder roots with primary structure are ectomycorrhizas, and hence mycorrhizal symbiosis plays an important role in the nutrient cycling of alder stands. It is known that the nutrient demand of alders is higher and N use efficiency is lower than those of other tree species (Binkley *et al.*, 1992). In order to satisfy the high demand for nutrients, beneficial rhizosphere conditions should be supported by alders (Löhmus *et al.*, 2006). The interaction of roots and soil microbial communities should be especially important in harsh site conditions, including reclaimed opencast oil shale mining areas (Löhmus *et al.*, 2006). It was found that black alder and silver birch on reclaimed alkaline mining spoil support rhizosphere microbial communities in order to improve mineral nutrition (Vares *et al.*, 2004; Löhmus *et al.*, 2007; Rosenvald *et al.*, 2010). Simultaneously with rhizosphere effect, morphological adaptations of fine roots directly affect the nutrition of trees. Fine roots play a key role in the boreal forest ecosystem, where they constitute a major carbon sink. Short roots form the most active part of the fine root system. They are mostly ectomycorrhizal and morphologically distinct from other fine roots and are usually less than 2 mm in diameter (Vogt and Persson, 1991). Short roots adapt according to soil conditions both anatomically and morphologically (Ostonen *et al.*, 1999, 2006; Löhmus *et al.*, 2006; II). The most frequently measured functional morphological parameters of fine roots are specific root length (SRL), specific root area (SRA) and root tissue density (RTD) (Pregitzer *et al.*, 2002; Ostonen *et al.*, 2007), which are believed to be indicative of environmental changes. Hence complex interaction between soil, rhizosphere effect and fine root morphological adaptations enhance the formation of sustainable and

productive forest ecosystems in post-mining areas (Lóhmus *et al.*, 2007; Rosenvald *et al.*, 2010).

2.3. Further research needs

Ecological restoration of post-mining areas offers the rare opportunity to examine the development of ecosystems starting at “point zero” (Hüttl and Weber, 2001). The current study was carried out in small-scale experimental plantations in order to estimate the suitability and productivity of different tree species under unfavourable soil conditions. It provided adequate results for this area and the present time. However, more studies in large-scale plantations need to be conducted to obtain wider knowledge of growth dynamics and plant–soil relationships and to provide recommendations for successful reclamation. Moreover, longer-term investigations are needed to verify sustainability of biomass production and suitability of species for reclamation of post-mining landscapes. Future research also should be focused on the effect of different tree species on the soil chemical properties and root investigations. Root research should be focused on the distribution patterns of root systems, also on dynamics of fine root biomass and production.

3. AIMS OF THE STUDY

The main hypotheses of the study were:

- (1) black alder can be preferred for the reclamation of exhausted oil shale mining areas due to its fast growth and ability to restore soil fertility (**I–III**);
- (2) the fact that the introduced lodgepole pine has larger needle length and area (which are species-specific morphological factors for photosynthesis and biosynthesis of organic matter) compared to the native Scots pine suggests that lodgepole pine may show faster growth and biomass formation than Scots pine on loamy soils of post-mining areas (**IV–VII**);
- (3) different species studied develop different strategies of morphological adaptations of fine roots, which are crucial in mineral nutrition processes and biomass formation in unfavourable growth conditions on post-mining areas (**I; II**).

The main aim of this thesis was to analyse the suitability of the studied species for the reclamation of oil shale post-mining areas (**I–VII**).

The specific objectives were:

- (1) to analyse the early dynamics of the survival, growth, biomass allocation and production in relation to the tree species in black alder, silver birch and Scots pine plantations on oil shale post-mining areas (**I; III**);
- (2) to estimate the nutrient concentration, allocation, accumulation and use efficiency in relation to the tree species and stand age in black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas (**I; III**);
- (3) to analyse fine root adaptations in relation to the tree species and stand age in young black alder, silver birch and Scots pine plantations on post-mining areas (**I; II**);
- (4) to compare the growth of native (Scots pine) and introduced (lodgepole pine) pines on oil shale post-mining areas by analysing biomass and nutrients composition (**IV–VII**).

4. MATERIAL AND METHODS

4.1. Description of the study areas and experiments

The study was carried out in the Narva reclaimed oil shale mining area in Northeast Estonia (59°15' N, 27°48' E and 59°15' N, 27°42' E). The mean annual temperature in the region during the studied period (2004–2008) was 5.8 °C, and mean annual precipitation was 747 mm. The plantations had been established directly on levelled quarry spoil. No soil fertilisation was done before planting. The soil type under middle-aged pine stands on the reclaimed oil shale mining area is Calcaric Regosol (Reintam, 2001).

The objects of investigations were native and introduced 1–25-year-old trees, on the basis of whose survival and growth it is possible to give recommendations for the recultivation of oil shale post-mining areas. The objects and experimental plantations were conventionally divided into two taking into account the age of trees:

- (1) 1–7-year-old black alder (*Alnus glutinosa* (L.) Gaertn.), silver birch (*Betula pendula* Roth.) and Scots pine (*Pinus sylvestris* L.) plantations;
- (2) 8–25-year-old of native Scots pine (*Pinus sylvestris* L.) and introduced lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) plantations.

4.1.1. Young black alder, silver birch and Scots pine plantations

Black alder, silver birch and Scots pine plantations of different age (1-, 2-, 4- and 7-year-old) were investigated (Table 1) (**I**; **II**; **III**). The planting density was 1.5 m × 1.5 m for Scots pine and 2.0 m × 2.0 m for black alder and silver birch. The experimental area (0.56 ha) with the studied species was established in May 2005 using 1-year-old seedlings. The seedlings were planted in 25 m × 25 m plots in three replications in the Latin square design. So, the total number of seedlings per species planted and measured during the study was 485, 468 and 745 for black alder, silver birch and Scots pine, respectively. Measurements, biomass estimation and chemical analyses of soil and plant material in plantations were carried out when they were 1 year old (August 2005), 2 years old (August 2006) and 4 years old (August 2008). The short-root morphology was assessed in October 2005 (**I**; **II**), 2006 and 2007.

Table 1. Stand and soil characteristics in the reclaimed oil shale mining area: mean height (H±SE), mean diameter at root collar (D±SE), soil pH, concentration of nitrogen (N) and available P in soil. Different superscript letters indicate significant differences between species at the same age according to Tukey HSD test

Species	Age of stand, year	Trees per ha	Survival, %	H, cm	D, cm	pH	N, %	P, mg kg ⁻¹
Black alder	1	2300	93.0	32.83±0.42 ^c	0.83±0.10 ^b	8.02±0.06	0.032±0.003	100.09±13.54
	2	2263	91.5	42.54±1.16 ^c	1.06±0.03 ^c	7.74	0.034	113.83
	4	2263	91.5	169.15±6.48 ^c	4.50±0.17 ^c	7.70±0.12	0.045±0.004	65.85±6.17
	7	2100	85.0	217.62±3.67 ^b	4.78±0.09 ^c	7.50±0.05	0.052±0.004	48.58±2.26
Silver birch	1	1600	64.0	16.62±0.34 ^b	0.30±0.03 ^a	8.05±0.03	0.031±0.005	79.18±9.81
	2	1540	61.6	29.41±1.43 ^b	0.49±0.03 ^b	7.87	0.021	88.21
	4	1540	61.6	91.56±4.05 ^b	1.56±0.07 ^b	7.82±0.06	0.040±0.001	80.53±7.39
	7	1017	40.7	123.11±5.11 ^a	1.77±0.08 ^a	7.51±0.08	0.045±0.004	50.39±2.63
Scots pine	1	3689	83.0	5.79±0.09 ^a	0.23±0.02 ^a	8.08±0.01	0.027±0.002	73.57±13.26
	2	3493	78.4	8.89±0.22 ^a	0.29±0.01 ^a	7.73	0.031	130.76
	4	3493	78.4	26.04±1.11 ^a	1.04±0.05 ^a	7.85±0.09	0.033±0.003	70.68±6.23
	7	3042	68.3	118.36±1.91 ^a	3.10±0.07 ^b	7.62±0.10	0.043±0.001	47.82±5.69

The measurements in the 1-year-old plantations were made separately in each replication. Considering that there were not any significant differences between replications within a tree species (Kuznetsova *et al.*, 2010), the later measurements were performed per plantation. Also 7-year-old plantations (total area 3 ha) were investigated, which were established in 2002 with two-year-old seedlings. Fieldwork was carried out in these plantations at the end of August 2008. A sample plot (0.1 ha) was established per each species plantation and all trees in the sample plot were measured (210, 122 and 365 trees for black alder, silver birch and Scots pine, respectively). The short-root morphology in these plantations was assessed in October 2006.

4.1.2. Scots pine and lodgepole pine plantations

Investigation was carried out in 8 experimental plantations of native Scots pine and introduced lodgepole pine established in 1979–1998 on the reclaimed oil shale mining area (Table 2) (IV–VII). Estimation and comparison of the growth of Scots pine and lodgepole pine were carried out in two 8-year-old plantations and in six 21–25-year-old plantations (Table 2). Plantations 1 and 2 were established with 1-year-old seedlings and plantation 3 with 3-year-old seedlings. Other studied plantations were established with 2-year-old seedlings. The investigated lodgepole pine plantations were established from seeds collected in Estonia (Luunja and Raadi).

Table 2. General characteristics of Scots pine and lodgepole pine plantations (H – tree height, DBH – diameter at breast height (*indicates diameter at root collar)

No of plantation	Species	Planting density, m	Age, year	Density, trees ha ⁻¹	Mean		Growing stock, scm ha ⁻¹
					H, m	DBH, cm	
1	Lodgepole pine	2×2	22	2450	8.8±0.3	9.0±0.7	81
2	Lodgepole pine	2×2	21	2300	9.1±0.3	10.9±0.6	113
3	Lodgepole pine	3×3	25	588	9.1±0.4	14.5±0.7	1
4	Scots pine	1.25×1.5	22	2040	7.9±0.2	8.5±0.6	55
5	Scots pine	1.25×1.5	23	1220	10.4±0.6	11.5±1.3	75
6	Scots pine	1.25×1.5	23	2590	9.1±0.4	9.0±1.1	88
7	Lodgepole pine	2×2	8	2200	1.20±0.03	3.28±0.07*	
8	Scots pine	1.5×1.5	8	3900	1.52±0.04	3.31±0.09*	

4.2. Analyses and measurements in experimental plantations

4.2.1. Measurements in young black alder, silver birch and Scots pine plantations

4.2.1.1. Estimation of aboveground biomass and production

The survival, diameter at root collar and height of trees were measured (Table 1). The aboveground biomass of the stand was estimated in August when it was the largest. For the estimation of aboveground biomass and production the sample tree (model tree) method was used (Bormann and Gordon, 1984; Löhmus *et al.*, 1996; Vares *et al.*, 2004; Uri *et al.*, 2007; Tullus *et al.*, 2009).

In 1- and 2-year-old stands the trees were categorised into three height classes on the basis of height distribution in the stand. One model tree from each height class was randomly selected. In 1-year-old stands the model trees were selected per replication (Kuznetsova *et al.*, 2010) and in 2-year-old stands per plantation. In 4- and 7-year-old stands the trees were divided into five height classes, and a model tree was selected randomly from each class. Additionally, we felled a tree from two classes with the largest number of trees. A total of seven model trees per plantation were sampled.

In 1- and 2-year-old stands the aboveground parts of the model trees were divided into three compartments: leaves, shoots (current-year shoots and branches (older shoots, age > 1 year)) and stems. The compartments were dried at 70 °C until constant weight and weighed to 0.001 g.

In 4- and 7-year-old stands the living crowns of the model trees were divided into three equal sections of length. In each section, different compartments including leaves, current-year shoots and branches were separated. The fresh mass of each compartment was determined. From every compartment, a subsample was taken for the determination of dry matter content. The subsamples were weighed fresh, dried and weighed to 0.001 g. The dry mass of different compartments was calculated for each model tree by multiplying its fresh mass by the proportion of dry matter. The stems were dried and weighed.

Total current annual production (CAP) of a tree consists of the annual increment of leaves, shoots and stem. The CAP of the leaves and current-year shoots is equal to their biomass. The production of older shoots (age > 1 year) was estimated by dividing shoot mass by shoot age. To estimate annual stemwood production, disks were taken from the middle of all stem sections, dried and polished, and the widths of annual rings were measured to 0.001 mm using the WinDENDRO (Regent Instruments Inc., Quebec, QC, Canada) software.

Annual wood increment of the model tree sections was calculated according to the following equation (Whittaker and Woodwell, 1968):

$$W = W_0(r^2 - (r - i)^2)/r^2, \quad (1)$$

where W is the annual dry mass increment in wood, W_0 the dry mass of wood, r the radius of the analysed disk and i is the thickness of the ring of the last year.

To estimate the aboveground biomass (B) and current annual production (CAP) of trees, the allometric equation 2, based on the data of the model trees, was used:

$$y = ax^b, \quad (2)$$

where y is the aboveground biomass (g) or production of the tree (g year^{-1}), x the diameter of the tree at root collar (cm), a and b are the parameters of the equation (Table 2 in **III**). The aboveground biomass of the 1-year-old stand was calculated earlier (**I**).

The masses of different compartments were calculated using the percentage distribution of the compartments obtained on the basis of the model trees. The relative annual aboveground production (CAP/B) per stand was calculated as well.

4.2.1.2. Estimation of belowground biomass and root characteristics

Belowground biomass was estimated by the method of excavation of the root system of model trees. In the youngest plantations (1-, 2-year-old), the root systems of all model trees were excavated and in 4- and 7-year-old plantations the root system of an average model tree was excavated and investigated. Earlier investigation (Uri *et al.*, 2007) showed that in stands of deciduous trees of the same age the ratio of aboveground and belowground biomass was practically constant and the ratio found on the basis of one model tree can be used for the whole stand, and it yields quite an exact estimation of the belowground biomass of the stand.

The excavated root systems were washed free of soil and separated into living and dead roots. The proportion of dead roots was negligible, hence dead roots were omitted from further analysis. To analyse belowground biomass allocation, root systems were divided into two diameter classes: $d < 2$ mm (fine roots) and $d \geq 2$ mm (coarse roots). In 4- and 7-year-old plantations only coarse roots were under observation. All fractions were dried at up to 70°C and weighed to 0.01 g.

In 1- and 2-year-old plantations the root ratio (RR, %; the proportion of the root system as part of total tree mass) and the ratio of fine roots (FR/R, %; the proportion of fine (<2 mm in diameter) roots in the root system) were calculated. The foliage/fine root (L/FR) ratio (Helmisaari *et al.*, 2007) was calculated by dividing the mass of leaves by the mass of fine roots of a tree. In 4- and 7-year-old plantations coarse root/(shoots+stem) ratio was calculated.

Short roots with living cortex (Ostonen *et al.*, 2007) were used to analyse morphological adaptations of fine roots. Prior to measuring morphological parameters, the roots of 10 random root samples per stand were washed with tap water to remove the soil particles. Two random living short-root subsamples (on average 15 short-root tips) were taken per sample and root tips were counted under a microscope. Short roots were considered alive if the exposed stele was still shiny and resilient (Vogt and Persson, 1991).

Short-root length, projection area and mean diameter (D_{SR} , mm) of the sample were measured using WinRHIZO™ Pro 2003b (Regent Instru-

ments Inc.). After measuring, short-root samples were dried at 70 °C for 2 h and weighed with an accuracy of 0.01 mg (W; mg). The method for determining short-root morphological parameters: mean short-root length (L; mm), specific root area (SRA; m² kg⁻¹), specific root length (SRL; m g⁻¹), tissue density (RTD; kg m⁻³) is given in detail in Ostonen *et al.* 1999 and 2007.

4.2.2. Measurements in Scots pine and lodgepole pine plantations

Field measurements were carried out in the studied plantations in 2004–2006. One sample plot (0.06–0.1 ha) was established in each plantation, except one small experimental lodgepole pine plantation (plantation 3), where all trees were measured ($n = 60$). The stem diameter at breast height (DBH) ($n = 122$ – 259) and the height (H) ($n = 17$ – 29) of 21–25-year-old trees in each plantation were measured. For all 8-year-old trees ($n = 220$ – 390) the diameter at root collar (D) and height (H) were measured. The diameter of trees was measured to the nearest 0.1 cm with a caliper. The height of trees was measured to the nearest 0.1 m using a Suunto clinometer. For measuring the height of young Scots pine and lodgepole pine the measuring stick was used (**IV**).

For the estimation of the state of trees in the study areas, parameters of the morphometric evaluation system recommended for Central Europe (Manual for Integrated..., 1993) was used. Considering that the assimilating mass and the photosynthetic productivity of conifers are allocated predominantly in the middle layers of the canopy (Mandre and Tullus, 2002), for morphological measurements current-year main shoots ($n = 15$ – 50) from each stand (plantations 1– 6: Table 2, **IV**; **VI**; **VII**) were collected randomly from the middle part of the tree crowns.

From the collected samples, the length of needles ($n = 150$ – 500) and shoots was measured, the dry mass of 100 needles and shoots dried at 70 °C in a thermostat was weighed, the thickness (dry mass per length) of needles (mg cm⁻¹) and shoots (g cm⁻¹) and the density of needles on shoots (needle number per unit shoot length) were calculated (**IV**; **VI**; **VII**).

To estimate and compare the growth and productivity of young Scots pine and lodgepole pine (plantations 7–8: Table 2, **V**), the aboveground biomass and biomass allocation of trees were determined from harvested

model trees. The trees growing on sample plots were divided into five height classes and one tree from each height class per plot was randomly selected and felled. The crowns of the model trees were divided into three sections of length (upper – 1, middle – 2, lower – 3) to compare the differences of the development of the crowns. In each section, two model branches were selected for morphological measurements of needles and shoots. Current-year and 1-year-old main shoots were taken for measurements from model branches. The dry mass of needle (g), the length of needles (cm), the length and thickness (dry mass per length) of shoots (g cm^{-1}) and the density of needles on shoots per each model branch were determined. The harvested trees were divided into aboveground compartments: needles, shoots and stems. After drying at 70 °C until constant weight the dry mass of the compartments was determined. All fractions were weighed to 0.001 g. The aboveground biomass of a tree was obtained as the sum of the biomasses of needles, shoots and stem.

4.3. Chemical analyses

4.3.1. Soil analysis

To characterise the growth substrate of trees 3–10 random soil samples from the 0–20 cm soil layer were taken per plantation. One composite soil sample per plantation represents Scots pine and lodgepole pine plantations and 2-year-old black alder, silver birch and Scots pine plantations. In 1-, 4- and 7-year-old black alder, silver birch and Scots pine plantations soil was analysed in three replicates per plantation. The soil samples were dried and sieved through a sieve with 2 mm mesh size. The soil samples were analysed for pH_{KCl} and $\text{pH}_{\text{H}_2\text{O}}$. Soil nitrogen was determined according to the Kjeldahl method; Tecator ASN 3313 was applied. Available phosphorus in the soil was extracted by ammonium lactate and measured by flow injection analysis with Tecator ASTN 9/84 (Růžička and Hansen, 1981). Available K was determined by the flame photometric method. Calcium and magnesium in soil were measured by flow injection analysis using Tecator ASTN 90/92. All soil samples were analysed in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences, except for the soil $\text{pH}_{\text{H}_2\text{O}}$, which was determined in the laboratory of the Department of Ecophysiology of the Forestry and Rural Engineering Institute of the Estonian University of Life Sciences with a pH meter (Mettler Toledo GmbH, InLab412 electrode).

4.3.2. Plant analysis

From 21–25-year-old plantations of Scots pine and lodgepole pine the current-year needles for chemical analysis were collected from 5–10 trees per each sample plot in autumn 2004–2006 after tree growth had stopped. The needles were dried and a composite sample per sample plot was created. The concentrations of mineral nutrients (N, P, K, Ca, Mg) were determined.

In young stands (2-, 4-, 7-year-old black alder, silver birch, Scots pine and 8-year-old Scots pine and lodgepole pine), the plant samples for nutrient analyses were collected at the end of August from three model trees. The concentrations of the main nutrients (NPK) were analysed separately in different biomass compartments of the model trees. The samples were collected evenly from different parts of the crown and one composite sample was made for each compartment per each tree.

In 2-, 4-, 7-year-old black alder, silver birch and Scots pine stands both the contents of nutrients (kg ha^{-1}) and their annual accumulation in the aboveground part ($\text{kg ha}^{-1} \text{ year}^{-1}$) of the stand were calculated; the biomass or the annual increment of a compartment was multiplied by the respective nutrient concentration. Nitrogen and phosphorus use efficiencies (NUE, PUE, kg kg^{-1}) were calculated as aboveground production per N or P accumulation in the aboveground parts of the stand per year.

Block digestion and steam distillation methods were used for testing the plant material for nitrogen concentration (Tecator AN 300). Digestion by flow injection analysis was used for testing the plant material for Kjeldahl phosphorus concentration (Tecator AN 5242) using the analyser FIAstar 5000. Potassium was determined by the flame photometric method. Calcium was determined in Kjeldahl Digest by FIAstar 5000, o-Cresolphthalein Complexone method, and magnesium by FIAstar 5000, titan yellow method (Růžička and Hansen, 1981). Chemical analyses were made in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

4.4. Statistical analysis

The taxation parameters of the stands on the sample plots including the mean height and diameter, stand density and growing stock were computed using FoxPro software. The normality of variables was checked by Lilliefors and Shapiro-Wilk's tests. When necessary, log- and root-transformations were used to normalise the data. The data were analysed by regression analysis, analysis of variance (ANOVA, GLM) and *t*-test. The Tukey and Bonferroni tests were used for multiple comparison of the means. Throughout the study, the means are presented with their standard errors (\pm SE) or with standard deviations (\pm SD). Correlations (*r*) between growth parameters and nutrients were calculated. Statistical analyses were performed with Statistica 7.0, Systat 10 and Excel 2003 software. The level of significance $\alpha = 0.05$ was accepted in all cases.

5. RESULTS

5.1. Early dynamics of the growth of black alder, silver birch and Scots pine plantations

5.1.1 Chemical characterisation of growth substrate

During seven years of tree growth the soil pH and P concentration decreased while an increase in the soil N concentration with stand age was observed for all studied species (Table 1) (III). However, no statistically significant differences with stand age were found for N and P concentrations in silver birch and P concentration in Scots pine (Tukey test, $p > 0.05$). The effect of different tree species on pedogenesis was similar. The soil nutrient concentrations did not differ between species at the same age ($p > 0.05$) (III).

5.1.2. Survival and growth of trees

The survival of 1-year-old seedlings varied by tree species and ranged as follows: black alder \geq Scots pine $>$ silver birch, $93 \pm 6\%$, $83 \pm 5\%$, $64 \pm 2\%$. The survival of silver birch was significantly lower than the survival of the other species (Tukey test, $p < 0.05$) (I). During the following 6 years the tree dieback for all species varied between 8% and 23% (Table 1). The values of mean height and diameter of black alder were significantly higher compared to the other studied species of the same age (Tukey test, $p < 0.05$) (Table 1) (III).

5.1.3. Biomass allocation and production

The results of regression analysis revealed a strong relationship between the stem diameter at root collar and the aboveground biomass and production (Table 2 in III). All regressions had high determination coefficients ($r^2 = 0.71\text{--}0.99$) and were highly significant ($p < 0.01$).

The effect of tree species on aboveground biomass allocation was significant. Scots pine had a significantly greater share of leaves and a smaller proportion of stem in the aboveground biomass than the deciduous trees (Figure 1).

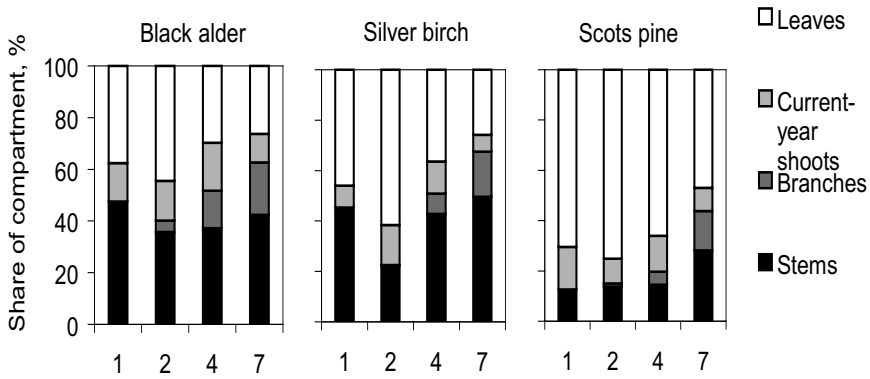


Figure 1. Aboveground biomass allocation in black alder, silver birch and Scots pine stands growing on a reclaimed oil shale mining area (1, 2, 4, 7 – age of stand in years).

Strong correlations were found between the share of different compartments of aboveground biomass and age, height and diameter of model trees (Table 3). It was found that the share of leaves decreased and the share of shoots increased with increasing age, height and diameter of trees for all studied species. The share of stem was not related to age and size of model trees for deciduous species, but the share of Scots pine stem was positively correlated with the age, height and diameter of the trees.

Table 3. Correlation coefficients (r) between relative shares of the biomass compartments (%) and age, mean diameter at root collar (D) and mean height (H) of the model trees (* $p < 0.001$)

Compartment	Black alder			Silver birch			Scots pine		
	Age	D	H	Age	D	H	Age	D	H
Leaves	-0.594*	-0.771*	-0.810*	-0.676*	-0.663*	-0.735*	-0.893*	-0.886*	-0.901*
Shoots	0.712*	0.861*	0.820*	0.809*	0.783*	0.784*	0.695*	0.732*	0.670*
Stem	-0.166	-0.147	-0.061	0.276	0.276	0.358	0.771*	0.736*	0.798*

After the first growing season the RR was similar in all species (Figure 2). After the second growing season the RR was similar for deciduous species, but significantly smaller for Scots pine. The FRR was for Scots pine

twice as high as for black alder or silver birch in both growing seasons (Figure 2). The L/FR ratio was the highest for silver birch and the smallest for black alder (Figure 2). The ratio of coarse-root biomass/aboveground woody biomass had a decreasing trend with stand age for Scots pine and black alder (Figure 2).

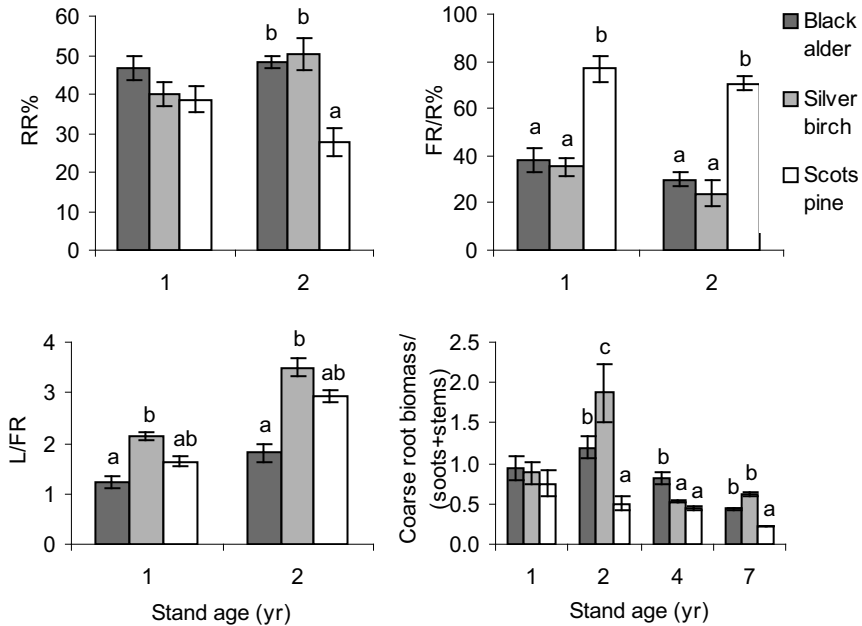


Figure 2. Root (RR%), fine root (FRR%), foliage to fine root (L/FR) and coarse root biomass / (shoots+stem) ratios in the studied plantations.

Comparative analysis of the biomass of different species in the studied plantations showed that during the first 7 years after the plantation was established black alder appeared to be the most productive species. The aboveground biomass and production of the black alder plantations were higher than in the silver birch and Scots pine plantations (Table 4). Relative annual aboveground production of stands was similar between species and decreased according to a power function with stand age for all studied species (Figure 2 in **III**).

Table 4. The aboveground biomass (B, kg ha⁻¹) and current annual biomass production (CAP, kg ha⁻¹ year⁻¹) of black alder, silver birch and Scots pine stands. 1, 2, 4, 7 – age of stand (years)

Compartment	1		2		4		7	
	B	CAP	B	CAP	B	CAP	B	CAP
Black alder								
Leaves	7.29	7.29	23.22	23.22	647.91	647.91	675.42	675.42
Current-year shoots	2.87	2.87	7.98	7.98	403.08	403.08	281.86	281.86
Branches	–	–	2.31	1.20	317.03	87.93	519.78	100.75
Stems	9.23	4.15	18.69	7.10	809.96	233.73	1086.19	320.87
Total	19.40	14.31	52.20	39.50	2177.98	1372.65	2563.25	1378.91
Silver birch								
Leaves	0.69	0.69	3.94	3.94	31.41	31.41	41.63	41.63
Current-year shoots	0.13	0.13	1.02	1.02	10.93	10.93	10.62	10.62
Branches	–	–	0.02	0.01	6.96	2.74	28.88	9.69
Stems	0.68	0.38	1.42	0.26	36.90	20.08	79.73	32.58
Total	1.50	1.20	6.40	5.22	86.20	65.16	160.85	94.51
Scots pine								
Leaves	1.34	1.34	2.10	1.66	120.93	106.02	892.71	542.24
Current-year shoots	0.32	0.32	0.27	0.24	26.16	26.16	173.90	173.90
Branches	–	–	0.04	0.02	9.46	3.05	296.99	114.79
Stems	0.24	0.14	0.39	0.09	26.60	6.55	535.22	280.33
Total	1.90	1.80	2.80	2.04	183.15	141.79	1898.82	1111.26

5.1.4. Nutrient allocation and accumulation

The concentrations of nutrients varied between tree species, compartments and stands of different age. For all studied species and stands of different age, the highest N, P and K concentrations were found in the leaves and the lowest in the stems, except for similar P concentrations in the leaves and shoots in 2-year-old black alder and Scots pine stands (Tukey test, $p < 0.05$) (Figure 3 in **III**). The differences in the concentra-

tions of nutrients between tree species were statistically significant. For example, in 2- and 4-year-old plantations the N concentration in leaves and current-year shoots did not differ significantly between black alder and silver birch, but these values were significantly higher than the respective values of Scots pine (Tukey test, $p < 0.05$). In 7-year-old plantations black alder had the highest N concentration in each compartment (Table 5) (Tukey test, $p < 0.05$).

Table 5. Mean (\pm SE) concentrations of N, P and K (%) in different tree compartments of 7-year-old studied species. Superscript letters indicate significant differences between species according to the Tukey HSD test

Compartment		Black alder	Silver birch	Scots pine
Leaves	N	2.97 ^c \pm 0.08	2.11 ^b \pm 0.11	1.24 ^a \pm 0.08
	P	0.19 ^a \pm 0.01	0.32 ^b \pm 0.04	0.15 ^a \pm 0.02
	K	0.66 ^{ab} \pm 0.03	0.72 ^b \pm 0.02	0.60 ^a \pm 0.02
Current-year shoots	N	1.38 ^c \pm 0.04	1.02 ^b \pm 0.09	0.55 ^a \pm 0.04
	P	0.15 ^b \pm 0.01	0.14 ^b \pm 0.01	0.09 ^a \pm 0.01
	K	0.35 \pm 0.02	0.34 \pm 0.05	0.46 \pm 0.03
Older shoots	N	1.06 ^c \pm 0.06	0.67 ^b \pm 0.07	0.39 ^a \pm 0.01
	P	0.10 ^b \pm 0.00	0.10 ^b \pm 0.01	0.07 ^a \pm 0.00
	K	0.25 \pm 0.01	0.24 \pm 0.03	0.26 \pm 0.02
Stems	N	0.61 ^b \pm 0.06	0.25 ^a \pm 0.02	0.26 ^a \pm 0.01
	P	0.07 \pm 0.00	0.08 \pm 0.02	0.07 \pm 0.01
	K	0.19 \pm 0.02	0.17 \pm 0.03	0.25 \pm 0.02

The amounts of N, P and K accumulated in the aboveground biomass and current annual production increased with stand age in all studied species and the highest values were found in the black alder plantations (Table 6). The largest amounts of N, P and K accumulated in biomass were located in the leaves and the smallest in the shoots for all studied species (Figure 4 in **III**). Considering changes in biomass allocation with stand age, the share of accumulated nutrients increased in stems and decreased in leaves with rising stand age (Figure 4 in **III**).

Our results showed differences in nutrient use efficiency between species. Black alder had a lower NUE than silver birch and Scots pine, while silver birch had the lowest PUE among the studied species (Table 6). The N : P : K ratio in current annual production differed between species. Black alder had the lowest P : N and K : N (Table 6).

The aboveground biomass was positively correlated with the P content in biomass ($r = 0.99$, $p < 0.05$) in black alder and with P and K contents ($r = 0.99$, $r = 0.99$, $p < 0.05$, respectively) in silver birch. The aboveground biomass of Scots pine correlated strongly with N, P and K contents ($r = 0.99$, $p < 0.05$ for all cases).

Table 6. Accumulation of N, P and K in aboveground biomass (B) and in annual biomass production (CAP), N : P : K ratios for aboveground production and N and P use efficiency (NUE, PUE) in the studied plantations

Species	Age of stand, year	N _B	P _B	K _B	N _{CAP}	P _{CAP}	K _{CAP}	N : P : K	NUE	PUE
		kg ha ⁻¹			kg ha ⁻¹ year ⁻¹				kg kg ⁻¹	
Black alder	2	0.936	0.068	0.203	0.817	0.055	0.178	100:7:20	48.3	718
	4	26.432	2.352	8.699	22.449	1.788	6.711	100:8:30	61.1	768
	7	36.121	3.010	8.819	27.002	2.008	6.309	100:7:23	51.1	687
Silver birch	2	0.141	0.011	0.027	0.131	0.010	0.025	100:8:19	39.7	520
	4	0.909	0.124	0.296	0.835	0.110	0.260	100:3:31	78.0	592
	7	1.383	0.242	0.543	1.134	0.186	0.415	100:16:37	83.3	508
Scots pine	2	0.037	0.004	0.016	0.032	0.003	0.014	100:9:44	63.8	680
	4	1.629	0.194	0.913	1.377	0.160	0.740	100:12:54	103.0	886
	7	13.891	1.934	7.726	8.848	1.246	5.086	100:14:58	125.6	892

5.1.5. Root characteristics

The effect of tree species on short root parameters was significant. Larger specific root area (SRA) and specific root length (SRL) values of short roots and lower short root tissue density (RTD) and diameter (D_{SR}) values were found for deciduous species than Scots pine (Tukey test, $p < 0.05$) (Figure 3).

The mean short-root mass (W) was the smallest for silver birch and black alder had the highest short root length (L) values (Tukey test, $p < 0.05$) (Figure 3).

A tendency towards decreasing of mean short root SRA and SRL and increasing of mean short root RTD with increasing stand age was observed for all studied tree species; however, correlations were not statistically significant.

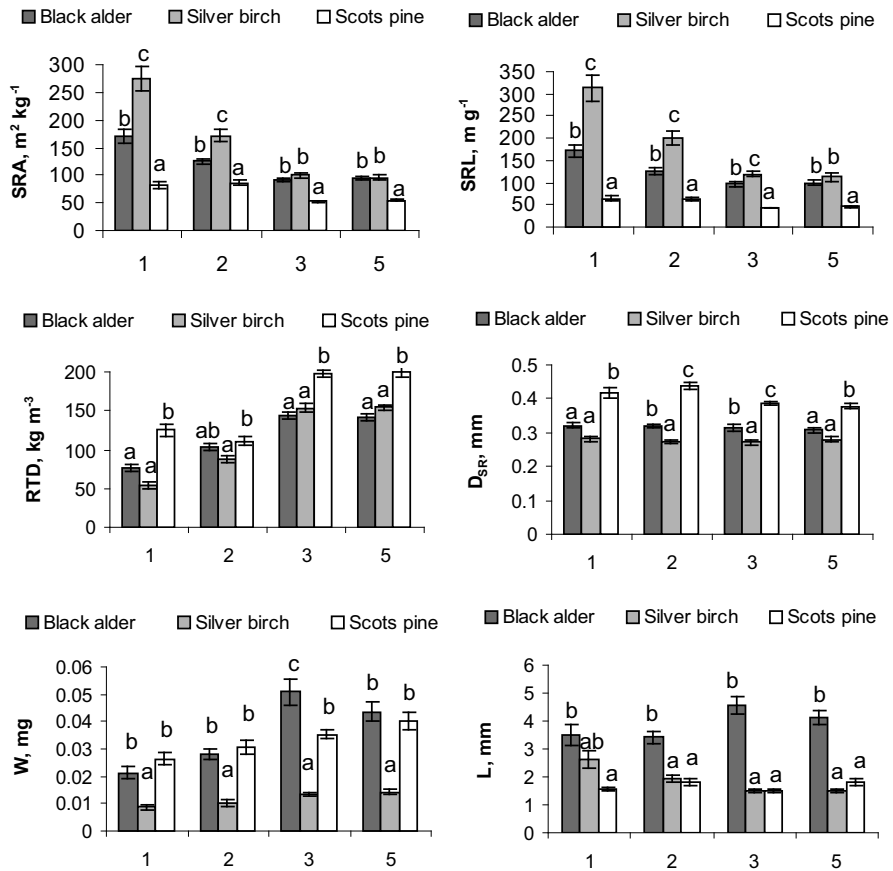


Figure 3. Mean short root characteristics in the studied stands (1, 2, 3, 5 – age of stand in years).

5.2. Scots pine and lodgepole pine plantations

5.2.1. Chemical composition of growth substrate

Comparison of native Scots pine and introduced lodgepole pine in the Narva reclaimed oil shale mining area showed some species-specific differences in tree morphology and nutrients in the relatively similar alkaline growth substrate (pH 8.0–8.2) in plantations of both studied pine species. The concentration of P, K and Mg in substrate of lodgepole pine was slightly higher compared to Scots pine; however, these differences were statistically insignificant (t -test, $p > 0.05$) (IV; VI; VII).

5.2.2. Growth and morphological parameters

Comparison of the height and diameter of 8-year-old pines in the Narva post-mining area showed that the mean height of the Scots pine stand was significantly larger than that of the lodgepole pine stand (Tukey test, $p < 0.05$), but there was no significant difference in the mean diameter of trees between the two tree species (Table 7).

In 8-year-old Scots pine and lodgepole pine stands the aboveground biomass allocation to compartments (needles, shoots, stem) within species and between species did not differ significantly (Tukey test, $p > 0.05$) (Table 2 and Figure 1 in V). Also, there were no statistically significant differences in the mean aboveground biomass between two species (Tukey test, $p < 0.05$); however, lodgepole pine had higher values of needle biomass and aboveground biomass than Scots pine (Table 7).

Table 7. Tree characteristics and biomass of the aboveground compartments of 8-year-old Scots pine and lodgepole pine (H – tree height, D – diameter at root collar). Values are given as the mean±SE. The superscript letters indicate a statistically significant difference

Species	D, cm	H, cm	Needle biomass, g	Shoot biomass, g	Stem biomass, g	Aboveground biomass, g
Scots pine	3.31±0.09	152.3±4.2 ^a	298.9±117.8	254.8±124.6	246.9±129.6	800.7±370.8
Lodgepole pine	3.28±0.07	120.0±2.9 ^b	476.9±200.4	294.7±158.8	282.2±124.1	1053.8±476.1

Analysis of the growth of 21–25-year-old Scots pine and lodgepole pine stands showed no significant differences in height and diameter values between species (Tukey test, $p > 0.05$) (Table 8).

Table 8. Mean characteristics of 21–25-year-old Scots pine and lodgepole pine stands (H – tree height, DBH – diameter at breast height). Values are given as the mean±SE

Species	H, m	DBH, cm
Scots pine	8.66±0.24	10.55±0.56
Lodgepole pine	8.87±0.20	11.55±0.45

Morphological analysis of current-year needles and shoots in Scots pine and lodgepole pine stands at different age showed differences between species. In 8-year-old pine stands significant differences between the two pine species were found in the length and dry mass of current-year needles, length and thickness of shoots and density of needles ($p < 0.05$) (Figures 3–5 in V). Comparison of the mean values of needle and shoot parameters between species in 21–25-year-old pine stands showed that the length and dry mass of 100 needles of Scots pine were smaller than those values for lodgepole pine (Figure 4). Scots pine formed significantly longer shoots compared to lodgepole pine. The dry mass of shoots and density of needles did not differ between species (Tukey test, $p > 0.05$).

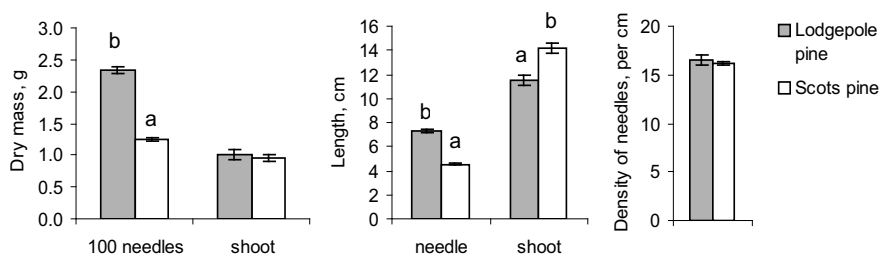


Figure 4. Morphological parameters of current-year needles and shoots of 21–25-year-old stands of Scots pine and lodgepole pine in the Narva post-mining area (mean±SE). Different letters indicate significant differences between means (Tukey test, $p < 0.05$).

5.2.3. Plant nutrient concentration

For both 8-year-old Scots pine and lodgepole pine plantations, the significantly highest concentrations of N, P and K were found in the current-year and 1-year-old needles and the lowest in the stems (Tukey test, $p < 0.05$) (Table 9). Although there were no statistically significant differences in N and P concentrations in needles between the two species (Tukey test, $p < 0.05$), a lower N concentration was observed in lodgepole pine needles. A higher concentration of K was found in the Scots pine needles ($p < 0.05$). The concentrations of N, P and K in the shoots revealed no differences between the species, except for the higher K concentration in the current-year shoots of Scots pine. The concentrations of elements in the stems did not differ between the species. The N : P : K ratio in the needles was 100 : 9.4 : 35.6 for Scots pine and 100 : 8.6 : 30 for lodgepole pine.

Table 9. Concentrations (%) of N, P and K in different tree compartments of 8-year-old Scots pine and lodgepole pine. Values are given as the mean±SE. The superscript letters indicate a statistically significant difference between compartments (Tukey test, $p < 0.05$)

Species	Element	Current-year needles	1-year-old needles	Current-year shoots	1-year-old shoots	Stem
Scots pine	N	1.59±0.03 ^a	1.38±0.03 ^b	0.72±0.06 ^c	0.58±0.06 ^c	0.34±0.03 ^d
	P	0.15±0.004 ^a	0.13±0.004 ^a	0.102±0.001 ^a	0.07±0.01 ^b	0.044±0.004 ^b
	K	0.57±0.03 ^a	0.52±0.03 ^a	0.63±0.04 ^a	0.27±0.01 ^b	0.19±0.02 ^b
Lodgepole pine	N	1.43±0.09 ^a	1.20±0.09 ^a	0.70±0.06 ^b	0.55±0.02 ^{bc}	0.28±0.01 ^c
	P	0.13±0.01 ^a	0.10±0.01 ^{ab}	0.10±0.002 ^{ab}	0.08±0.002 ^b	0.04±0.003 ^c
	K	0.42±0.024 ^a	0.35±0.033 ^a	0.37±0.01 ^a	0.28±0.01 ^b	0.17±0.01 ^c

Comparison of the nutrients in current-year needles of 21–25-year-old Scots pine and lodgepole pine showed that the concentrations of P, K and Ca in Scots pine needles were significantly higher than in the needles of lodgepole pine (Tukey test, $p < 0.05$) (Figure 5). No statistically significant differences were found between the studied species in N and Mg concentrations. The N : P : K ratio in lodgepole pine needles was 100 : 5.9 : 23.1 and in Scots pine needles 100 : 8.1 : 38.7. It was found that the N : P and N : K ratios were lower in Scots pine needles compared to lodgepole pine (Kuznetsova and Mandre, 2005; VI; VII).

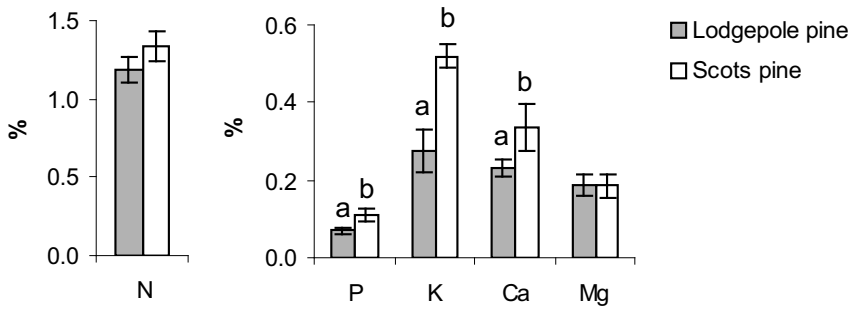


Figure 5. Mean concentrations of elements in current-year needles of Scots pine and lodgepole pine (mean \pm SD, $n = 3$). Different letters indicate significant differences between means (Tukey test, $p < 0.05$).

6. DISCUSSION

6.1. Characterisation of growth substrate

The success of restoration in the harsh conditions of post-mining landscapes depends on factors governing the survival and growth of seedlings. The growth of seedlings is affected mainly by habitat resources and tree species specificity as well as by the interaction of microbial communities in the rhizosphere and soil (Lõhmus *et al.*, 2006). As a result of mining, the relief is rugged, and the soil is heterogeneous and extremely stony. Oil shale mining spoil is very alkaline ($\text{pH}_{\text{KCl}} = 8.0$), the initial N and organic content, also water-holding capacity and microbial biomass are low (Lõhmus *et al.*, 2007; **II**). These may be the reasons why the first years of stand development under such harsh conditions are most critical for tree survival and growth. However, our results revealed a tendency of soil improvement in the oil shale mining area during the first seven years of tree growth. The soil pH showed a decreasing and the soil N concentration an increasing trend with stand age. Our findings are in accordance with other authors who also showed a decrease of the soil pH and an increase of soil organic matter and N content in afforested post-mining areas (Reintam *et al.*, 2002; Šourková *et al.*, 2005; Lõhmus *et al.*, 2007; Banning *et al.*, 2008). The decrease in the soil pH is caused not only by plant litter input and decomposition, but also by rhizodeposition, including acidic root exudates, because in studies of chronosequences in black alder and silver birch stands on post-mining areas the acidifying effect of the rhizosphere, by up to 1.5 pH units, was revealed (Lõhmus *et al.*, 2007; **II**).

Previous research (Reintam and Kaar, 2002) showed that pedogenesis of open-cast detritus differs in intensity and chemically by regions, depending significantly on tree species and density of vegetation. Numerous studies also suggest that nutrient availability is greater in deciduous rather than evergreen forests (Son *et al.*, 2007; Ste-Marie *et al.*, 2007). In comparison with conifers, speedy litter decomposition and enrichment of soil under deciduous trees are described by many researchers (Marschner, 2002; Ste-Marie *et al.*, 2007). However, on the basis of the present study, the effect of different tree species on soil nutrient composition was similar (**I**; **III**; **IV**). Although the species of conifers used in our study were rather tolerant of unfavourable growth conditions, relationships between soil and tree species were not especially evident. According to the literature,

lodgepole pine succeeds in nutrient-poor soils (Weetman *et al.*, 1985) and it is not very demanding about the soil pH, although its growth becomes inhibited when the soil pH > 8 (Koch, 1996). Scots pine is likewise relatively tolerant of disbalanced nutrients and quite high soil pH (Mandre and Ots, 1995). The relatively slow decomposition of the litter of conifers (Hendrickson and Burgess, 1989; Prescott *et al.*, 1992) may have been a reason of the similarity and N deficit in the growth substrate in both of our pine sites.

The effect of tree species on soil nutrients is not excluded during the following development of young plantations. It is known that the presence of N₂ fixers, such as alders, generally increases rates of uptake and return of all nutrients. Moreover, on sites where N supply limits forest productivity, the addition of alders to conifer stands increases productivity, as well as levels and availability of N, without decreasing soil pH (Binkley *et al.*, 1992). We observed a small increase in N concentration in black alder leaves with increasing N in the growth substrate, but not in the tree species that do not fix N₂. Due to a low N retranslocation from leaves, alder litter is rich in this nutrient and mineralises easily (Dawson and Funk, 1981; Löhmus *et al.*, 2002), which improves soil N status. In general, the forest floor under deciduous trees shows high N mineralisation rates (Kanerva and Smolander, 2007; Uri *et al.*, 2008). Our results indicated improving P nutrition through the decrease of soil pH (**II**; **III**). It is known that the loss in soil available P may relate to increasing uptake and assimilation of P by plants during stand development (Šourková *et al.*, 2005). In older black alder and silver birch leaves the P concentration was by about 26–34% higher compared with the youngest trees, which might be connected with increased microbial activity in soil. It is known that alders increase P availability through the activity of their roots and associated microbial communities (Giardina *et al.*, 1995; Uri *et al.*, 2002). Studies conducted in our plantations showed that microbial abundance was initially very low in oil shale mining spoil and increased with the age of stands. Moreover, in the second year after planting, when the survived plants have overcome planting shock, plants support rhizosphere microbial communities massively, but in the middle-aged stands, in improved soil, the support of rhizosphere communities is less important (**II**; Löhmus *et al.*, 2007; Rosenvald *et al.*, 2010). A possible explanation is that during the first year the intensive strategy of the fine root development prevailed in order to exploit the oil shale mining spoil by fine roots as much as

possible, and there was a deficit in assimilates allocated below ground (Löhmus *et al.*, 2007).

6.2. Survival, growth and biomass of trees

6.2.1. Young black alder, silver birch and Scots pine plantations

In our study we found that the survival and growth varied among tree species. The survival, height and diameter of black alder were the highest among the studied tree species. Our findings are in accordance with the results of Oliveira *et al.* (2005) and Kupka and Dimitrovský (2006), who found that *Alnus glutinosa* had the best adaptation to anthropogenic substrates in brown coal mining areas. Silver birch had the lowest survival rate among the studied species. The lower survival of silver birch may be due to superficial root systems of young birches, which could be easily damaged by alternating freezing-melting cycles in the topsoil.

Our results showed that black alder had the largest absolute biomass and production among the studied species; similarly Wittwer and Stringer (1985) concluded in a study with 5-year-old trees of five deciduous species that in both seedling and coppice stands, the total biomass of *A. glutinosa* was significantly greater than for other species. Many papers report high biomass and production of deciduous species in recultivated abandoned agricultural land and post-mining substrates. So, according to Pregent and Camire (1985), the aboveground biomass of a 4-year-old black alder culture on an abandoned agricultural site could be as high as 15.8 t ha⁻¹ and Johansson (2000) found that the aboveground biomass for 4–5-year-old black alder ranges from 2.0 to 13.4 t ha⁻¹. Mean annual increment values found in the literature for 4–12-year-old black alder on agricultural land range from 0.5 to 10.2 t ha⁻¹ year⁻¹ (Wittwer and Stringer, 1985; Johansson, 2000). A relatively high biomass production at 2.3 to 8.8 t ha⁻¹ year⁻¹ of 4–8-year-old stands of birch was found on agricultural land (Telenius, 1999; Uri *et al.*, 2007; Walle *et al.*, 2007). On clayey–sandy nutrient-poor post-mining substrates the aboveground biomass production of 4-year-old fast-growing poplar, willow and aspen ranges from 5.3 to 19.6 t ha⁻¹ (Bungart and Hüttl, 2001). Comparing the results of our study of biomass production for alder and birch stands with the above-presented results, it can be concluded that values found in post-mining areas are smaller than those reported in other studies.

However, we should take into account that the period of fast growth of the trees studied in this work is still ahead and their present small biomass may also be due to their slow adaptation to hard growth conditions. The first years of stand development are most critical for plant survival and growth in the harsh conditions of an oil shale post-mining area (Lõhmus *et al.*, 2006). From the literature it is known that in Finland birches show maximum production at the age of 10–12 years (Raulo, 1977). On the most fertile sites type in Estonia the maximum biomass increment of silver birch occurs at the age of 20–25 years (Tullus *et al.*, 1996). Current biomass increment of grey alder is the highest at young age, most probably at the age 6–10(12) years (Rytter, 1996). Magnani *et al.* (2000) in their study of Scots pine stands of different age found that maximum aboveground primary production occurs at the age of 14–18 years with the height of trees 7.7–9.9 m. Karu (2005) found that the height, diameter and biomass increment of Scots pine begins to decrease at the age of 25 and at the height of 6–8 m.

Our study demonstrated that biomass allocation both above- and belowground was tree species specific. Comparison of the share of different compartments in the biomass of stands did not reveal significant differences between the deciduous species, but in Scots pine more biomass was allocated to needles and less to roots than in the case of deciduous trees. At low nitrogen supply, the fast-growing species invest relatively more biomass in their roots than do slow-growing ones (van der Werf *et al.*, 1993). In our study there was a tendency towards higher RR for alder and birch than for Scots pine. However, Scots pines had about twice as high a share of fine roots in the root system as the deciduous trees. One possible reason for this is the size of the trees and their root systems: both were the smallest in pine. Also black alder and silver birch need more coarse roots due to their greater aboveground biomass and in order to ensure the stability of the tree (Coutts, 1983). In harsh soil conditions it is important first to invest more in fine roots to secure survival. Silver birch, black alder and Scots pine differed in their L/FR ratio. Black alder had the smallest ratio and also had the greatest first year survival; silver birch had the highest L/FR ratio and the lowest survival.

Our study demonstrated that aboveground biomass allocation was related to age and size of trees. These results are in good accordance with other studies that discovered the changes in biomass allocation with the increas-

ing of age and size of trees (Vanninen *et al.*, 1996; Mäkelä and Vanninen, 1998; Portsmuth *et al.*, 2005; Niinemets, 2006). The ratio of coarse roots/shoots+stem in black alder and Scots pine stands showed the decreasing trend with stand age. Our results are in accordance with Helmisaari *et al.* (2002), who found that in Scots pine stands on *Vaccinium* site type the ratios of belowground/aboveground biomass and fine root/needle biomass decreased with stand age.

6.2.2. Scots pine and lodgepole pine plantations

From the literature we can find that lodgepole pine has a vastly better height growth than Scots pine, which could be related to the higher relative growth rate of the former (Ågren and Knecht, 2001; Despain, 2001; Strand *et al.*, 2006). However, our findings in 8-year-old stands showed that the average height growth of Scots pine surpassed significantly the height growth of lodgepole pine and in root collar diameters no statistically significant differences between the species were found. Comparison of the mean heights and diameters of 21–25-year-old lodgepole pine and Scots pine showed also no differences between the species. Our results are in accordance with the research results obtained by Kasesalu (2000), who found a similar growth of lodgepole pine and Scots pine stands in *Myrtillus* site type. Moreover, the growth of lodgepole pine on a reclaimed oil shale mining area is the same as that of 20-year-old lodgepole pine in *Myrtillus* site type (Kasesalu, 2000). Also the growth of lodgepole pine on the post-mining area was similar to the growth of lodgepole pine of the same age in Söe arboretum established on abandoned agricultural land and better than in nutrient-poor *Calluna* site type (VII). According to Estonian classification of site quality classes (Metsa korraldamise..., 2006), the growing stock of the studied Scots pine stands corresponds to quality class II. Our results are in accordance with earlier research results of Kaar (2002), who found that 30–40-year-old Scots pine stands belong to II–IV quality class. Also, our results are similar to the dimensions of Scots pine on a post-mining area published by Korjus *et al.* (2007).

The mean tree aboveground biomass of 8-year-old Scots pine growing on the post-mining area was 0.8 kg. From the literature we can find different results of Scots pine biomass. Xiao and Ceulemans (2004) found that the average aboveground biomass of 10-year-old trees growing on nutrient-rich forest soil is 10.64 kg per tree. Helmisaari *et al.* (2002)

reported that in 15-year-old trees growing in nutrient-poor *Vaccinium vitis-idaea* forest site type the average tree aboveground biomass is 1.5 kg. The average aboveground biomass of lodgepole pine growing on the post-mining area was 1.1 kg. It is smaller than 4.25 kg for 11-year-old lodgepole pines growing on nutrient-poor soil studied by Bothwell *et al.* (2001), but greater than 0.25 kg, which was found by Turner *et al.* (2004) for 11-year-old lodgepole pines growing in Yellowstone National Park on dry and nutrient-poor soil. Thus, the biomass values of young trees were smaller on the oil shale post-mining area than on nutrient-poor forest soils. This can be explained by the extremely harsh initial growth conditions on the post-mining area.

The present study revealed that 8-year-old Scots pine and lodgepole pine did not differ significantly in the aboveground biomass and biomass allocation; however, needle mass and total aboveground biomass of lodgepole pine were a little higher compared to Scots pine. These results are in accordance with the results of Ågren and Knecht (2001) and Norgren (1996), who reported that lodgepole pine allocates a larger proportion of aboveground biomass to the needles than Scots pine. Our results of aboveground biomass allocation in young Scots pine and lodgepole pine are in accordance with data published by other researchers for Scots pine (Xiao and Ceulemans, 2004; Karu, 2005) and for lodgepole pine (Turner *et al.*, 2004). We found that lodgepole pine allocated 27% of the aboveground biomass to the stem and Scots pine 31%; however, the mean stem mass of lodgepole pine was greater than that of Scots pine (respectively 282.2 g and 245.0 g). This is in agreement with the results concerning the aboveground biomass in young and middle-aged Scots pine and lodgepole pine trees obtained by Albrektson *et al.* (1995), who reported that lodgepole pine allocates a lower proportion of its aboveground biomass to the stem while still producing a greater total stem mass than Scots pine. It seems probable that the higher stemwood production of lodgepole pine is accomplished through a faster total biomass development (Norgren, 1996). A little larger relative allocation to the stem and shoots of Scots pine compared to lodgepole pine in the present study is in agreement with the results of Norgren (1996), indicating a strategy for improving the physical stability to withstand strong winds and heavy snow loads when trees grow taller. A higher relative allocation to thin roots of lodgepole pine may contribute to its superior production (Norgren, 1996). Further research has to be conducted on roots of lodgepole pine growing

on post-mining areas. As the stand of lodgepole pine was planted at a density of 2×2 m and Scots pine at 1.5×1.5 m, the larger proportion of needles in lodgepole pine in our case may be due to better conditions of its root nutrition because a tree having better nutrition conditions is capable of growing more needles under the same light conditions than a tree whose nutrition conditions are not as favourable.

We used needle and shoot morphological parameters to estimate the formation of tree crown and growth of trees. The morphological parameters indicated that the formation of the crown varied between species. Our investigations in 8-year-old and 21–23-year-old Scots pine and lodgepole pine stands showed that current-year needles of lodgepole pine were significantly longer and heavier than Scots pine needles. Also, Norgren (1996) reported that young lodgepole pine formed longer and greater in mass current-year needles than Scots pine. The longer needles may be due to the genotype; however, from the literature (Laas, 2004) it is known that the length of needles of both species is in the same range (3–9 cm). The morphological parameters of shoots and needles differed significantly between the species in 8- and 21–25-year-old plantations. In stands of both ages lodgepole pine produced shorter and thicker shoots with longer and heavier needles. The density of needles on shoot differed significantly between the species in 8-year-old plantations, where lodgepole pine had greater needle number per unit shoot length than Scots pine. This is compatible with the results of Norgren (1996), showing that young lodgepole pine has a higher density of needles than Scots pine.

6.3. Nutrient allocation and accumulation in trees

The plant chemical diagnostic method is one of the possibilities of assessing the nutrition status of trees (Brække, 1996). To estimate the nutrition of trees, we compared nutrient concentrations and their ratios with scales of optimum nutrient concentrations. It is known that the interaction of different mineral elements in plant tissues and their balance are of great importance in tree growth and survival under stress conditions (Ingestad and Ågren, 1988; Marschner, 2002; Portsmouth *et al.*, 2005).

6.3.1. Young black alder, silver birch and Scots pine plantations

In our study the N concentration in alder leaves (2.5–2.9%) was a little lower than in general in Europe (2.0–4.0%) (Saarsalmi, 1995; Löhmus *et al.*, 1996; Uri *et al.*, 2002; Vares *et al.*, 2004). Also the concentrations of N in silver birch leaves and Scots pine needles were lower than needed for optimum growth according to Ingestad (1962), but the concentration of P was almost optimal for silver birch and Scots pine foliage compared to Ingestad's (1962) scale. Leaf N and P concentrations of black alder and silver birch found in the present study were quite similar to the respective values on abandoned agricultural land (Vares *et al.*, 2004; Uri *et al.*, 2007). Compared to the scale of Ingestad (1962), deficiency of K in Scots pine needles and silver birch leaves was detected. According to nutrition studies (Ingestad, 1987), the optimum N : P : K ratios for silver birch and Scots pine are 100 : 13 : 65 and 100 : 14 : 45, respectively. For black alder we used the optimal ratio for grey alder 100 : 18 : 50 (Ingestad, 1987). Comparing the N : P : K ratios for aboveground production in the present study (Table 6), it is evident that the relative P and K concentrations in annual production were lower than optimum in black alder. For silver birch and Scots pine the P : N ratios were close to optimum, while K : N in silver birch was twice lower than the Ingestad's optimum and the K : N ratio in Scots pine was a little higher than the optimum. So we can conclude that the pines in our plantations were well supplied with these nutrients.

Our findings of higher concentrations of nutrients in leaves and smaller in stems are in the same range with the respective results of other researchers in young silver birch (Uri *et al.*, 2007), black alder (Vares *et al.*, 2004) and Scots pine (Jach *et al.*, 2000) stands. Higher aboveground N, P and K contents were found in black alder than in the other studied species. The nutrient content per unit of dry biomass in 7-year-old black alder in the present study was in a range comparable with the respective values in 8-year-old silver birch stand (Uri *et al.*, 2007) and with 7-year-old hybrid aspen (Tullus *et al.*, 2009) on abandoned agricultural land. Thus, it can be concluded that in the post-mining area the nutrient accumulation of black alder was similar to that in a fertile agricultural land.

Some investigations show that different species growing in the same growth conditions use different amounts of nutrients to produce the same amount of biomass or stemwood (Alban *et al.*, 1978; Eriksson and Rosén, 1994).

In trees growing on reclaimed oil shale mining areas the amounts of NPK accumulated in biomass were largest for black alder, which was certainly related to the bigger biomass of these stands. However, the amounts of nutrients needed for producing a unit of aboveground biomass were significantly different between species. It was revealed that in similar growth conditions black alder used more N and silver birch more P for biomass production compared to the other studied species. Scots pine used N and P for biomass production more efficiently than black alder or silver birch. Higher N use efficiency in Scots pine in our study is in accordance with the results of Cui (1998), who showed that N use efficiency in *Pinus koraiensis* is a third higher than that of *Betula platyphylla*. Our data about lowest N use efficiency of black alder compared to the other studied species confirmed the findings of Binkley *et al.* (1992), who reported that N₂-fixing alders have lower N use efficiency than non-fixing tree species. These authors also reported a significant increase in soil N availability under N₂-fixing tree species such as alder, and nutrient use efficiency should decrease with increasing rates of uptake (Binkley *et al.*, 1984, 1992).

6.3.2. Scots pine and lodgepole pine plantations

For the assessment of the nutrient concentrations in the needles of pines we used the scale of optimal nutrient concentrations in current-year needles recommended by Ingestad (1962) and Brække and Salih (2002) for Scots pine (VI) and that by Brockley (2001) for lodgepole pine (IV; V; VII). The scale of optimal nutrients in needles recommended by Brække and Salih (2002) was worked out in Scots pine stands in Scandinavia and the scale suggested by Brockley (2001) was developed for lodgepole pine in its natural area in North America. Compared to these scales, our findings suggest N, P and K deficiency in Scots pine needles in stands of both ages studied (V; VI). The concentrations of N, P and K in lodgepole pine needles were also below the optimal level (IV). The plantations of Scots pine and lodgepole pine had a sufficient supply of Ca and Mg. Comparison to the optimum ratio of nutrients (Ingestad, 1979) showed that the ratios of nutrient elements in Scots pine needles were unbalanced in stands at both ages and the proportion of P and K in the needles was below the optimum (V; VI). Comparison of the ratios N : P and N : K in the needles of lodgepole pine with the relevant scale of Brockley (2001)

allows us to state unbalanced ratios and P and K deficiency in lodgepole pine (Kuznetsova and Mandre, 2005; **IV**).

It was found that lodgepole pine had longer and heavier needles with lower concentrations of N, P and K than Scots pine (**IV**; **V**). A lower N concentration in lodgepole pine needles compared to Scots pine has earlier been reported (Norgren and Elfving, 1994; Albrektson *et al.*, 1995). This fact allows us to state that lodgepole pine is able to form a larger needle with a lower concentration of N than Scots pine, which can be due to the higher N use efficiency of the former. Norgren (1996) suggested that the faster relative growth rate in lodgepole pine seedlings compared to Scots pine is linked with a higher leaf area and nitrogen use efficiency. Therefore we believe that having a higher N use efficiency is an advantage for lodgepole pine growth on nitrogen-poor post-mining areas.

6.4. Short root adaptations

Morphological parameters of short roots are best indicators of different root adaptation strategies because that functional compartment of the fine root system, which contains the primary structure and commonly has the highest rate of EcM colonization, assimilates most nutrients (Vogt and Persson, 1991; Ostonen *et al.*, 2007). Many studies have examined short root morphology in relation to species and soil conditions (Löhmus *et al.*, 1989, 2006; Ostonen *et al.*, 2006, 2007; **II**). Our results showed that short root morphological parameters of the studied species growing on reclaimed mine sites were affected both by tree species and stand age (**I**; **II**). It is known that trees adapt to nutrient-poor soils by increasing either the mass and length of fine roots (extensive adaptation) or the nutrient uptake efficiency of fine roots or associated microorganisms, or both (intensive adaptation) (Löhmus *et al.*, 2006; **II**).

Our results indicate different strategies of short-root morphological adaptations in coniferous (Scots pine) and deciduous tree species (black alder and silver birch) on oil shale mining areas. Both SRA, which affects uptake rates of nutrients, and SRL, indicating intensive exploitation of the soil by short roots per root mass unit, were higher for deciduous species, being the highest for silver birch. Scots pine had higher RTD and D. Analogously, Ostonen *et al.* (2006, 2007) reported that SRL and SRA of short roots

were greater for silver birch than for Norway spruce and Scots pine. In addition, Comas *et al.* (2002), comparing 1-year-old seedlings, showed that fast-growing deciduous species have thinner short roots with greater SRL than Scots pine. Curt and Prevosto (2003) reported that Scots pine has a relatively coarse fine root system, whereas silver birch has thin and densely branched roots that provide an efficient foraging system. Conifers use a more extensive strategy (increasing the mass and length of short roots) for nutrient acquisition (Ostonen *et al.*, 2006, 2007). In the case of Scots pine, an extensive strategy, which leads to an expansion of the short-root system, was also verified by the allocation of biomass in 1- and 2-year-old stands. The proportion of short roots in the root system of Scots pine was approximately twice as high as in the deciduous species (I). The higher SRL and SRA of deciduous species indicate that deciduous species prefer an intensive strategy in the uptake of nutrients: they form a large assimilating area per mass unit of short roots. The highest SRL and SRA of short roots of silver birch indicate a lower short root cost. However, one cannot rule out the possibility that the lowest survival of silver birch is due to its too thin roots and the high ramification of roots decreasing water conductivity (Sellin and Kupper, 2005) and causing a shortage of assimilates.

The effect of stand age was detected for many morphological parameters (II). The decreasing trend of short root SRA and SRL and increasing trend of RTD with stand age for all studied species were observed. Our results are in accordance with other investigations about changes in root morphological parameters in similar growth conditions (Löhmus *et al.*, 2007; Rosenvald *et al.*, 2010). Our results differ from the study carried out in a chronosequence of 10-, 30-, 60- and 120-year-old Norway spruce stands, where age had no effect on SRL of the fine roots (Borja *et al.*, 2008); however, younger spruce stands were not included in the study. Borja *et al.* (2008) concluded that functional changes in fine roots occur in response to quantitative change in biomass (production of more or longer roots) rather than as a result of morphological adaptations. However, silver birch is oriented more towards fine-root adaptations than increasing fine root biomass compared to coniferous tree species (Kalliokoski *et al.*, 2009). Also, Löhmus *et al.* (2007) found that birch is oriented more towards fine-root adaptations than support of rhizosphere communities than the black alder.

7. CONCLUSIONS

1. The effect of soil heterogeneity on the growth and adaptation of trees was minor (**I**). A tendency towards the decreasing of soil pH and P concentration with stand age was observed, while the soil N concentration increased. The effect of different tree species on the nutrient composition of soil was similar (**III**; **IV**; **VI**; **VII**).
2. Among the studied native tree species, black alder had the highest survival, growth and biomass compared to silver birch and Scots pine (**I**; **III**).
3. Scots pine allocated more biomass into leaves and fine roots while black alder and silver birch into stems and coarse roots. The lower L/FR biomass ratio was in proportion to better survival of seedlings; the lowest and highest values were found for black alder and silver birch, respectively (**I**).
4. Scots pine and lodgepole pine growing on a reclaimed oil shale mining area did not differ significantly in growth (**IV–VII**), aboveground biomass and biomass allocation patterns (**V**). However, a slightly larger aboveground biomass and a larger share of needles for lodgepole pine compared to Scots pine were observed (**V**).
5. The largest amounts of N, P and K were accumulated in the aboveground part in black alder stands due to the larger biomass of these stands. However, the N and P use efficiency for the production of a unit of biomass was different between species. Black alder and silver birch used more N and P for biomass production; Scots pine used nutrients most efficiently (**III**).
6. No statistical differences in N and P concentrations in needles between Scots pine and lodgepole pine were found. However, a slightly lower N concentration and larger mass and length of needles were found for lodgepole pine (**IV–VII**). We can suppose that lodgepole pine has a higher N use efficiency for the production of a unit of biomass than Scots pine.
7. Alkaline substrate on the post-mining area complicates assimilation of nutrients and causes their unbalanced ratios in trees. All studied tree species in young plantations suffered from N and K deficiency and black alder also suffered from P deficiency compared to optimum nutrient concentrations (**III**). Unbalanced ratios of nutrients and N, P, K deficiency in needles of 21–25-year-old Scots pine and lodgepole pine compared to optimum levels were found (**IV**; **VI**; **VII**).

8. Different strategies of short root morphological adaptations were observed in coniferous and deciduous tree species on the oil shale post-mining area. Higher short root specific root area (SRA) and specific root length (SRL) values, and lower short root tissue density (RTD) and diameter (D_{SR}) values were found in deciduous species compared to Scots pine (**I**). For Scots pine, extensive building of a fine root system was inherent, whereas deciduous trees improved mineral nutrition more by morphological adaptations of fine roots (**I**). The tendency towards the decreasing of mean short root SRA and SRL and increasing of mean short root RTD with the growing of stand age was observed (**II**).
9. As to the early development of stands, black alder was best adapted to the harsh conditions of the post-mining substrate; it was efficient in nutrient assimilation and produced a high biomass. Hence it should be the preferred species for the reclamation of oil shale mining areas (**I; III**). Both Scots pine and lodgepole pine may be considered as species that are well adapted to the mining substrate. Lodgepole pine could be used for primary reclamation of post-mining landscapes and for greenery, but not for replacing Scots pine (**IV–VII**).

Considering the ecological and economic aspects, it is possible to make some practical recommendations concerning the species suitable for the reclamation of post-mining areas:

1. Taking into account the deficiency of N in the soils of post-mining landscapes and the ability of black alder to fix N_2 and improve soil N status, black alder is most highly recommended for the afforestation of these landscapes.
2. On post-mining areas where N supply limits forest productivity, the addition of alders to conifer stands increases productivity, as well as levels and availability of N.

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SUMMARY IN ESTONIAN

Kodumaiste ja võõrliigiliste puistute kasv

põlevkivikarjääride tasandatud puistangutel

Kaevandamisega rikutud maade taastamine on tänapäeval väga aktuaalne probleem nii majanduslikus kui ka keskkonnakaitselises tähenduses. Põlevkivi, Eesti põhilise energiatoorme pealmaakaevandamisel tekib jätkuvalt rekultiveerimist vajavaid puistanguid. Tavaliselt on taastamise eesmärk saada kaevandatud piirkonnale võimalikult eelnevaga sarnane pikaajaline jätkusuutlik ökosüsteem. Karjääriviisilisel kaevandamisel hävitatakse taimkate ja mullakiht, seetõttu võib mulla ja kogu ökosüsteemi arengut karjääripuistangutel vaadelda kui primaarsuktsessiooni. Põlevkivi kaevandamise tagajärjel tekkinud pinnastel on ekstreemsed kasvutingimused. Karjääripuistangu kui kasvukoha spetsiifilisus seisneb selles, et see on kivine, vähese lämmastiku ja orgaanilise aine sisaldusega, leeliseline ja rikutud veerežiimiga. Kuna looduslikult arenevad taimkate ja muld karjääripuistangutel aeglaselt ja kivisuse pärast ei sobi need põllumajanduslikuks kasutamiseks, siis on eelistatud puistangute metsastamine. Metsastamine on ökoloogilisest ja majanduslikust aspektist lähtuvalt otstarbekas ja perspektiivne rekultiveerimise viis. Karjääripuistangute metsastamisega taastatakse taimkate ja mulla viljakus, samuti on metsad efektiivsed süsihappegaasi sidujad, võimaldades tasakaalustada antropogeenset CO₂ emissiooni, millel on suur lokaalne ja globaalne tähtsus. Majanduslikult on metsad puidu ja potentsiaalse taastuvenergia allikaks.

Vaatamata eelnevale edukale metsastamisele on tänaseks üles kerkinud mõned aspektid, millele tuleb tähelepanu pöörata. Esiteks on rekultiveeritud aladel kujunenud liiga suur hariliku männi osakaal. Teiseks probleemiks on tehnogeense mulla kvaliteedi halvenemine seoses sügavama põlevkivikihi kaevandamisega, mis suurendab puistangumulla kivisust. Seetõttu võib halveneda kultuuride kasvamine ning puistute edasine areng. Lahendamaks neid probleeme, on vajalik välja selgitada ökoloogiliselt ja majanduslikult otstarbekamad rekultiveerimisviisid. Tähtis on ka sobivate puuliikide valik. Erinevate puuliikide kasvatamine suurendab rekultiveeritavate alade bioloogilist mitmekesisust, vähendades seal monokultuuride osatähtsust. Karjääripuistangute metsastamiseks sobivamate liikide valikul on kohalike liikide kõrval kasutatud ka võõrpuuliike, sealhulgas

keerdmändi. Eriliigiliste puistute rajamisega kiirenevad rikutud aladel mullatekkeprotsessid. Okaspuupuistutega võrreldes on lehtpuu- või segapuistute rajamine keskkonkaitselisest ja sotsiaalmajanduslikust aspektist efektiivsem, sest lehtpuud on kiiremakasvulised, suurema haiguskindluse ja väiksema tuleohuga.

Käesolevas töös on esitatud kompleksed uurimustulemused kaevandusjärgsete alade taastamiseks rajatud erinevate puuliikide kultuuride kohta. Käesoleva töö tulemused on innovatiivsed, sest biomassi produktsioon ja juurte morfoloogilised adaptatsioonid, samuti aineringe karjääripuistangute puistutes, on Eestis senini olnud suhteliselt väheuuritud teema. Saadud uuringutulemuste põhjal on võimalik anda soovitusi puuliikide valikuks põlevkivikarjääride metsastamisel ökoloogilisest ja majanduslikust aspektist lähtuvalt.

Käesoleva uuringu põhieesmärgiks oli hinnata sanglepa, arukase, hariliku männi ja keerdmänni sobivust põlevkivikarjääripuistangute rekultiveerimiseks, analüüsides nende kasvu, biomassi, toitainete sisaldust ja peenjuurte morfoloogilist adaptatsiooni (I–VII). Käesolevas uuringus olid püstitatud järgmised hüpoteesid:

- 1) sanglepp on sobivaim puuliik puistangute rekultiveerimiseks ja mullaomaduste parandamiseks (I–III);
- 2) keerdmänd, võrreldes hariliku männiga, võib kaevandusjärgsel maastikul paremini kasvada, arvestades tema suuremat okka pindala ja pikkust (IV–VII);
- 3) erinevad liigid arendavad erinevaid imijuurte morfoloogiliste adaptatsioonide strateegiaid, mis on tähtsad mineraalse toitumise tagamiseks ja biomassi produtseerimiseks ebasoodsate kasvutingimustega karjääripuistangutel.

Doktoritöö detailsed eesmärgid olid: 1) analüüsida puude kasvamamineku, kasvu, biomassi allokatsiooni ja produktsiooni dünaamikat sanglepa, arukase ja hariliku männi kultuurides (I; III); 2) hinnata toitainete sisaldust, kogunemist, allokatsiooni ja kasutamise efektiivsust sanglepa, arukase ja hariliku männi kultuurides (I; III); 3) analüüsida peenjuurte morfoloogilisi parameetreid ja nende muutusi sõltuvalt kultuuri vanusest noortes sanglepa, arukase ja hariliku männi kultuurides (I; II); 4) analüüsida ja võrrelda kodumaise hariliku männi ja võõrliigilise keerdmänni kasvu, biomassi ja toitainete sisaldust (I–IV).

Tulemused ja arutelu

Taimede kasv ja biomassi moodustumine karjääripuistangutel on olulised parameetrid, hindamaks liigi sobivust taastamisprotsessil. Meie tulemused näitasid, et esimese 7 aasta jooksul uuritud kultuuride kasvamaminek ja kasv põlevkivi karjääripuistangutel erinesid oluliselt puuliigiti (**III**). Pärast seitsmendat kasvuaastat oli parima kasvamaminekuga ning parima kõrgus- ja jämeduskasvuga sanglepp, talle järgnesid harilik mänd ja arukask. Kui 7-aastases sanglepakultuuris oli puude säilivus 85%, keskmine kõrguskasv 217,6 cm ja jämeduskasv 4,8 cm, siis hariliku männi kultuuris olid vastavad näitajad 68,3%, 118,4 cm ja 3,1 cm, ning arukasekultuuris 40,7%, 123,1 cm ja 1,8 cm. Kase väiksem ellujäämus võib olla seotud sellega, et noortel puudel on pindmine juurestik ja külmakahjustus on tõenäoline. Sanglepa kultuuridel olid ka maapealne biomass ja produktsioon tunduvalt suuremad arukase ja hariliku männi näitajatest. Kultuuride suhtelises kasvukiiruses olulist erinevust puuliikide vahel ei olnud (**III**).

Ilmnesid puuliikidevahelised erinevused maapealse ja maa-aluse biomassi fraktsioonidesse jaotumuses (**I**; **III**). Uuritud lehtpuude biomassi allokatsioon oli sarnane. Kui lehtpuudel oli enamik biomassist koondunud tüvedesse ja jämejuurtesse, siis männil oli see koondunud okastesse ja peenjuurtesse. Puude maapealse biomassi jaotumus sõltus puu vanusest ja suurusest. Vanuse ja kõrguse kasvades suurenes võrsete ja tüve osakaal ning vähenes lehtede osatähtsus. Leiti, et arukasel oli esimestel istutusjärgsetel aastatel biomassi suhe lehed/peened juured oluliselt suurem (**I**).

Võrreldes käesolevas uuringus puistute algset kasvu ja biomassi kirjandusandmetega, võib järeldada karjääripuistangutel kasvavate puude aeglasemat kasvu ja väiksemat produktiivsust. Kuigi peaks arvestama, et nendel puudel on kiire kasvuperiood veel ees ja et praegune väike biomass võib olla tingitud ka puude aeglasest adaptatsioonist raskete kasvutingimustega.

Äsjatasandatud põlevkivikarjääride puistangutel on esialgu väga väike lämmastiku ja orgaanilise aine sisaldus ning mulla kõrge pH taseme tõttu on raskendatud P omastamine. Meie tulemused näitasid kasvukohatingimuste paranemise trendi juba esimese 7 aasta jooksul (**III**). Mulla uuringud näitasid, et mulla pH väärtus ja fosforisisaldus mullas vähenesid ning lämmastikusisaldus suurenes puistu vanuse suurenedes ja mulla arenedes. Olulist erinevust toitainete sisalduses erinevate puuliikide all kasvusubstraadis aga ei täheldatud (**III**).

Toitainete sisalduses olid erinevused puuliikide, erinevate fraktsioonide ja erineva vanusega puistute vahel. N, P ja K sisaldus oli suurem lehtedes ja väiksem tüvedes. N sisaldus biomassi fraktsioonides erines oluliselt puuliigiti. Näiteks 2- ja 4-aastastes kultuurides oli N sisaldus lehtedes ja jooksva aasta võrsetes sarnane sanglepal ja arukasel, olles oluliselt suurem hariliku männi näitajatest. Seitsme-aastastes kultuurides oli sanglepal kõrgeim N sisaldus igas fraktsioonis, võrreldes arukase ja männi näitajatega (III). Samuti täheldati N ja P sisalduse suurenemist sanglepa lehtedes ja P sisalduse suurenemist kase lehtedes puistu vanuse kasvades. Akumuleerunud N, P ja K hulk suurenes puistu vanusega kõikide uuritud puuliikide puhul, kõrgemad näitajad olid sanglepikutes. Suurimad NPK varud olid kõikide puuliikide puhul lehtedes. Akumuleerunud toitainete osatähtsus suurenes tüvedes ja vähenes lehtedes puistu vanuse suurenemisel. Lämmastiku ja fosfori kasutamise efektiivsus puistutes erines puuliigiti. Lehtpuud karjääripuistangutel vajavad rohkem toitaineid biomassi produtseerimiseks, mis on kooskõlas ka kirjandusandmetega. Toitainete varud 7-aastasest sanglepapuistus olid sarnased kirjanduses esitatud tulemustele noortes arukase- ja hübriidhaavakultuurides endistel põllumaadel. Võrreldes aga toitainete sisaldust lehtedes nende optimaalse sisalduse skaaladega, selgus, et kõikide uuritud puuliikide noored puistud kannatavad toitainete puuduse all (III).

Taime ja mikroobikoosluse koosmõju on eriti oluline taimekasvuks ebasoodsate tingimustega kasvukohas, nagu põlevkivikarjääride puistangud, kus kivine põuakartlik pinnas on algselt leeliselise reaktsiooniga ja väga vähese orgaanika- ning lämmastikusisaldusega. Mulla, mikroorganismide ja juurte koosmõjul luuakse risosfääris üksteist toetav süsteem, mis lõppkokkuvõttes tagab mineraaltoitainete parema kättesaadavuse ja omastamise. Puude juurtoitumist mõjutab ka toitaineid ja vett omastavate juurte morfoloogia. Puude veevarustuse ja mineraaltoitumise tagavad primaarse ehitusega (elusa esikoorega) imijuured, mis adapteeruvad kasvukoha muldalingimustega anatoomilis-morfoloogiliste muutuste kaudu. Muutusi imijuurte ehituses peegeldavad morfoloogilised parameetrid (imijuurte keskmine pikkus (mm), läbimõõt (mm), eripind (m^2/kg), eripikkus (m/g) ning kudede tihedus (kg/m^3)). Juurtoitumist mõjutavad peenjuurte morfoloogilised adaptatsioonid ja risosfääriefekt on olulised protsessid metsa ökosüsteemi arenguks ja funktsioneerimiseks.

Uurisime imijuurte morfoloogia ajalist dünaamikat rekultiveeritud põlevkivikarjääride sanglepikute, kaasikute ja männikute vanusereas (ühe,

kahe, kolme ja viie aasta vanustes puistutes) (**I**; **II**). Tulemused näitasid, et puude imijuurte morfoloogilised adaptatsioonid on liigispetsiifilised. Selgus, lehtpuude imijuure keskmine eripind (SRA) ja eripikkus (SRL) on suuremad ning pindtihedus (RTD) ja diameeter (D) väiksemad, võrreldes hariliku männiga (**I**). Lehtpuude imijuurte suurem eripind ja eripikkus näitavad, et toitainete omastamiseks kasutavad lehtpuud intensiivset taktikat, moodustades võimalikult suure toitaineid omastava pinna imijuurte massiühiku kohta. Männi puhul on olulisim ekstensiivne adaptiivne strateegia, mis viib peenjuurte süsteemi suurenemisele, mis leidis kinnitust ühe- ja kaheaastaste puistute biomassi allokatsiooni uurimisel, nimelt peente, <2 mm juurte osatähtsus juurestikus on männil kaks korda suurem kui lehtpuudel (**I**). Samuti selgus, et arukasel oli suurem imijuurte SRL ja SRA kui sanglepal. Noores eas panustab arukask intensiivse strateegia osas rohkem imijuurte morfoloogilisele adapteerimisele ja sanglepp mikroobide toetusele. Morfoloogilistel parameetritel ilmnisid ajalised trendid, mis on lisaks puu vanuse kasvamisele arvatavasti seotud ka mullatingimuste paranemisega. Imijuure keskmine kudede tihedus suurenes ning eripikkus ja eripind vähenesid puistu vanuse kasvades.

Käesolevas töös võrreldi 8- ja 21–25-aastaste kodumaise hariliku männi (*Pinus sylvestris* L.) ja introductseeritud keerdmänni (*Pinus contorta* var. *latifolia*) kultuuride kasvu põlevkivikarjääri puistangutel (**IV–VII**). Kaheksa-aastase hariliku männi ja keerdmänni puistu kasvu võrdlusel selgus, et hariliku männi keskmine kõrgus on oluliselt suurem kui keerdmänni kõrgus. Kahe liigi keskmise juurekaeladiameetri võrdlusel usaldusväärset statistilist erinevust ei täheldatud. Liigisiselt ei erinenud hariliku männi ega ka keerdmänni biomassi jaotumus fraktsiooniti. Ka liikidevaheline biomassi fraktsioonide võrdlus statistilist erinevust ei näidanud. Statistiliselt olulisi erinevusi kahe puuliigi maapealses biomassis ei olnud, kuid keerdmännil oli veidi suurem biomass ja okaste osatähtsus maapealsest biomassist (**V**). Biomassi allokatsiooni poolest olid harilik mänd ja keerdmänd sarnased kirjanduses leitud tulemustega vastavate liikide kohta.

21–25-aastase hariliku männi ja keerdmänni kasvu võrdlus näitas, et kõrgus- ja jämeduskasvu poolest olulist erinevust männiliikide vahel polnud (**IV**; **VI**; **VII**). Meie tulemused on kooskõlas kirjandusandmetega, kus leiti, et Eesti tingimustes keerdmänni ja hariliku männi kasv mustika kasvukohatüübis on sarnane. Samuti võib järeldada, et keerdmänni kasv karjääripuistangutel on sarnane mustika kasvukohatüübis kasvava keerdmänniga. Keerdmänni kasv karjääris oli sarnane endisel

põllumaal kasvava keerdmänniga, olles parem toitainevaeses kanarbiku kasvukohatüübis kasvavast sama vanast keerdmännist (VII). Hariliku männi kultuurid on üldiselt hästi kasvanud, uuritud puistud kuuluvad II boniteediklassi (VI). Käesolevas uurimistöös oli hariliku männi kasv võrreldav teiste autorite uuringute tulemustega karjääripuistangutele istutatud männikultuuride kohta.

Nii 8- kui ka 21–25-aastaste mändide okka- ja võrseparameetrite hindamise tulemusena võib järeldada, et karjääripuistangutel kasvaval keerdmännil on pikemad ja raskemad okkad ning lühemad ja paksemad võrsed kui harilikul männil (IV–VII). Käesoleva töö tulemused on kooskõlas kirjanduses leitud andmetega.

Hariliku männi ja keerdmänni okaste toitumise iseloomustamiseks kasutati elementide optimaalsete kontsentratsioonide skaalasid. Leiti, et mõlema liigi ja uuritud vanuste puhul oli N, P ja K sisaldus optimumist väiksem (IV–VII). Toiteelementide vahekorra ilmnes, et nii harilik mänd kui keerdmänd kannatavad fosfori- ja kaaliumipuuduse all. Samuti leidsime, et keerdmänni okkad sisaldavad hariliku männiga võrreldes veidi vähem lämmastikku, samas on okaste mass ja pikkus tunduvalt suuremad. See annab võimaluse väita, et keerdmänd suudab väiksema lämmastikuhulga juures moodustada suurema okkapinna kui harilik mänd, mis võib olla seotud keerdmänni lämmastiku kasutamise suurema efektiivsusega.

Järeldused ja vajadus edasiseks uurimiseks

1. Mulla heterogeensuse mõju oli nõrk noortes kultuurides (I). Mulla keemiliste näitajate osas ilmnes mulla pH ja mulla P sisalduse vähenemise ja mulla N sisalduse suurenemise trend puistu vanuse suurenedes (III). Erinevate puuliikide mõju mulla toitainete sisaldusele oli sarnane (III; IV; VI; VII).
2. Kultuuride kasvu uuring esimese 7 aasta jooksul näitas, et sanglepa kasvamine, kõrguskasv ja jämeduskasv ning maapealne biomass olid tunduvalt suuremad arukase ja hariliku männi vastavatest näitajatest (I; III).
3. Biomassi allokatsioon puudes oli liigispetsiifiline. Harilikus männis on okaste ja peenjuurte osatähtsus biomassist suurem lehtpuudega võrreldes (I). Väiksem lehed/peenjuured biomassi suhe oli proportsionaalne parema puude kasvaminekuga; väikseim vastav näitaja oli sanglepal ja suurim arukasel (I).

4. Uurimistulemuste põhjal võib järeldada, et olulisi erinevusi hariliku männi ja keermänni kasvus (**IV–VII**), maapealses biomassis ja biomassi allokatsioonis (**V**) karjääripuistangutel ei esinenud, kuigi keermännikultuuris täheldati veidi suuremat puude maapealse osa biomassi ja okaste osatähtsust hariliku männiga võrreldes (**V**).
5. Puistu maapealse osa NPK varud ja aastane kogunemine olid suurimad sanglepakultuurides, tulenevalt nende suurimast biomassist ja produktsooniist. Siiski selgusid erinevused puuliikide vahel toitainete kasutamise efektiivsuses biomassi ühiku moodustamiseks. Sanglepal ja arukasel oli N ja P kasutamise efektiivsus biomassi produtseerimiseks väiksem, harilik mänd oli kõige efektiivsem toitainete kasutamises (**III**).
6. Hariliku männi ja keermänni lämmastiku- ja fosforisisaldus jooksva aasta okastes ei erinenud oluliselt, kuigi keermänni okkad sisaldasid natuke vähem lämmastikku kui hariliku männi okkad ja olid oluliselt pikemad ja raskemad (**IV–VII**). See annab võimaluse oletada, et keermänd suudab väiksema lämmastikuhulga juures moodustada suurema okkapinna kui harilik mänd, seega on ta suurema lämmastiku kasutamise efektiivsusega.
7. Leeliseline kasvukeskkond komplitseerib toitainete omastamist ning disbalanseerib toitainete suhteid. Kõik puuliigid karjääripuistangute noortes kultuurides kannatavad lämmastiku ja kaaliumi (sanglepp lisaks veel fosfori) puuduse all, võrreldes optimaalse toitainete sisaldusega (**III**). Selgus, et 21–25-aastase hariliku männi ja keermänni jooksva aasta okkad kannatavad N, P ja K defitsiidi all ja toitainete suhted on tasakaalustamata (**IV; VI; VII**).
8. Imijuurte morfoloogilised adaptatsioonid karjääripuistangutel on liigispetsiifilised (**I**). Männi puhul on olulisim ekstenziivne kohanemisstrateegia, mis viib peenjuurte süsteemi suurenemisele. Lehtpuud parandavad mineraalset toitumist imijuurte morfoloogilise adapteerimise kaudu. Lehtpuude imijuurte suurem eripind ja eripikkus näitavad, et toitainete omastamiseks kasutavad lehtpuud intensiivset taktikat, moodustades võimalikult suure toitaineid omastava pinna imijuurte massiühiku kohta (**I**). Täheldati puistu vanuse mõju imijuurte morfoloogiale. Ilmnes imijuurte eripinna ja eripikkuse vähenemise ja imijuurte pindtiheduse suurenemise trend puistu vanuse kasvades (**II**).
9. Võttes arvesse algset puistute arengut, oli sanglepp paremini kohanenud rasketes kasvutingimustes kaevandusjärgsetel aladel, samuti oli ta efektiivne toitainete omastamises ja suure biomassi moodustamises,

seega võib sanglepp olla parim valik karjääripuistangute rekultiveerimiseks (**I; III**). Käesoleva uuringu tulemustest järeldub, et nii harilik mänd kui ka keermänd olid hästi kohanenud karjääripuistangu ekstreemsetes tingimustes. Arvestades kahe puuliigi sarnast kasvu, võib keermändi kasutada puistangute esialgseks taastamiseks haljastamise eesmärgil, mitte aga hariliku männi asendamiseks (**IV–VII**).

Antud töö põhjal, arvestades ökoloogilist ja majanduslikku aspekti, oleks soovitatav karjääripuistangutele istutada rohkem sangleppa, mis kiiremini rikastab mulda toitainetega ja soodustab mullateket, ning rajada segapuistuid (näit. männi-sanglepupuistuid), kus sanglepp võib suurendada mändide produktiivsust ja toitainete kättesaadavust.

Käesolev töö on pikaajaliste uuringute esialgne osa. Ta annab ülevaate noorte puude adapteerumisest ja kasvust. Uuringutulemused võivad olla meetodiliseks aluseks või lähtematerjaliks rikutud alade rekultiveerimisega seotud töödele. Uuringuid tuleb jätkata puistute kasvukäigu, biomassi tootmise ja taim–muld seoste osas, et saaks teha põhjalikumaid järeldusi erinevate puuliikide sobivuse kohta. Arvestades pinnaste heterogeensust, peaks uuringuga hõlmama rohkem puistuid. Edasine uuring tuleb suunata puude kasvu mõjutavate tegurite selgitamisele, eriti taim–muld seosele. Tähtis on uurida erinevate puuliikide mõju mulla arengule, samuti juurte arengut karjääripuistangute ekstreemsetes tingimustes.

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Survival of black alder (*Alnus glutinosa* L.), silver birch (*Betula pendula* Roth.) and Scots pine (*Pinus sylvestris* L.) seedlings in a reclaimed oil shale mining area

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ABSTRACT

Early survival and growth of black alder, silver birch and Scots pine were investigated on reclaimed extremely stony and heterogeneous calcareous (pH 8) opencast oil shale mining areas (OOSMAs). Biomass allocation, production, leaf and root adaptations, and mineral nutrition in relation to tree species and soil heterogeneity were analysed. The adaptive strategies of tree species in first-year plantations on OOSMA were different. Scots pine allocated 1.5–2 times more biomass into leaves and fine roots than deciduous trees. The lower leaf/fine root biomass ratio was in proportion to the better survival (%) of seedlings, decreasing in the following order: black alder (93%) ≥ Scots pine (83%) > silver birch (64%). Deciduous trees improved mineral nutrition more by fine-root morphological adaptations than Scots pine; e.g. the mean specific root length (SRL, m g^{-1}) of short roots increased in the following order: Scots pine (62) < black alder (172) < silver birch (314). The effect of soil heterogeneity on growth and adaptations was minor. All studied species suffered from P and N, and deciduous species also from K deficiency. In the first year after planting, black alder was best adapted to the harsh conditions of the post-mining substrate. The approaches of this study can be used for other regions where wastelands require reclamation.

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1. Introduction

Every year the opencast mining of oil shale in Northeast Estonia produces significant areas of degraded land, which needs restoration. Presently two underground mines and two opencast mines are in operation. As of 2006 the area damaged by oil shale opencast mining was 13,098 ha, of which 10,347 ha has been afforested (Kaar and Tomberg, 2006). The opencast oil shale mine sites are characterized by unfavourable conditions: heterogeneity, stoniness up to 100%, limited moisture, low nitrogen and organic content of mining spoil, and inhibited phosphorus uptake due to high pH (~8). These

conditions make the selection of species for afforestation very complicated and cause survival problems of young plantations.

The goal of restoration is usually to develop a long-term sustainable ecosystem native to the area where mining occurred (Chambers et al., 1994). The restoration of post-industrial landscapes is often a challenge regarding multifunctional land use issues. Multifunctionality is important from the point of view of both natural capital and socio-economic values (Haines-Young et al., 2006). On the other hand, restoration provides several opportunities for the optimal use of landscape functions (de Groot, 2006). Afforestation is a potentially sustainable reclamation strategy for post-mining sites (Parrotta et al., 1997; Filcheva et al., 2000; Singh et al., 2002; Dutta and Agrawal, 2003; Pietrzykowski and Krzaklewski, 2007). Also, afforestation is an optimal tool for the reclamation of opencast mining areas in northeastern Estonia (Kaar, 2002). A total of 52 indigenous and introduced species have been planted; species of *Larix* have shown the best growth among coniferous trees, and the native deciduous species silver birch (*Betula pendula*) and black alder (*Alnus glutinosa*) have been the most successful deciduous trees (Lõhmus et al., 2007). New stands are of better quality than the overmoist stands that grew there before mining (Kaar, 2002). Presently conifer plantations make up over 90% of the afforested area, with Scots pine (*Pinus*

Abbreviations: OOSMA, opencast oil shale mining area; LOI (%), loss on ignition; *H* (cm), height of trees; *B* (g), biomass; RR (%), root ratio; FR/R (%), fine root ratio; L/FR, foliage/fine root ratio; SLA ($\text{m}^2 \text{kg}^{-1}$), specific leaf area; LWA (g m^{-2}), leaf weight per area; FOE ($\text{g g}^{-1} \text{yr}^{-1}$), foliar assimilation efficiency; NUE ($\text{g g}^{-1} \text{yr}^{-1}$), N use efficiency; PUE ($\text{g g}^{-1} \text{yr}^{-1}$), P use efficiency; SRL (m g^{-1}), specific root length; SRA ($\text{m}^2 \text{kg}^{-1}$), specific root area; RTD (kg m^{-3}), root tissue density; *D* (mm), diameter; *L* (mm), length; *V* (mm^3), volume of the root tip; RTFM (mg^{-1}), root tip frequency per dry mass; RTFL (cm^{-1}), root tip frequency per root length; Ecm, ectomycorrhizal short roots.

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silvestris) stands predominating (86%) (Löhmus et al., 2006a). The quality of the substrate has declined and its stoniness has increased due to the thickening overburden in new mining areas. These harsh growing conditions might limit growth and survival of different tree species at different rates, and hence the reasonable choice of tree species for the reclamation of levelled opencast mines will be even more important in the future. For successful forestation and stability of plantations, the proportion of deciduous trees in the new stands should rise to 40–60%. Deciduous species have a number of advantages: the increased N and P availability in the soil, faster growth at young age and higher resistance to pests, diseases and fires in comparison with conifer monocultures (Kaar and Raid, 1996; Kaar, 2002; Vares et al., 2004; Löhmus et al., 2006a). While most plant species appear to act as catalysts for ecosystem rehabilitation, broadleaf species seem to yield better results than conifers. Fast-growing black alder and silver birch are particularly suitable to establish; they grow well on degraded sites (Kaar and Raid, 1996; Kaar, 2002; Singh et al., 2002; Vares et al., 2004), and yield high quality timber. Hence they are preferred on mining spoil areas (Kaar, 2002). Black alder could be considered to be a “biological fertilizer” which improves soil nitrogen status, fixing N_2 in symbiosis with *Frankia* in its root nodules and increases phosphorus availability in soil by the activity of its roots and associated microbial communities (Giardina et al., 1995; Uri et al., 2002). Although Scots pine is a pioneer species, it is mostly a stress-tolerator (Grime, 1979).

Foliar and fine-root adaptations are among the key factors determining growth rate and species performance. However, the potential of different tree species for recultivation of exhausted opencast oil shale mines in relation to fine-root and leaf adaptations and to decreasing site quality in opencast oil shale mining areas are still poorly investigated. The higher growth rate of black alder corresponds to the higher activity of microbial communities in its rhizosphere, and the higher specific root area of short roots compared to conifers (Vares et al., 2004; Löhmus et al., 2006b).

In this study, one-year-old black alder, birch and pine plantations established on calcareous spoil of opencast oil shale mines as perspective species for cultivation in alkaline wastelands were studied. The first years of stand growth are most critical for plant survival and development in the harsh conditions of an oil shale mining area (Löhmus et al., 2006a,b).

The main aim of the present study was to analyse the early survival and adaptive strategy of black alder, silver birch and Scots pine seedlings in first-year plantations on oil shale mining spoil. In particular, we studied whole-tree biomass allocation and above-ground production, root and leaf adaptations, foliar assimilation and nutrient use efficiencies in relation to tree species and soil heterogeneity.

2. Materials and methods

2.1. Plantation

The study plantations were established on skeletal calcareous quarry detritus of an opencast oil shale mining area in Narva, North-east Estonia (59°15'N, 27°42'E).

The area of the plantation was 0.7 ha. The mean soil parameters were the following: loss on ignition (LOI) 4.1%, pH_{KCl} 8.0, total nitrogen content 300 mg kg^{-1} , lactate soluble phosphorus 84.3 mg kg^{-1} . According to data of the Estonian Meteorological and Hydrological Institute, the growing season 2005 was rich in precipitation, which most probably favoured the survival of the seedlings. Three indigenous species – Scots pine (*P. sylvestris* L.), silver birch (*B. pendula* Roth.) and black alder (*A. glutinosa* (L.) Gaertn.) – were planted in $25 \text{ m} \times 25 \text{ m}$ plots in three replications in the Latin square design in

May 2005. One-year-old bare-rooted seedlings were used, and the planting arrangement $1.5 \text{ m} \times 1.5 \text{ m}$ for Scots pine; $2.0 \text{ m} \times 2.0 \text{ m}$ for black alder and for silver birch was employed. At the end of August 2005 survival (%), height H (cm) and height increment ΔH (cm) of trees in all replications were measured. In order to compare the growth potential of different tree species, the relative height increment $\Delta H/H$ (%) was calculated for the living trees.

2.2. Sampling and processing of model trees

2.2.1. Sampling

Trees in each replicate plot were categorized into three height classes: small, medium and high. When the leaf mass was close to maximum and no leaf fall occurred (early September 2005), one tree from each height class per plot was randomly selected and carefully excavated, for a total of 27 model trees.

2.2.2. Biomass, production and allocation

The aboveground part of model trees was divided into three compartments: leaves, shoots without leaves (trees had only current-year shoots) and stems. After drying at 70°C until constant weight the dry mass of all fractions was determined. The compartments were weighed to 0.001 g. Annual aboveground production of a tree, ΔB_{tree} (g yr^{-1}), was calculated (1):

$$\Delta B_{\text{tree}} = B_{\text{leaves}} + B_{\text{shoots}} + 0.5B_{\text{stem}}, \quad (1)$$

where B_{leaves} , biomass of leaves (g); B_{shoots} , biomass of shoots (g); and B_{stem} , biomass of stem (g).

As one-year-old seedlings were planted, the biomass and production of current-year shoots were equal. The production of the stem was calculated by dividing stem mass by the number of growing seasons. The relative annual production per tree $\Delta B/B$ was calculated as well.

Root ratio (RR, %; the proportion of the root system as part of total tree mass) and the ratio of fine roots (FR/R, %; the proportion of fine (<2 mm in diameter) roots in the root system) were calculated. The foliage/fine root (L/FR) ratio (Helmisaari et al., 2007) was calculated by dividing the biomass of leaves by the biomass of fine roots of a tree.

2.2.3. Leaf characteristics

From each model tree, all leaves or at least 25 leaves with petiole were taken and dried under pressure. Average single leaf area (including the petiole) was measured using the WINFOLIA programme and needle area using WINSEEDLE software. All measured single leaf blades with petiole and single pine needles were weighed to 0.0001 g . Specific leaf area SLA ($\text{m}^2 \text{ kg}^{-1}$) and leaf weight per area LWA (g m^{-2}) were calculated. Foliar assimilation efficiency (FOE; $\text{g g}^{-1} \text{ yr}^{-1}$) was calculated by dividing annual aboveground production by leaf mass. Foliar N and P use efficiency was calculated as aboveground production per foliar N or P accumulation (NUE, PUE $\text{g g}^{-1} \text{ yr}^{-1}$).

2.2.4. Root characteristics

Root systems were washed with tap water free of soil after excavation (10–15 min washing time of a root system) and separated into living and dead roots. Before processing the root systems were stored in plastic bags in soil in a freezer at 5°C not longer than three days after excavation. We tried to keep N and K leaching from roots low according to Clemensson-Lindell and Persson (1992). For alders, root nodules were separated (Löhmus et al., 2006a). The proportion of dead roots was negligible, and hence dead roots were omitted from further analysis. To analyse belowground biomass allocation, root systems were divided into two diameter classes:

$d < 2$ mm (fine roots) and $d \geq 2$ mm (coarse roots). From all fine roots of a tree or from bigger black alder root systems, a sub-sample of fine roots (approximately a third of the fine roots of a tree) was taken to estimate specific root length SRL (m g^{-1}), specific root area SRA ($\text{m}^2 \text{kg}^{-1}$), root tissue density RTD (kg m^{-3}) and average diameter D (mm).

Short roots (Ostonen et al., 2007) were used to analyse morphological characteristics. In our study we found only first- and second-order short roots. Two random sub-samples (on average 15 short-root tips) from each tree were taken, and root tips were analysed under a microscope. Mean short-root diameter (D , mm), length (L , mm) and surface area were measured. Short-root SRL, SRA, RTD, mean volume of the root tip (V , mm^3) and root tip frequencies per dry mass (RTFM, mg^{-1}) and per root length (RTFL, cm^{-1}) were calculated (Ostonen et al., 1999, 2006, 2007). For the measurement of fine- and short-root morphological parameters, WinRHIZO TM PRO 2003b software was used. Fine and short-root samples were dried at 70°C and weighed to 0.01 g and 0.01 mg, respectively.

2.3. Chemical analysis

Total soil N was determined using the Kjeldahl method, phosphorus in the soil was extracted by ammonium lactate and measured by flow injection analysis (Tecator ASTN 9/84) (Ruzicka and Hansen, 1981) in the Laboratory of Biochemistry of the Estonian University of Life Sciences. Soil LOI was determined at 360°C ; pH_{KCl} of soil samples was measured. Leaf macronutrients (N, P, K, Mg, Ca) per replication were determined by inductively coupled Plasma Mass Spectrometry (ICP, wet digestion with $\text{HNO}_3\text{-H}_2\text{O}_2$) in the laboratory of the Finnish Forest Research Institute.

2.4. Statistical methods

The normality of variables was checked using Lilliefors and Shapiro–Wilk's tests. In order to normalize the variables, log- and root-transformations were used. To check the differences between means of short-root and foliar parameters and between mean nutrient concentrations, the t -test was used; for other parameters, multiple comparison of means using the Tukey HSD test was applied. Pearson correlation coefficients (r) between growth parameters and leaf or soil nutrients were calculated. The STATISTICA 7.0 software was used, and a significance level of $\alpha = 0.05$ was accepted in all cases.

3. Results

3.1. First-year survival and height increment

The first-year survival (%) and tree height varied by species, but did not differ between replications within species. The average survival of species (mean \pm SE) ranged as follows: black alder \geq Scots pine $>$ silver birch, $93 \pm 6\%$, $83 \pm 5\%$ and $64 \pm 2\%$. The first year was the most critical for the survival of silver birch, whose survival was significantly lower than the survival of the other species (Tukey test, $p < 0.05$).

The mean height decreased in the order black alder $>$ silver birch $>$ Scots pine, 32.8 ± 0.4 cm, 16.6 ± 0.4 cm and 5.8 ± 0.1 cm, respectively (Tukey test, $p < 0.05$). The average relative height increment of the species was highest for Scots pine (0.63 ± 0.01), followed by black alder (0.35 ± 0.01) and silver birch (0.25 ± 0.01). The effect of soil heterogeneity (replication) was significant for the relative height increment in all studied species (Table 1).

Table 1

Mean (\pm standard error) height increment ($\Delta H/H$) of trees in replication plots.

Replication plot	Tree species		
	Black alder	Silver birch	Scots pine
1	0.32 ± 0.01^a	0.25 ± 0.02^{ab}	0.55 ± 0.02^a
2	0.33 ± 0.01^a	0.29 ± 0.02^b	0.60 ± 0.02^a
3	0.40 ± 0.01^b	0.22 ± 0.02^a	0.70 ± 0.02^b

Different superscript letters indicate statistically significant differences between replication means in the Tukey test at $p \leq 0.05$.

3.2. Biomass allocation and production

The effect of tree species on above- and belowground biomass allocation was significant (Tables 2 and 3). Deciduous species were quite similar in the aboveground biomass allocation, and only black alder had a greater share of shoots than silver birch (Table 2). Scots pine had a significantly greater share of leaves and a smaller proportion of stem in the aboveground biomass than the deciduous trees. The RR and its variability were similar for all species (Table 2) and FR/R was twice as high for Scots pine than for black alder or silver birch. The L/FR ratio was highest for silver birch, and smallest for black alder. Despite the soil heterogeneity, there were no significant differences in biomass allocation between replications within the studied tree species.

The largest aboveground biomass (B) occurred in the black alder stand. The aboveground biomasses in silver birch and Scots pine stands were similar (Table 3). In addition, the annual aboveground production (ΔB) was higher in the black alder stand than in the Scots pine and silver birch stands. The relative aboveground production ($\Delta B/B$) was significantly higher for Scots pine than for silver birch or black alder (Table 3).

3.3. Root morphological characteristics

Sensitive root characteristics responding significantly to soil heterogeneity were short-root RTD for Scots pine and SRL for silver birch. For black alder, no significant differences between the replicate plot means of short-root morphological parameters were found.

3.3.1. Fine roots

The mean D of fine roots decreased in the following order: $D_{\text{pine}} > D_{\text{alder}} > D_{\text{birch}}$; SRL decreased in the reverse order (Table 4). The fine-root SRA and SRL were significantly higher for silver birch than for the other species. The fine root RTD was similar for all studied species.

3.3.2. Short roots

The mean functional characteristics SRA, SRL and RTD were significantly different between all investigated tree species (t -test, $p < 0.05$) (Fig. 1). The mean SRA and SRL increased in the order pine $<$ alder $<$ birch, and the mean RTD increased in the reverse order.

D , L , V and RTFL varied significantly between tree species, and only the mean short-root mass W and the mean RTFM of black alder and Scots pine were similar (Table 5). Short roots of Scots pine were the shortest and thickest; D decreased similarly to RTD: $D_{\text{pine}} > D_{\text{alder}} > D_{\text{birch}}$. The mean short-root length increased in the order: pine $<$ birch $<$ alder, and hence RTFL increased in the reverse order. The mean short-root volume decreased in the order: $V_{\text{alder}} > V_{\text{pine}} > V_{\text{birch}}$. The mean short-root mass W was approximately 2.5 times smaller for silver birch than for the other species; accordingly the mean RTFM was the highest for silver birch.

Table 2

Aboveground biomass allocation, root ratio (RR%), fine root ratio (FR/R%), foliage/fine root ratio (L/FR) of tree species, growing on a reclaimed oil shale mining area.

Tree species	Percentage of aboveground biomass (%)			RR (%)	FR/R (%)	L/FR
	Leaves	Shoots	Stems			
Black alder	37.6 ± 2.6 ^a	14.8 ± 1.6 ^b	47.6 ± 3.3 ^b	46.6 ± 3.1	38.2 ± 4.8 ^a	1.22 ± 0.12 ^a
Silver birch	46.0 ± 4.0 ^a	8.7 ± 1.0 ^a	45.3 ± 4.7 ^b	39.9 ± 3.2	35.3 ± 3.6 ^a	2.15 ± 0.24 ^{ab}
Scots pine	70.5 ± 1.6 ^b	16.9 ± 1.2 ^b	12.6 ± 2.3 ^a	38.7 ± 3.1	76.9 ± 5.7 ^b	1.63 ± 0.17 ^{ab}

Different superscript letters indicate a statistically significant difference in the Tukey test at $p \leq 0.05$.

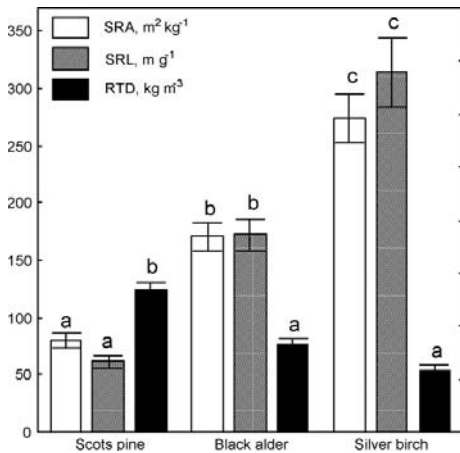


Fig. 1. Mean short root functional characteristics of one-year-old seedlings: root tissue density (RTD, kg m⁻³), specific root area (SRA, m² kg⁻¹), specific root length (SRL, m g⁻¹). Different letters indicate significant differences between means (t -test, $p < 0.05$). Bars indicate standard errors.

Table 3

The aboveground biomass (B , kg ha⁻¹), annual aboveground production (ΔB , kg ha⁻¹ yr⁻¹) and relative annual aboveground production ($\Delta B/B$) of studied stands.

Tree species	Number of trees	B (kg ha ⁻¹)	ΔB (kg ha ⁻¹ yr ⁻¹)	$\Delta B/B$
Black alder	2300	19.4 ^b	14.3 ^b	0.76 ^a
Silver birch	1600	1.5 ^a	1.2 ^a	0.77 ^a
Scots pine	3688	1.9 ^a	1.8 ^a	0.94 ^b

Different superscript letters indicate a statistically significant difference in the Tukey test at $p \leq 0.05$.

Table 4

Mean fine-root ($d < 2$ mm) characteristics of one-year old seedlings, diameter (D , mm), specific root area (SRA, m² kg⁻¹), specific root length (SRL, m g⁻¹), root tissue density (RTD, kg m⁻³).

Tree species	D (mm)	SRA (m ² kg ⁻¹)	SRL (m g ⁻¹)	RTD (kg m ⁻³)
Black alder	0.723 ± 0.032 ^b	34.9 ± 2.4 ^a	15.5 ± 1.5 ^b	168 ± 10
Silver birch	0.578 ± 0.024 ^a	59.7 ± 6.7 ^b	26.5 ± 2.3 ^c	154 ± 14
Scots pine	0.852 ± 0.020 ^c	28.5 ± 1.5 ^a	10.41 ± 0.57 ^a	172 ± 7

Different letters indicate significant differences between means (Tukey test, $p < 0.05$).

Table 5

Mean short-root morphological characteristics of one-year-old seedlings.

Tree species	D (mm)	L (mm)	V (mm ³)	W (mg)	RTFM (mg ⁻¹)	RTFL (cm ⁻¹)
Black alder	0.32 ± 0.01 ^b	3.51 ± 0.38 ^c	0.28 ± 0.03 ^c	0.021 ± 0.002 ^b	55.3 ± 7.1 ^a	3.36 ± 0.44 ^a
Silver birch	0.28 ± 0.01 ^a	2.65 ± 0.32 ^b	0.15 ± 0.02 ^a	0.009 ± 0.001 ^a	125.6 ± 16.7 ^b	4.06 ± 0.42 ^b
Scots pine	0.43 ± 0.02 ^c	1.48 ± 0.09 ^a	0.21 ± 0.01 ^b	0.026 ± 0.002 ^b	42.4 ± 3.9 ^a	7.33 ± 0.76 ^c

Different letters indicate significant differences between species means in the t -test at $p \leq 0.05$.

Table 6

Foliar characteristics, foliage N, P use efficiency in studied plantations: foliar assimilation efficiency (FOE, g g⁻¹ leaf yr⁻¹), specific leaf area (SLA, m² kg⁻¹), leaf weight per area (LWA, g m⁻²), N use efficiency (NUE, g g⁻¹ yr⁻¹) and P use efficiency (PUE, g g⁻¹ yr⁻¹).

Characteristics	Black alder	Silver birch	Scots pine
FOE (g g ⁻¹ leaf yr ⁻¹)	2.1 ^a	1.8 ^a	1.3 ^b
SLA (m ² kg ⁻¹)	12.4 ^b	13.4 ^c	9.8 ^a
LWA (g m ⁻²)	83.5 ^b	77.6 ^a	117.9 ^c
NUE (g g ⁻¹ yr ⁻¹)	98.1 ^{ab}	81.7 ^a	116.1 ^b
PUE (g g ⁻¹ yr ⁻¹)	1905.6 ^b	924.3 ^a	1175.5 ^a

Different letters indicate significant differences between tree species in the Tukey test and t -test at $p \leq 0.05$.

3.4. Foliar morphological characteristics

Leaf/needle area, leaf mass (except leaf mass of silver birch) and SLA demonstrated significant differences between replicate plots, sensitively responding to soil heterogeneity. The t -test revealed significant differences between all studied foliar characteristics of the deciduous species. Black alder had higher mean single leaf area (7.7 ± 0.7 cm²), leaf mass (0.065 ± 0.006 g) and LWA (83.5 ± 1.6 kg m⁻²) and smaller SLA (12.4 ± 0.3 m² kg⁻¹) than silver birch (4.6 ± 0.6 ; 0.03 ± 0.004 ; 77.6 ± 2.8 ; 13.4 ± 0.5 , respectively).

The mean foliar assimilation efficiency (FOE, g g⁻¹) of model trees (aboveground production per unit weight of leaves) was highest for black alder (Tukey test, $p < 0.05$) (Table 6). The foliar NUE for forming tree production was higher in Scots pine needles than in the leaves of deciduous species. The PUE was highest in black alder leaves; foliar N and P use efficiencies did not differ between silver birch and Scots pine (Tukey test, $p < 0.05$) (Table 6).

3.5. Nutrients and growth

Foliar chemical composition (N, P, K, Mg, Ca) was different for the deciduous species and Scots pine (t -test, $p < 0.05$) for all nutrients except P (Table 7); birch and alder had higher foliar N, Ca and Mg concentrations than Scots pine. Silver birch leaves had the highest K concentration. The only difference between the deciduous species was in leaf Ca concentration, which was higher for black alder than for silver birch. Mass ratios of four macronutrients ($N = 100\%$) of leaves for comparing with Ingestad ratios (Ingestad and Lund, 1979) are given in Table 8.

A strong positive correlation between tree diameter and needle N concentration ($r = 0.99$, $p < 0.05$) was found in Scots pine. A strong positive correlation between tree height and foliar

Table 7

Mean nutrient (N, P, K, Mg, Ca) concentrations in leaves of silver birch, black alder and Scots pine seedlings grown for one year in plantation on oil shale mining detritus.

Nutrient	Black alder	Silver birch	Scots pine
N (%)	2.27 ± 0.25 ^b	2.12 ± 0.16 ^b	1.148 ± 0.053 ^a
P (mg kg ⁻¹)	1168 ± 141 ^a	1873 ± 435 ^a	1134 ± 153 ^a
K (mg kg ⁻¹)	9430 ± 1072 ^{ab}	9686 ± 64 ^b	7430 ± 267 ^a
Mg (mg kg ⁻¹)	6550 ± 641 ^b	5126 ± 411 ^b	2013 ± 220 ^a
Ca (mg kg ⁻¹)	14,900 ± 208 ^c	12,600 ± 493 ^b	4366 ± 947 ^a

Different letters indicate significant differences between tree species in the *t*-test at $p \leq 0.05$.

Table 8

Proportions by weight of nutrients (N = 100) P, K, Ca and Mg in leaves of one-year-old seedlings of black alder, silver birch and Scots pine.

Tree species	P:N	K:N	Ca:N	Mg:N
Black alder	5.1 ^a	41.5 ^a	65.6 ^b	28.8 ^b
Silver birch	8.9 ^{ab}	45.8 ^a	59.5 ^{ab}	24.2 ^{ab}
Scots pine	9.9 ^b	64.7 ^b	38.1 ^a	17.5 ^a

Different letters indicate significant differences between tree species in the *t*-test at $p \leq 0.05$.

P concentration was found in silver birch ($r = 0.99$, $p < 0.05$). A strong positive relationship between average leaf area and foliar P concentration ($r = 0.99$, $p < 0.05$) and a negative correlation between SLA and soil N concentration ($r = -0.99$, $p < 0.05$) were found in silver birch, and a positive correlation between leaf area and soil P concentration was found in black alder ($r = 0.99$, $p < 0.03$).

4. Discussion

4.1. Survival and growth of trees

The success of restoration in the harsh conditions of post-mining landscapes depends on factors governing the survival and growth of seedlings. The growth of seedlings is affected mainly by habitat resources and tree species specificity as well as by the interaction of microbial communities in the rhizosphere and soil (Löhmus et al., 2006b). Due to the planting shock, the weather conditions of the first season are very important; however, high precipitation in growing season favoured the survival of trees in our study.

Habitat resources in the quarry detritus of oil shale mining areas strongly affect the adaptation of trees. In the first year the plantations are characterized by full light due to the unclosed canopy, the absence of a humus horizon, stony and alkaline calcareous quarry detritus with low water-holding capacity and microbial biomass (Löhmus et al., 2006a).

In our study we found that first-year survival and growth varied among tree species, whereas the effect of both tree species and soil heterogeneity was significant. Our results are in accordance with the results of Casselman et al. (2006) for reclaimed coal mines. We found that the survival and relative height increment of black alder was the highest among the studied tree species. Oliveira et al. (2005) found *A. glutinosa* to have the greatest survival rate in a field trial with *A. glutinosa*, *Salix atrocinerea* and *Acer negundo* planted in a highly alkaline anthropogenic sediment. The results of Vares et al. (2003) on abandoned agricultural land revealed a better growth of black alder plantations compared to other deciduous species, and the survival rate of alders was high after the first growing season (87–94%).

4.2. Biomass allocation

Our study demonstrated that biomass allocation both above- and belowground was tree species specific; however, RR was similar in all species, with means varying from 39% to 47%. Accordingly, some authors concluded that the root system may account for 30–60% of the total biomass of young trees (Taylor and Davies, 1990; Messier and Puttonen, 1995). At low nitrogen supply, the fast growing species invest relatively more biomass in their roots than do slow growing ones (Van der Werf et al., 1993). In our study there was a tendency towards higher RR for alder and birch than for Scots pine, although the differences were not significant. However, the Scots pines had about twice as high a share of fine roots in the root system as the deciduous trees. One possible reason for this is the size of the trees and their root systems; both were the smallest in pine. Also black alder and silver birch need more coarse roots due to their greater aboveground biomass and in order to ensure the stability of the tree (Courtts, 1983). In harsh soil conditions it is important first to invest more in fine roots to secure survival. Silver birch, black alder and Scots pine differed in their leaf/fine root ratio. Black alder had the smallest ratio and also had the greatest first-year survival; silver birch had the highest leaf/fine roots ratio and the smallest survival, respectively. The lower survival of silver birch may also be due superficial root systems of young birches that could be easily damaged by bingo caused by alternating freezing–melting cycles in the topsoil.

In our study the proportion of roots and stems of silver birch was 39.9% and 27%, respectively. Portsmouth and Niinemets (2006) found that at higher irradiance the share of the roots of first-year seedlings of *B. pendula* was 56%, and that of the stems 16%. Lower stem mass ratio and larger root mass ratio at higher irradiance are a common counter-reaction in temperate trees (Reich et al., 1998).

Black alder had the highest whole-tree biomass; similarly Wittwer and Stringer (1985) concluded in a study with five-year-old trees of five deciduous species that in both seedling and coppice stands, the total biomass of *A. glutinosa* was significantly greater than for other species.

4.3. Root characteristics

We investigated fine- and short-root morphological adaptations in relation to habitat resources and tree species specificity. We observed ectomycorrhizal (EcM) short roots, although EcM colonization (%) was not estimated in our study. In a 28-year-old black alder stand on an oil shale mining area, the EcM colonization of short-root tips represented 80–90% (Tedersoo et al., 2009).

4.3.1. Fine roots

The functional efficiency of fine roots is closely related to the energy costs of the development and maintenance of different root systems (Persson, 1983). If the quality of the soil is poor, there is a tendency for the tree root system to develop long roots that rapidly penetrate large soil volumes (Ingestad and Lund, 1979; Persson, 1983). As shown by the excavation of root systems in our study, this tendency was most strongly expressed in Scots pines.

Fine roots of Scots pine seedlings on mining spoil had larger diameters and smaller SRL compared to the deciduous species. Bauhus and Messier (1999) found that conifers optimize soil exploitation efficiency through the relatively slow development of coarse root systems, while the deciduous trees maintain highly ramified thin fine roots to optimize the use of the exploited soil volume. However, in our study this was only partly confirmed: the highest RTFM of short roots was found for silver birch (159 mg⁻¹),

followed by black alder (55 mg^{-1}) and Scots pine (42 mg^{-1}), and the highest RTFL of short roots was found in Scots pine. Deciduous species compensated for the smaller share of fine roots in the root system with higher fine-root SRL and SRA compared to Scots pine. The high fine-root SRL value for silver birch ($26.5 \pm 2.3 \text{ m g}^{-1}$) in our study was comparable with data from Van Hees and Clercx (2003), who found the mean fine-root SRL of young silver birch seedlings to be 24.7 m g^{-1} in a plantation growing in full light. The fine-root SRA ($59.7 \text{ m}^2 \text{ kg}^{-1}$) of silver birch grown on the oil shale mining spoil was slightly higher than the SRA ($46.5 \text{ m}^2 \text{ kg}^{-1}$) of one-year-old potted silver birch seedlings found in a study by Aspelmeier and Leuschner (2006).

4.3.2. Short roots

Morphological parameters of short roots are the best indicators of different root adaptation strategies, because that functional compartment of the fine root system, which contains the primary structure and commonly has the highest rate of EcM colonization, assimilates most nutrients (Ostonen et al., 2007). Our results confirmed different strategies of short-root morphological adaptations in coniferous (Scots pine) and deciduous tree species (black alder and silver birch) in oil shale mining areas. Scots pine had larger short-root RTD than the deciduous trees, as well as smaller SRL and SRA. Ostonen et al. (2006) studied older stands (4 and 27 years old) of the same species in an oil shale mining area and found similarly greater SRL and SRA of short roots for deciduous species, but smaller RTD than for Scots pine. In addition, Comas et al. (2002), comparing one-year-old seedlings, showed that fast-growing deciduous species have thinner short roots with greater SRL than Scots pine. Conifers use a more extensive strategy (increasing the mass and length of short roots) for nutrient acquisition (Löhmus et al., 2006a; Ostonen et al., 2006, 2007), and so does the Scots pine. The higher SRL and SRA of deciduous species indicate that deciduous species prefer an intensive strategy in the uptake of nutrients: they form a large assimilating area per mass unit of short roots. The highest SRL and SRA of short roots of silver birch indicate the smaller short root cost. However, one cannot rule out the possibility that the lowest survival and smallest relative height increment of silver birch are due to its too thin roots and the high ramification of roots decreasing water conductivity (Sellin and Kupper, 2005) and causing a shortage of assimilates.

4.4. Leaf characteristics

Leaf adaptations in first-year plantations were tree species specific. According to Alama et al. (2004), under the worst conditions of mineral nutrition, silver birch formed the smallest and thinnest leaves. In a study of the drought response of silver birch, Aspelmeier and Leuschner (2006) found the highest leaf area per plant and SLA in the clone originating from the driest environment. In our study SLA was most probably affected by soil heterogeneity, because all plants grew in full light.

Average single leaf area and dry mass were significantly higher for black alder than for silver birch; SLA and LWA differed significantly between the tree species. The SLA of black alder ($12.4 \text{ m}^2 \text{ kg}^{-1}$) in our study was comparable to the results of Vares et al. (2004), who reported $13.1 \text{ m}^2 \text{ kg}^{-1}$ mean SLA for black alder at Sirgala oil shale mining area. From Van Hees and Clercx (2003) it is known that young silver birch SLA in full light is $13.2 \text{ m}^2 \text{ kg}^{-1}$, which is similar to our data. The mean leaf dry mass per unit area (LWA) of black alder in our study (83.5 g m^{-2}) was comparable to the 78.6 g m^{-2} calculated for black alder in an oil shale mining area by Vares et al. (2004) and to the 77.4 g m^{-2} calculated for black alder in Estonia by Niinemets and Kull (1994). The LWA of silver birch (78 g m^{-2}) was greater than reported in Portsmouth and Niinemets

(2006) for seedlings at full sunlight and low nutrient availability (60 g m^{-2}). Our results showed that alder foliage was most efficient, similarly Vares et al. (2004) found that foliar assimilation efficiency for 21-year-old alders was higher in the oil shale mining area than in other growth conditions in Estonia.

4.5. Nutrients and growth

Coniferous species have lower concentrations of leaf nutrients and longer leaf life span than deciduous species. These are important mechanisms for nutrient economy, making possible the colonization of low fertility soils (Aerts, 1996). Also in our study the N (%) in Scots pine needles was approximately twice lower than in black alder or silver birch leaves.

A number of authors have emphasised that nutrient use efficiency increases as soil nutrients decrease (Vitousek, 1984; Distel et al., 2003). Our results showed that the Scots pine compensated for its small N content in leaves through a higher efficiency of N use than for silver birch and black alder. This is in accordance with the results of Cui (1998), who showed that N use efficiency in *Pinus koraiensis* is a third higher than that of *Betula platyphylla*. According to Ingestad (1962), the optimum N concentration in Scots pine needles is 2.4–3.0% and in birch leaves 3.4–4.0%. Hence in our study the N% in silver birch and Scots pine seedlings was much lower than optimal. Alder leaves are characterized by a high concentration of N: 2.57–3.47% (Llinares et al., 1992). In our young black alders, however, the average N concentration was low (2.3%).

Ingestad's ratios P:K:Ca:Mg ($N = 100$) at optimum nutrition for silver birch and Scots pine are 13:65:7:8.5 and 14:45:6:6, respectively. For black alder the optimal ratios for grey alder (*Alnus incana*) 18:50:5:9 (Ingestad, 1987) were used. The P:N ratio for black alder was 3.5, for silver birch 1.5 and for Scots pine 1.4 times less than the respective optimum value. The K:N ratio was 1.4 times higher than the optimum for Scots pine, but 0.8 and 0.7 times lower than the optimum for black alder and silver birch, respectively. Ca and Mg were assimilated to a large extent by all species studied, most probably due to the increased availability of Ca and Mg as a result of rhizosphere acidification (Marschner, 2002; Löhmus et al., 2007).

The leaf P concentration was lower than the optimal value in all of the studied species. This is most probably caused by the high pH of the growth substrate, due to which Ca and Mg phosphates are poorly soluble, and its low water storage capacity. Alders have a high requirement for P (Ingestad, 1987; Giardina et al., 1995), and in our case black alder showed the greatest P deficit, irrespective of the fact that alders increase phosphorus availability in soil by the activity of their roots and associated microbial communities (Giardina et al., 1995; Uri et al., 2002). Phosphorus deficiency may slow down the development of alder roots and nodules and also inhibit the nitrogen-fixing capacity of alders (DeBell and Radwan, 1984). Nevertheless, the black alder seedlings had the highest absolute height in our experiment, and this species also had the best survival rates. A possible reason of the best survival and growth of black alder is significantly higher foliar P use efficiency in black alder than in Scots pine or silver birch. According to several authors (Wells et al., 1986; Allen, 1987; Fürst, 1997), the Scots pine foliar P concentration deficiency level is 1000 mg kg^{-1} , so the Scots pine foliar P concentration ($1134 \pm 153 \text{ mg kg}^{-1}$) on calcareous quarry detritus was near critical. The foliar K concentrations of both silver birch and black alder were lower than optimal (according to Ingestad (1987) and Fürst (1997)). Considering the optimal ratio of nutrients by Fürst (1997), K (with respect to N) was not limiting in pine. We found positive correlations between tree size and foliar N and P concentrations. Tree or leaf size correlated positively with N or P availability, whereas pine was affected more by N and deciduous trees by P.

5. Conclusion

The survival and growth of first-year plantations of silver birch, black alder and Scots pine on opencast oil shale mining areas were different. Scots pine allocated approximately twice as much biomass into leaves and fine roots than deciduous trees. In proportion to the better survival (%) of seedlings, the lower leaf/fine root biomass ratio decreased in the order black alder \geq Scots pine $>$ silver birch. For Scots pine, extensive building of a fine root system was inherent, whereas deciduous trees, especially silver birch, improved mineral nutrition more by morphological adaptations of fine roots. The effect of soil heterogeneity on growth and adaptations was minor. All studied tree species suffered from N and P deficiency, and deciduous trees also suffered from K deficiency. During the first year after planting, black alder was best adapted to the harsh conditions of the post-mining substrate, and hence it should be the best choice for the reclamation of oil shale mining areas concerning the early development of stands. The approaches of this study can be used for other regions where created wastelands require reclamation.

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Black alder as a promising deciduous species for the reclaiming of oil shale mining areas

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Abstract

Black alder (*Alnus glutinosa*) plantations of different age were investigated on reclaimed oil shale mining areas in Northern Estonia with the aim of analysing the impact of microbial communities in the rhizosphere and bulk soil, and the effect of fine root adaptations on stand development and productivity. Biolog Ecoplates were used to determine the community-level physiological profiles (CLPP) in the rhizosphere and bulk soil samples. CLPP were summarized as AWCD (average well color development, OD 48h⁻¹). The rhizosphere/bulk soil ratio of AWCD was an order higher in the 4-yr-old stand than in the first year after planting or in middle-aged stands. The substrate-induced respiration (SIR) and basal respiration (BAS) of bulk soil samples were measured, and the metabolic quotient $q(\text{CO}_2) = \text{BAS}/\text{SIR}$ was calculated. Short root morphological studies were carried out using WinRHIZOTM Pro 2003b. SIR increased from 0.23 to 2.73 mgCg⁻¹, while $q(\text{CO}_2)$ and mean specific root length (SRL, m g⁻¹) decreased with increasing stand age (from 1 to 26 years) from 0.51 to 0.25, and from 172 to 90 m g⁻¹ respectively. Soil pH decreased 1 unit during the first 26 years. According to efficient adaptive strategies, the survival and productivity of black alder stands on oil shale mining areas are high, and hence black alder is a perspective tree species for the afforestation of these areas.

Keywords: Alnus glutinosa, Biolog Ecoplates, fine root adaptations, oil shale mining area, rhizosphere processes, substrate-induced and basal respiration.



1 Introduction

1.1 Reclamation of disturbed landscapes in Northern Estonian oil shale mining area

Every year opencast mining in the Northeast Estonian oil-shale field – the largest commercially exploited oil-shale deposit in the world (>6600 million tons) – creates substantial areas of wasteland. Presently, 2 underground mines and 2 open pit mines are in operation. In this area the overburden reaches ranges of 0-70 m due to the gentle southward dipping of the Ordovician strata. Mining in pits began to spread intensively in 1959. Pits are used in digging up to depth of 40 m; if oil shale is deeper than 50 m underground, mining is used. Nowadays around 50% of oil shale is mined in pits. The relief of the alkaline (pH~8) wasteland is rugged, the soil heterogeneous and extremely stony. Stone content varies from 15 to 100%; the N and organic content of oil shale mining spoil is low. Hence, afforestation is an optimal tool for the reclamation of these disturbed landscapes, as well as being a sustainable management option to create renewable energy sources.

The extensive afforestation of exhausted opencast oil-shale mines in Northeast Estonia was begun in 1960, and on the 1st of January 2005, exhausted oil-shale mines covered 12,900 ha of land, of which 10,200 ha had been forested. Until recent years a disproportionately large proportion of conifers (>90%), mainly Scots pine (*Pinus sylvestris*), has been planted (86% of the area). A total of 52 indigenous and introduced woody species were planted, where different introduced species of *Larix* (*Larix europaea*, *L. sibirica*, *L. kurilensis*) showed the best growth among coniferous trees, and the native deciduous species silver birch (*Betula pendula*) and black alder (*Alnus glutinosa*) were the most successful deciduous trees. They exceed pine stands of the same age (25-30 years) by 4 to 7 metres in height. The recommended planting density for black alder is 2000 - 2500, and hence thinning at a young age is unnecessary. In very stony areas (stones compromise 50-70%), black alder. is more suitable to promote soil formation processes and surpassed the growth of silver birch.

1.2 Advantages of alders among woody species

Alders have a number of advantages over other cultivated species: the increased N and P availability in the soil under alders, faster growth at a young age and higher resistance to pests, diseases and fires, especially in comparison with conifer monocultures. Owing to the ability to fix N₂ by the symbiosis of actinomycetes *Frankia* in alder root nodules, the soil under alders is enriched in nitrogen. Due to the low nitrogen retranslocation from senescing leaves (from 2.5 to 14%), alder leaf litter is extremely rich in nitrogen and mineralises easily [1, 2]. Alders increase phosphorus availability in the soil through the activity of their roots and associated microbial communities [3, 4]. Thus alders improve both soil N and P status. The majority of alder roots with primary structure are ectomycorrhizas, and hence mycorrhizal symbiosis plays an important role in the



nutrient cycling of alder stands. The nutrient demand of alders is higher and N use efficiency is lower than that of other tree species. In order to satisfy the high demand for nutrients, beneficial rhizosphere conditions should be supported by alders [5].

1.3 Rhizosphere processes and fine-root adaptations in black alder

The potential of black alder for the recultivation of exhausted opencast oil shale mines in relation to fine-root adaptations and rhizosphere processes is still poorly understood. Populations of microbes in the rhizosphere differ quantitatively and qualitatively from those in the bulk soil; their numbers are generally higher, and different populations are commonly represented [6]. It has been shown that, in black alder, the size of the total microbial population and the numbers of ammonifying and proteolytic microorganisms are higher in the soil-root interface than in bulk soil, litter, and root-free soil under trees [7]. Although rhizodeposition strongly affects the structure and activity of soil microbial communities and plant nutrition, few studies focus on the root surface bacteria of forest trees. The interaction of roots and soil microbial communities should be especially important in harsh site conditions, including reclaimed opencast oil-shale-mining areas [5].

Biolog Ecoplates, where all substrates are known as root exudates, were used to determine the community-level physiological profiles (CLPP) of culturable bacteria in soil-root interface and bulk soil samples [8]. The method characterizes the part of culturable bacteria and not fungi, but in studied alder sites the fungal/bacterial ratio [9] should be low, due to the soil pH_{KCl} range (from 7.0 to 8.0). An advantage of Biolog microplates is that they allow one to assess the functional diversity of the culturable microbial community. It is assumed that higher activity and diversity values for culturable microbial communities correspond to respectively higher values of total rhizosphere communities and can be used as indicators of their activity and diversity. In order to estimate the soil microbial biomass and metabolic activity of humus-degrading microorganisms present in the bulk soil, respiration techniques SIR and BAS were measured [10–12].

In considering microbial communities in the rhizosphere, the morphological and functional variability of fine roots is important. The impact of fine-root morphological parameters on rhizosphere processes in trees has not yet been thoroughly investigated. We measured short-root size and functional parameters: specific root area (SRA) and specific root length (SRL) [5, 13, 14] in alder stands. The results of different approaches: measurements of the size and activity of microbial communities by respiration in soil, the assessment of culturable bacterial communities with Biolog Ecoplates, the foliar assimilation efficiency of the above-ground part of trees, and short root morphology, especially the functional parameter SRA, were in close accordance [5].

The impact of alder species on fine-root morphology was significant, and short root tips were larger for black alder than or grey alder. For the investigated microbiological characteristics, no alder-species-related differences were revealed. The AWCD values of culturable bacterial communities in the soil-root



interface compared to those in the bulk soil correlated positively with specific short-root area and negatively with foliar assimilation efficiency [5]. The first years of stand development are most critical for tree survival, and it is for that reason that one-, four- and 27-yr-old stands were included in the study. The higher growth rate of black alder corresponds to the higher activity of microbial communities in their rhizosphere, and the higher specific root area of short roots than in the case of conifers [5, 14, 15].

1.4 Aims and objectives of study

- (1) To analyse the impact of microbial communities in the rhizosphere and in the bulk soil, and of fine-root adaptations on the development and productivity of black alder stands on reclaimed oil-shale mining areas.
- (2) To make recommendations concerning the suitability of black alder for the recultivation of exhausted oil-shale opencast mines.

2 Materials and methods

2.1 Stand and soil characteristics

A one-yr-old black alder plantation (Narva II, 3 replication plots) established in 2005 and a 4-yr-old plantation (Narva I) established in 2002 on oil shale mining spoil were investigated in October 2005 and 2004 respectively. A middle-aged Sirgala stand was established in 1978 [15] the present soil type is *Spolic Anthrosol* [14], and the stand was involved in the study in October 2002 and 2004. The planting arrangement was in all cases 2x2 m, bare-root seedlings were one year old in Sirgala and Narva I, and in Narva II were two years old. Stand and soil characteristics are presented in Table 1, initial N and organic content is low, and in young stands a significant proportion of the organic matter is formed from oil shale mining residues [16].

Table 1: Stand and soil characteristics in 2005. DBH (cm) – diameter at breast height (*indicates diameter at root collar); H- tree height (m), N% and LOI% indicate the percentage of nitrogen and loss on ignition respectively.

Stand	Age	Trees per ha	DBH	H	N%	LOI%
Sirgala	27	1650	14.8	20.3	0.55	15.0
Narva I	5	2100	*2.8	0.98	0.04	1.3
Narva II	1	2300	*0.8	0.33	0.03	4.7

2.2 Soil sampling and processing

Ten samples from the 0-10 cm soil layer (20x20 cm²) were taken randomly in the Sirgala black alder stand in October in 2002 and 2004. One third of the root



system was taken from the 4-yr-old Narva II stand, and the whole root system with the soil of 10 randomly selected trees was taken from the one-year-old Narva I stand (from all 3 replicate plots) in October 2004 and 2005, respectively. A compound subsample per plot was processed according to the methodology proposed by Gobran and Clegg [17]. Gobran and Clegg [17] introduced a conceptual model for nutrient availability in the mineral soil-root system, in which the fine roots and associated organisms maintain a higher nutrient availability in the soil-root interface than in the bulk soil.

All roots were carefully removed by hand from the field-moist mineral soil, which was then passed through a 2-mm mesh sieve to yield the bulk soil fraction. The dead roots, nodules, and coarse roots (≥ 2 mm in diameter) were separated; the remaining fine roots ($d < 2$ mm) and soil were gently shaken for 1 min in a plastic container to separate the soil aggregates from the roots. The remaining fine roots with adhering soil yielded the rhizosphere fraction.

2.3 Chemical analysis

Nitrogen in the rhizosphere and bulk soil samples was determined using the Kjeldahl method with a Tecator ASN 3313. Loss on ignition (LOI) was determined at 360°C; the pH_{KCl} of samples was measured. Analyses were performed at the Biochemistry Laboratory of the Estonian University of Life Sciences.

2.4 Microbiological methods

Biolog Ecoplates (Biolog Inc.) where all carbon sources are known as root exudates were used to determine the community-level physiological profiles of culturable bacterial samples in the soil-root interface and bulk soil; 1g of fresh material was used in all cases, and the data were recalculated on the basis of the dry matter. Biolog profiles were summarized as AWCD (average well color development). AWCD - average well color development; this is the sum of all 31 substrates' utilization values by culturable bacteria, divided by 31. A 150- μl aliquot of a 10^{-4} dilution of the bulk soil or soil-root interface sample was added to each of the 96 wells (31 carbon sources and control in 3 replications) in the microplate. Plates were incubated at 25°C and colour development was measured every 24 h for 120 h as absorbance at 590 nm, with optical density plate reader Multiscan 340 C. Based on the examination of the kinetic curves of the AWCD, 48h measurements were chosen for further data analysis.

Active microbial biomass was determined using substrate-induced respiration (SIR) [10–12]. Microbial respiration activity (BAS) was measured by trapping the evolved carbon dioxide in sodium hydroxide. The carbon availability index, also called metabolic quotient $q(\text{CO}_2)$, which relates the respiration rate without added substrate (BAS) to respiration after the addition of sufficient readily available substrate (SIR), was also calculated.



2.5 Morphological parameters of fine roots

The fine-root parameters of black alder were measured in 10 samples per year and plot, and 2-3 subsamples were processed per sample. Only short roots with a living cortex were considered: the diameter, length, volume and mass of root tips, as well as specific root area and specific length, were estimated. The methods are the same as in [13], except for the diameter, root length and root projection area measurements, which in the present work were carried out using WinRhizo 2003B (Regent Instruments) [14].

2.6 Statistical methods

Kolmogorov-Smirnov, Lilliefors and Shapiro-Wilk's tests were used to check the normality of variables. When necessary, log- and root-transformations were used to normalize the data. Differences between stand means of short-root characteristics were checked at 95% confidence intervals. The level of significance of $\alpha = 0.05$ was accepted in all cases. The STATISTICA 7.0 software was used.

3 Results and discussion

3.1 Strategies to optimise mineral nutrition

To sustain and improve mineral nutrition in the harsh conditions of the levelled hills of oil shale mining spoil, trees must invest assimilates according to an extensive or intensive strategy. Concerning the optimality theory, the cost/benefit ratio of operating roots is a key factor for forest productivity [18].

There are two main strategies to optimise the mineral nutrition of plants: A) Extensive, by increasing the mass, surface area and length of fine roots, leading to the increase of the rhizosphere.

B) Intensive, by increasing or maintaining the efficiency of fine roots and rhizosphere processes through morphological adaptations of fine roots [13, 19], and/or the activity of root-associated microorganisms for plant mineral nutrition could be increased or maintained.

Hence an extensive strategy leads to an increase in fine root system, but an intensive strategy is based on more efficient use of the mass unit of ectomycorrhizas.

3.2 Dynamics of fine root adaptations and pH in black alder stands

The mean specific root area of ectomycorrhizas was 171 ± 12 , 155 ± 8 , and 82 ± 4 $\text{m}^2 \text{kg}^{-1}$ in one-, four- and 27-yr-old black alder stands respectively (Table 2), whereas in the 27-yr old stand the value was significantly higher.

The mean diameter and weight of a short root tip were significantly smaller in a one-yr-old plantation than in older stands, most probably as a result of planting shock. Mean specific root length decreased significantly in correlation with increasing stand age (Fig.1A).



Phosphorus nutrition was improved through the increasing of rhizosphere pH by up to 1.4 units compared to the bulk soil; soil pH decreased 1 unit during the first 26 years Fig. 1B).

Table 2: Mean short-root morphological parameters (\pm standard errors) in black alder stands. Different letters indicate significant differences between means by 95% confidence intervals, $P < 0.05$.

Stand	Diameter (mm)	Length, (mm)	Weight, (mg)	SRA, ($m^2 kg^{-1}$)
Sirgala 27 yr	0.291 ^a \pm 0.005	3.02 ^a \pm 0.18	0.035 ^b \pm 0.003	82 ^a \pm 4
Narva I 4 yr	0.392 ^c \pm 0.005	4.10 ^b \pm 0.19	0.034 ^b \pm 0.002	155 ^b \pm 8
Narva II 1 yr	0.321 ^b \pm 0.008	3.51 ^a \pm 0.38	0.021 ^a \pm .002	171 ^b \pm 12

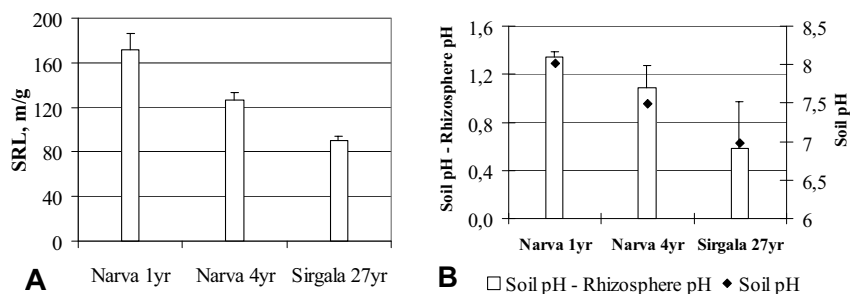


Figure 1: A: Decrease in mean SRL of short roots with increasing stand age; B: Acidifying effect of rhizosphere and soil pH(KCl) dynamics in black alder stands on reclaimed oil shale mining area. Bars indicate standard errors.

3.3 Activity dynamics of microbial communities in rhizosphere and soil

Oil shale mining spoil is extremely low in nitrogen and organic matter. Additionally, the microbial abundance is initially very low, as can be seen in Fig. 2A. The soil improvement during the first 25 years is remarkable (Table 1, Fig.1B and 2A).

The metabolic quotient $q(CO_2)$ was similar in two young stands, decreasing approximately twice during stand development (Fig. 2B) This reflects successional changes in microbial community structure, where in the soil of the young stands the microbial community consists mainly of r- strategist species that rapidly utilize root derived organic substrates and are not as efficient in the formation of biomass.



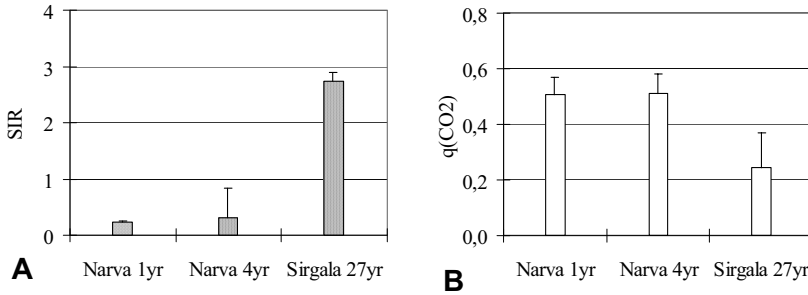


Figure 2: A: Dynamics of SIR (mg C g⁻¹); B: Decrease in metabolic quotient q(CO₂) with increasing age of black alder stands on reclaimed oil shale mining area. Bars indicate standard errors.

In older stands where plant litter has been accumulating, the microbial community also contains K-strategic species that are characterized by a slow growth rate and stable biomass development.

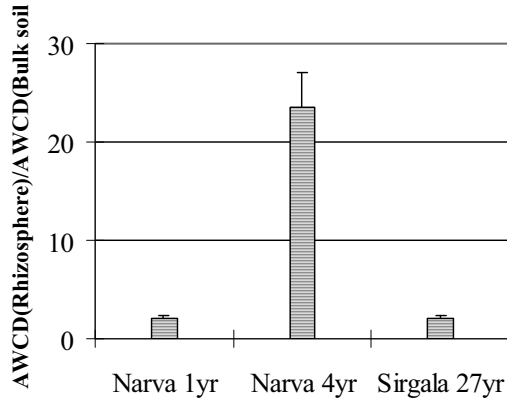


Figure 3: Rhizosphere /bulk soil AWCD ratio in black alder stands on reclaimed oil shale mining area. Bars indicate standard errors.

The greatest difference between one-, 4- and 27-yr-old stands was revealed in the rhizosphere/bulk soil AWCD ratio, which reflects the difference between activities of rhizosphere and bulk soil microbial communities (Fig. 3). Hence, in the second year after planting, when survived plants have overcome planting shock, the intensive strategy prevails, and plants support rhizosphere microbial communities massively. The rhizosphere/bulk soil activity ratio is an order higher than in the first year after planting or in a middle-aged stand. In our earlier investigation it was revealed that the better the soil conditions, the smaller the difference between the activities and diversities of microbial communities in the rhizosphere and soil. Hence, by improved soil the support of rhizosphere communities is less crucial.



Why are the rhizosphere communities poorly supported in the first year after planting, when the need is most urgent? It seems that during the first year the intensive strategy of the development of the fine root system prevails in order to exploit the oil shale mining spoil by fine roots as much as possible, and there is a deficit in assimilates allocated below ground. That priority is reflected by the highest short root SRL being found in the one-yr-old stand (Fig. 1A), although the SRA of ectomycorrhizas is similar in one-yr-old and 4-yr-old stands. That is in close accordance with the low support of rhizosphere microbial communities, because in our earlier investigation the Rhizosphere /bulk soil AWCD ratio, ratio for Shannon diversity indices, and SRA were positively correlated ($r=0.65$, $P<0.05$) in both cases [5].

In Sirgala, the analysis of topsoil nutrients showed a remarkable increase in total N and available P under the canopy of the black alder plantation in comparison to the neighboring Scots pine stand of the same age. A more than twice higher total topsoil N and available P content were found in the alder plantation compared to the pine stand [15]. The above-ground productivity in the 21-year-old black alder plantation on the reclaimed oil-shale mining area in Sirgala was comparable with the value for stands of the same age growing on fertile mineral soils. The biomass accumulation ratio, foliar assimilation efficiency and N use efficiency were highest in the Sirgala plantation. In Sirgala, the planting density ensured nearly optimal photosynthetic conditions, and the planting of 2,000 to 2,500 black alders per hectare on exhausted opencast oil-shale mines was recommended.

4 Conclusions

Black alder grows rapidly on recultivated oil shale areas; its survival after establishment is very good. A favorable environment for microbes in rhizosphere and bulk soil is created on oil shale mining detritus under black alders. The morphological adaptations of ectomycorrhizas support the effective functioning of the developing ecosystem. Therefore black alder is a very promising tree species for the recultivation of exhausted opencast oil shale mines.

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Aboveground biomass and nutrient accumulation dynamics in young black alder, silver birch and Scots pine plantations on reclaimed oil shale mining areas in Estonia

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ABSTRACT

The growth, aboveground biomass production and nutrient accumulation in black alder (*Alnus glutinosa* (L.) Gaertn.), silver birch (*Betula pendula* Roth.) and Scots pine (*Pinus sylvestris* L.) plantations during 7 years after planting were investigated on reclaimed oil shale mining areas in Northeast Estonia with the aim to assess the suitability of the studied species for the reclamation of post-mining areas. The present study revealed changes in soil properties with increasing stand age. Soil pH and P concentration decreased and soil N concentration increased with stand age. The largest height and diameter of trees, aboveground biomass and current annual production occurred in the black alder stands. In the 7-year-old stands the aboveground biomass of black alder (2100 trees ha⁻¹) was 2563 kg ha⁻¹, in silver birch (1017 trees ha⁻¹) and Scots pine (3042 trees ha⁻¹) stands respective figures were 161 and 1899 kg ha⁻¹. The largest amounts of N, P, K accumulated in the aboveground part were in black alder stands. In the 7th year, the amount of N accumulated in the aboveground biomass of black alder stand was 36.1 kg ha⁻¹, the amounts of P and K were 3.0 and 8.8 kg ha⁻¹, respectively. The larger amounts of nutrients in black alder plantations are related to the larger biomass of stands. The studied species used N and P with different efficiency for the production of a unit of biomass. Black alder and silver birch needed more N and P for biomass production, and Scots pine used nutrients most efficiently. The present study showed that during 7 years after planting, the survival and productivity of black alder were high. Therefore black alder is a promising tree species for the reclamation of oil shale post-mining areas.

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1. Introduction

The opencast mining of oil shale in Northeast Estonia creates significant areas of degraded land that need restoration. By the year 2006 the area damaged by oil shale opencast mining was 13,098 ha, of which 10,347 ha was afforested (Kaar and Tomberg, 2006). The relief of the alkaline (pH ~ 8) wasteland is rugged. Oil shale mining spoil is heterogeneous and extremely stony with low nitrogen and organic content (Kaar, 2002; Lõhmus et al., 2006a). Since the use of the post-mining landscapes for agriculture is made difficult by heterogeneity of the soil and by poor moisture conditions, their afforestation is more suitable (Kaar, 2002). Afforestation is a sustainable reclamation option for post-mining landscapes (Singh et al., 2002; Lõhmus et al., 2006a; Pietrzykowski and Krzaklewski, 2007) to reduce CO₂ emission and to create renewable energy sources. Results of previous research (Kaar, 2002) of restoration of

post-mining areas in Estonia showed that new stands are of better quality than the stands that grew there before mining. A total of 52 indigenous and introduced species have been used for restoration. Various introduced larch species (*Larix europaea*, *L. sibirica*, *L. kurilensis*) have shown the best growth among coniferous trees, and the native deciduous species of silver birch and black alder have been the most productive deciduous trees (Kaar, 2002; Kuznetsova and Pärn, 2004; Korjus et al., 2007). Until recent years a disproportionately large proportion of conifers (>90%), mainly Scots pine (86% of the area) has been planted (Lõhmus et al., 2006a). Moreover, the opencast mining area in Northeast Estonia has been moving toward areas with deeper excavation (Kaar, 2002; Korjus et al., 2007) and the quality of the post-mining substrate has declined and its stoniness has increased due to the thickening overburden in new mining areas. These harsh growing conditions might limit growth and survival of different tree species at different rates, and hence the reasonable choice of tree species for the reclamation of levelled opencast mines will be even more important in the future.

Deciduous species have several advantages (faster growth, higher resistance to pests, diseases and fires) over conifers on post-

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mining sites, and their use in reclamation should rise (Kaar, 2002; Vares et al., 2004; Löhmus et al., 2007). Black alder can be considered to be a “biological fertiliser”, which improves soil nitrogen status, fixing N₂ in symbiosis with *Frankia* in its root nodules and increasing phosphorus availability in soil by the activity of its roots and associated microbial communities (Giardina et al., 1995; Uri et al., 2002). However, the potential of different tree species for the recultivation of exhausted opencast oil shale mines in relation to biomass production, nutrient accumulation and nutrient use efficiency is still poorly investigated. Analysis of morphological and chemical characteristics of trees has often been used to evaluate the nutritional status (Brække, 1996) as well as biomass increment and growth conditions of trees (Niinemets et al., 2002). The success of the restoration of damaged areas has been assessed by evaluating the growth and biomass production of various plants (Kumar et al., 1995; Singh and Singh, 1999). Previously it has been found that the higher growth rate of black alder growing on oil shale post-mining areas corresponds to the higher activity of microbial communities in its rhizosphere, and the higher specific root area of its short roots than in the case of conifers (Vares et al., 2004; Löhmus et al., 2006b; Ostonen et al., 2006). Also, Vares et al. (2004) found the aboveground productivity in a 21-year-old black alder plantation on reclaimed oil shale mining area to be comparable with that of the stands of the same age growing on fertile mineral soils.

The present study deals with survival, growth, biomass production and nutrient accumulation of young black alder, silver birch and Scots pine stands growing on reclaimed oil shale mining areas. The main aim of the study was to assess the suitability of the studied species for the reclamation of oil shale post-mining areas. The working hypothesis of the present study was that black alder can be the preferred species for the recultivation of the exhausted oil shale mining area due to its faster growth and ability to restore soil fertility. Our findings are important for a better understanding of the development of stands and allow giving recommendations for restoration of exhausted oil shale mining areas in ecologically and economically changing conditions. The approaches of this study can be used for other regions where wastelands require reclamation.

The specific objectives of this study were (i) to analyse the early dynamics of the survival, growth, aboveground biomass allocation and production in relation to the tree species in black alder, silver birch and Scots pine plantations on reclaimed oil shale mining area; and (ii) to analyse the nutrient concentration, allocation, accumulation and nutrient use efficiency in relation to the tree species and stand age in the studied plantations.

2. Material and methods

2.1. Study areas

The study was carried out in experimental plantations established on Narva reclaimed oil shale mining area, Northeast Estonia (59° 15' N, 27° 42' E). According to the data of the Narva meteorological station, which is closest to the experimental area, the mean annual temperature in the region during the studied period was 5.8 °C, and mean annual precipitation was 747 mm. The plantations had been established directly on levelled quarry spoil. No soil preparation was done before planting. The soil type under middle-aged pine stands on reclaimed oil shale mining area is *Calcaric Regosol* (Reintam et al., 2002).

Black alder, silver birch and Scots pine plantations of different age (1-, 2-, 4- and 7-year-old) were investigated. The planting density was 1.5 m × 1.5 m for Scots pine, and 2.0 m × 2.0 m for black alder and silver birch. The experimental area (0.56 ha) with studied species was established in May 2005 using 1-year-old seedlings. Species were planted in 25 m × 25 m plots in three replications

in the Latin square design. So, the total number of seedlings per species planted and measured during the study were 485, 468 and 745 for black alder, silver birch and Scots pine, respectively. Measurements and biomass estimation in the plantations were carried out when they were 1 year old (August 2005), 2 years old (August 2006) and 4 years old (August 2008). The measurements in 1-year-old plantations were made separately in each replication. Considering that there were not any significant differences between replications within a tree species (Kuznetsova et al., 2010), the later measurements were performed per plantation. Also 7-year-old plantations (total area 3 ha) were investigated, which were established in 2002 with 2-year-old seedlings. Fieldwork was carried out in these plantations at the end of August 2008. A sample plot (0.1 ha) was established per each species plantation and all trees in sample plot were measured (210, 122 and 365 trees for black alder, silver birch and Scots pine, respectively). The survival and biomass of the 1-year-old stands were published earlier (Kuznetsova et al., 2010) and in this paper we present results about the initial performance and further growth of the plantations.

2.2. Estimation of aboveground biomass and production

The survival, diameter at root collar and height of trees were measured per each species and age-class. The aboveground biomass of the stand was estimated in August when it was the largest. For the estimation of aboveground biomass and production sample tree (model tree) method was used (Bormann and Gordon, 1984; Löhmus et al., 1996; Vares et al., 2004; Uri et al., 2007; Tullus et al., 2009).

In 1- and 2-year-old stands the trees were categorised into three classes on the basis of height distribution in the stand (Table 1). One model tree from each height class was randomly selected. In 1-year-old stands the model trees were selected per replication (Kuznetsova et al., 2010) and in 2-year-old stands per plantation. In 4- and 7-year-old stands the trees were divided into five height classes, and a model tree was selected randomly from each class. Additionally, we felled a tree from two classes with the largest number of trees. A total of 7 model trees per plantation were sampled (Table 1).

In 1- and 2-year-old stands the aboveground parts of the model trees were divided into three compartments: leaves, shoots (current-year shoots and branches (older shoots, age > 1 year)) and stems. Then the compartments were dried at 70 °C until constant weight and weighed to 0.001 g.

In 4- and 7-year-old stands the living crowns of the model trees were divided into three equal sections of length. In each section, different compartments including leaves, current-year shoots and branches were separated. The fresh mass of each compartment was determined. From each compartment, a subsample was taken for the determination of dry matter content. The subsamples were weighed fresh, dried and reweighed to 0.001 g. The dry mass of different compartments was calculated for each model tree by multiplying its fresh mass by the proportion of dry matter. The stems were dried and weighed.

Total current annual production (CAP) of a tree consists of the annual increment of leaves, shoots and stem. The CAP of the leaves and current-year shoots is equal to their biomass. The production of older shoots (age > 1 year) was estimated by dividing shoot mass by shoot age. To estimate annual stemwood production, disks were taken from the middle of all stem sections, dried and polished, and the widths of annual rings were measured to 0.001 mm using the WinDENDRO (Regent Instruments Inc., Quebec, QC, Canada) software.

Annual wood increment of the model tree sections was calculated according to the following equation (Whittaker and

Table 1
Distribution of trees between height classes. The number of model trees taken from respective height class is shown in parenthesis.

Species	Age (year)	Height classes (range in cm)				
		I	II	III	IV	V
Black alder	1	0–20 (1)	20–50 (1)	50–70 (1)		
	2	0–30 (1)	30–45 (1)	45–80 (1)		
	4	0–60 (1)	60–120 (1)	120–180 (2)	180–240 (2)	240–300 (1)
	7	0–120 (1)	120–180 (2)	180–240 (2)	240–300 (1)	300–340 (1)
Silver birch	1	0–15 (1)	15–20 (1)	20–30 (1)		
	2	0–15 (1)	15–30 (1)	30–40 (1)		
	4	0–60 (1)	60–80 (2)	80–120 (2)	120–140 (1)	140–160 (1)
	7	0–70 (1)	70–100 (1)	100–140 (2)	140–180 (2)	180–250 (1)
Scots pine	1	0–5 (1)	5–8 (1)	8–12 (1)		
	2	0–10 (1)	10–14 (1)	14–20 (1)		
	4	0–20 (1)	20–30 (2)	30–40 (2)	40–60 (1)	60–80 (1)
	7	0–70 (1)	70–120 (1)	120–150 (2)	150–180 (1)	180–220 (1)

Woodwell, 1968):

$$W = \frac{W_0(r^2 - (r - i)^2)}{r^2}, \quad (1)$$

where W is the annual dry mass increment in wood, W_0 the dry mass of wood, r the radius of the analysed disk and i is the thickness of the ring of the last year.

To estimate the aboveground biomass (B) and current annual production (CAP) of growing trees, allometric Eq. (2), based on the data of the model trees, was used:

$$y = ax^b, \quad (2)$$

where y is the aboveground biomass (g) or production of the tree (g yr^{-1}), x the diameter of the tree at root collar (cm), a and b are the parameters of the regression equation (Table 2).

The masses of different compartments were calculated using the percentage distribution of the compartments obtained on the basis of the model trees. The relative annual aboveground production (CAP/ B) per stand was calculated as well.

2.3. Soil analysis

To characterise the growth substrate of trees 10 random soil samples from the 0–20 cm soil layer were taken per plantation. Then the soil samples were combined into three soil samples per plantation for chemical analysis, except in the 2-year-old plantations, where data of one composite sample per plantation are represented in the study. The soil samples were dried and sieved through a sieve with mesh size 2 mm. The pH_{KCl} of soil samples was measured. Soil nitrogen (N, %) was determined according to Kjeldahl; Tecator ASN 3313 was applied. Determination of avail-

able (ammonium lactate extractable) phosphorus (P, %) in the soil was performed by flow injection analysis with Tecator ASTN 9/84 (Ruzicka and Hansen, 1981). All soil samples were analysed in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

2.4. Plant analysis

The chemical analyses were carried out from 3 trees per plantation. The concentrations of the main nutrients (N, P, K) were analysed separately in different compartments of the model tree (leaves, current-year shoots, older shoots and stem). The samples were collected evenly from different parts of the crown and one composite sample was made for leaves, current-year shoots, older shoots and stems per each tree.

Block digestion and steam distillation methods were used for testing the plant material for nitrogen concentration (N, %) (Tecator AN 300). Digestion by flow injection analysis was applied for testing the plant material for Kjeldahl phosphorus (P, %) concentration (Tecator AN 5242), using the analyser Fiastar 5000 (ISO/FDIS 15681). To analyse the plant material for potassium concentration (K, %), the flame photometric method was employed. Analyses were performed in the Laboratory of Biochemistry of the Estonian University of Life Sciences.

The contents of N, P, K (kg ha^{-1}) and their annual accumulation in the aboveground part ($\text{kg ha}^{-1} \text{ yr}^{-1}$) of the stand were calculated; the biomass or the annual increment of a compartment was multiplied by the respective nutrient concentration. Nitrogen and phosphorus use efficiency (NUE, PUE, kg kg^{-1}) were calculated as aboveground production per annual N or P accumulation in the aboveground parts of the stand per year.

Table 2

Parameters of the regression equation (2) for the estimation of the aboveground biomass (B) and aboveground biomass production (CAP) in relation to diameter at root collar based on data from model trees ($n=3-7$) of black alder, silver birch and Scots pine: (a) intercept and (b) slope of regression, level of significance $p < 0.01$ in all cases, r^2 coefficient of determination.

Species	Age of stand (year)	B			CAP		
		a	b	r^2	a	b	r^2
Black alder	2	14.169	3.408	0.971	10.174	3.614	0.939
	4	9.916	2.866	0.965	8.220	2.706	0.948
	7	27.715	2.345	0.992	29.273	1.945	0.991
Silver birch	2	20.078	2.709	0.999	15.153	2.533	0.989
	4	17.863	2.233	0.933	13.846	2.193	0.910
	7	26.061	2.506	0.964	16.675	2.415	0.977
Scots pine	2	11.360	2.324	0.708	11.196	2.627	0.716
	4	29.580	2.468	0.998	24.471	2.349	0.996
	7	37.621	2.313	0.969	24.236	2.242	0.967

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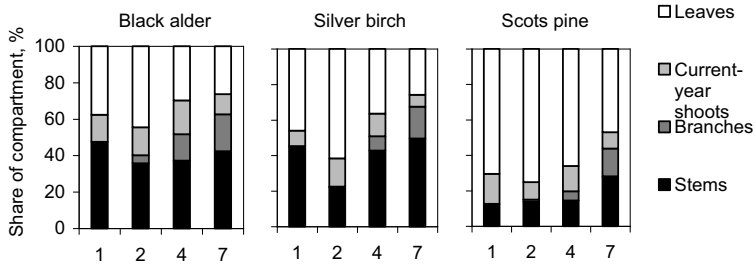


Fig. 1. Aboveground biomass allocation in black alder, silver birch and Scots pine stands growing on a reclaimed oil shale mining area (1, 2, 4, 7 – age of stand in years).

2.5. Statistical methods

Normality of variables was checked by Lilliefors and Shapiro–Wilk’s tests. When necessary, log- and root-transformations were used to normalise the data. The data were analysed by simple regression analysis and by analysis of variance (ANOVA, GLM). The Tukey test was used for multiple comparison of means. Correlations (*r*) between growth parameters and nutrients were calculated. Throughout the study, the means are presented with the standard error of the mean (\pm SE). Statistical analyses were carried out with the software Statistica 7.0 and the level of significance $\alpha = 0.05$ was accepted in all cases.

3. Results

3.1. Soil parameters

The changes in soil pH, N and P concentrations depended on age of plantation ($F_{[1,30]} = 67.5; 38.4; 17.2; p < 0.001$ for soil pH, N and P concentrations, respectively), but not on species ($F_{[2,30]} = 0.27; 0.49; 1.04; p > 0.05$ for respective values) and interaction between species and age ($F_{[2,30]} = 0.28; 0.52; 1.03; p > 0.05$ for respective values). During 7 years of trees growth the decrease of soil pH and P concentration and increase the soil N concentration with stand age for all studied species appeared (Table 3). However, there were not statistically significant differences in N and P concentrations in silver birch and P concentration in Scots pine between stands of different age (Tukey test, $p > 0.05$).

3.2. Survival and growth

Survival of 1-year-old plantations varied by tree species and ranged as follows: black alder ($93 \pm 6\%$) \geq Scots pine

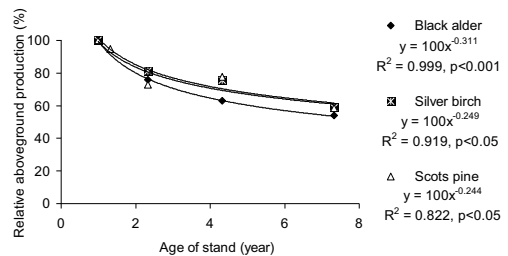


Fig. 2. Relative aboveground production of the black alder, silver birch and Scots pine stands on a post-mining area.

($83 \pm 5\%$) $>$ silver birch ($64 \pm 2\%$). The survival of silver birch was significantly lower than the survival of the other species (Tukey test, $p < 0.05$) (Kuznetsova et al., 2010). During the following 6 years the tree dieback for all species varied between 8% and 23% (Table 3). The values of mean height and diameter of black alder were significantly higher compared to the other studied species of the same age (Tukey test, $p < 0.05$) (Table 3).

3.3. Aboveground biomass allocation and production

The results of regression analysis revealed strong relationships between the diameter of the root collar and the aboveground biomass and production (Table 2). All regressions had high determination coefficients ($r^2 = 0.71–0.99$) and were highly significant ($p < 0.01$). The effect of tree species on aboveground biomass allocation was significant. Scots pine had a signif-

Table 3

Stand and soil characteristics in the reclaimed oil shale mining area: mean height ($H \pm SE$), mean diameter at root collar ($D \pm SE$), soil pH, concentration of nitrogen (N) and available P in soil.

Species	Age of stand (year)	Trees per ha	Survival (%)	H (cm)	D (cm)	pH	N (%)	P (mg kg ⁻¹)
Black alder	1	2300	93.0	32.83 \pm 0.42 ^c	0.83 \pm 0.10 ^b	8.02 \pm 0.06	0.032 \pm 0.003	100.09 \pm 13.54
	2	2263	91.5	42.54 \pm 1.16 ^c	1.06 \pm 0.03 ^c	7.74	0.034	113.83
	4	2263	91.5	169.15 \pm 6.48 ^c	4.50 \pm 0.17 ^c	7.70 \pm 0.12	0.045 \pm 0.004	65.85 \pm 6.17
	7	2100	85.0	217.62 \pm 3.67 ^b	4.78 \pm 0.09 ^c	7.50 \pm 0.05	0.052 \pm 0.004	48.58 \pm 2.26
Silver birch	1	1600	64.0	16.62 \pm 0.34 ^b	0.30 \pm 0.03 ^a	8.05 \pm 0.03	0.031 \pm 0.005	79.18 \pm 9.81
	2	1540	61.6	29.41 \pm 1.43 ^b	0.49 \pm 0.03 ^b	7.87	0.021	88.21
	4	1540	61.6	91.56 \pm 4.05 ^b	1.56 \pm 0.07 ^b	7.82 \pm 0.06	0.040 \pm 0.001	80.53 \pm 7.39
	7	1017	40.7	123.11 \pm 5.11 ^a	1.77 \pm 0.08 ^a	7.51 \pm 0.08	0.045 \pm 0.004	50.39 \pm 2.63
Scots pine	1	3689	83.0	5.79 \pm 0.09 ^a	0.23 \pm 0.02 ^a	8.08 \pm 0.01	0.027 \pm 0.002	73.57 \pm 13.26
	2	3493	78.4	8.89 \pm 0.22 ^a	0.29 \pm 0.01 ^a	7.73	0.031	130.76
	4	3493	78.4	26.04 \pm 1.11 ^a	1.04 \pm 0.05 ^a	7.85 \pm 0.09	0.033 \pm 0.003	70.68 \pm 6.23
	7	3042	68.3	118.36 \pm 1.91 ^a	3.10 \pm 0.07 ^b	7.62 \pm 0.10	0.043 \pm 0.001	47.82 \pm 5.69

Superscript letters indicate significant differences between species at the same age according to Tukey HSD test.

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Table 4

The aboveground biomass (B, kg ha⁻¹) and current annual biomass production (CAP, kg ha⁻¹ yr⁻¹) of black alder, silver birch and Scots pine stands. 1, 2, 4, 7 – age of stand (years).

Fraction	1		2		4		7	
	B	CAP	B	CAP	B	CAP	B	CAP
Black alder								
Leaves	7.29	7.29	23.22	23.22	647.91	647.91	675.42	675.42
Current-year shoots	2.87	2.87	7.98	7.98	403.08	403.08	281.86	281.86
Branches	–	–	2.31	1.20	317.03	87.93	519.78	100.75
Stems	9.23	4.15	18.69	7.10	809.96	233.73	1086.19	320.87
Total	19.40	14.31	52.20	39.50	2177.98	1372.65	2563.25	1378.91
Silver birch								
Leaves	0.69	0.69	3.94	3.94	31.41	31.41	41.63	41.63
Current-year shoots	0.13	0.13	1.02	1.02	10.93	10.93	10.62	10.62
Branches	–	–	0.02	0.01	6.96	2.74	28.88	9.69
Stems	0.68	0.38	1.42	0.26	36.90	20.08	79.73	32.58
Total	1.50	1.20	6.40	5.22	86.20	65.16	160.85	94.51
Scots pine								
Leaves	1.34	1.34	2.10	1.66	120.93	106.02	892.71	542.24
Current-year shoots	0.32	0.32	0.27	0.24	26.16	26.16	173.90	173.90
Branches	–	–	0.04	0.02	9.46	3.05	296.99	114.79
Stems	0.24	0.14	0.39	0.09	26.60	6.55	535.22	280.33
Total	1.90	1.80	2.80	2.04	183.15	141.79	1898.82	1111.26

icantly greater share of leaves and a smaller proportion of stem in the aboveground biomass than the deciduous trees (Fig. 1).

Comparative analysis of the biomass of different species in the studied plantations showed that during the first 7 years after the plantation establishment black alder appeared to be the most

productive species. The aboveground biomass and production of the black alder plantations were higher than in the silver birch and Scots pine plantations (Table 4). Relative annual aboveground production (CAP/B) of stands was similar between species and decreased according to a power function with stand age for all studied species (Fig. 2).

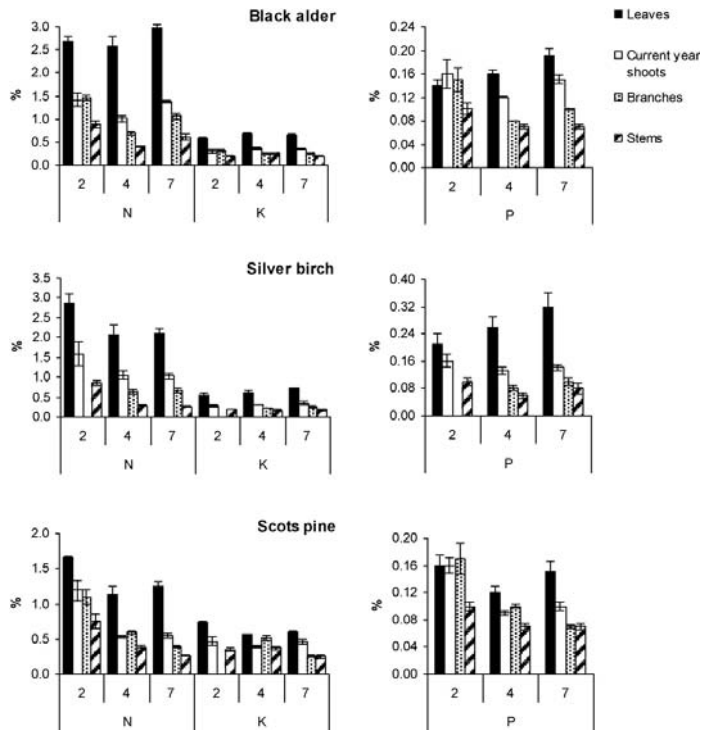


Fig. 3. Mean (±SE) N, P and K concentrations (%) of different tree compartments in the studied black alder, silver birch and Scots pine stands (2, 4, 7 – age of stand in years).

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Table 5
 Mean (\pm SE) concentrations of N, P and K (%) in different tree compartments of 7-year-old trees of the studied species.

Stand	Leaves			Current-year shoots			Branches			Stems		
	N	P	K	N	P	K	N	P	K	N	P	K
Black alder	2.97 ^a \pm 0.08	0.19 ^a \pm 0.01	0.66 ^{ab} \pm 0.03	1.38 ^a \pm 0.04	0.15 ^a \pm 0.01	0.35 \pm 0.02	1.06 ^a \pm 0.06	0.10 ^b \pm 0.00	0.25 \pm 0.01	0.61 ^b \pm 0.06	0.07 \pm 0.00	0.17 \pm 0.02
Silver birch	2.11 ^b \pm 0.11	0.32 ^b \pm 0.04	0.72 ^b \pm 0.02	1.02 ^b \pm 0.09	0.14 ^b \pm 0.01	0.34 \pm 0.05	0.67 ^b \pm 0.07	0.10 ^b \pm 0.01	0.24 \pm 0.03	0.25 ^a \pm 0.02	0.08 \pm 0.02	0.17 \pm 0.03
Scots pine	1.24 ^c \pm 0.08	0.15 ^a \pm 0.02	0.60 ^a \pm 0.02	0.55 ^a \pm 0.04	0.09 ^a \pm 0.01	0.46 \pm 0.03	0.39 ^a \pm 0.01	0.07 ^a \pm 0.00	0.26 \pm 0.02	0.26 ^a \pm 0.01	0.07 \pm 0.01	0.25 \pm 0.02

Superscript letters indicate significant differences between species according to Tukey HSD test.

3.4. Nutrient allocation and accumulation

The concentrations of nutrients varied between tree species, compartments and stands of different age. For all studied species and stands of different age, the highest N, P and K concentrations were found in the leaves and the lowest in the stems, except for similar P concentrations in the leaves and shoots in 2-year-old black alder and Scots pine stands (Tukey test, $p < 0.05$) (Fig. 3). The differences in the concentrations of nutrients between tree species were statistically significant. For example, in 2- and 4-year-old plantations the N concentration in leaves and current-year shoots did not differ significantly between black alder and silver birch, but these values were significantly higher than the respective values of Scots pine (Tukey test, $p < 0.05$). In 7-year-old plantations black alder had the highest N concentration in each compartment (Table 5) (Tukey test, $p < 0.05$).

The amounts of N, P and K accumulated in the aboveground biomass and current annual production increased with stand age in all studied species and the highest values were found in the black alder plantations (Table 6). The largest amounts of N, P and K accumulated in biomass were located in the leaves and smallest in the shoots for all studied species (Fig. 4). Considering changes in biomass allocation with stand age, the share of accumulated nutrients increased in stems and decreased in leaves with rising stand age (Fig. 4).

Our results showed that black alder had a lower NUE than silver birch and Scots pine, and silver birch had a lower PUE than the other studied species (Table 6). The N:P:K ratio in current annual production differed between species. Black alder had the lowest P:N and K:N (Table 6).

The aboveground biomass was positively correlated with the P content in biomass ($r = 0.99$, $p < 0.05$) in black alder and with P and K contents ($r = 0.99$, $r = 0.99$, $p < 0.05$, respectively) in silver birch. The aboveground biomass of Scots pine correlated strongly with N, P and K contents ($r = 0.99$, $p < 0.05$ for all cases).

4. Discussion

Considering that the levelled dumps of oil shale mining spoil are heterogeneous, stony and alkaline with a low initial N and organic content (Kaar, 2002; Löhmus et al., 2006a, 2007), the first years of stand development in these harsh conditions are most critical for tree survival and growth. However, our results showed that soil improvement was remarkable in the oil shale mining area during the first 7 years. The initially high pH decreased and the soil N concentration increased with stand age. Analogous results were obtained also by other researchers, who showed decrease of soil pH and increase of soil organic matter and N content in afforested post-mining areas (Reintam et al., 2002; Šourková et al., 2005; Löhmus et al., 2006a; Banning et al., 2008). Numerous studies suggest that nutrient availability is greater in deciduous rather than evergreen forests (Son et al., 2007; Ste-Marie et al., 2007). We did not observe significant differences in nutrient concentrations of soil between the studied species. A possible reason is that these plantations are still young and during the following stand development the effect of tree species is not excluded. It is known that the presence of N₂ fixers, such as alders, generally increases rates of uptake and return of all nutrients. Moreover, on sites where N supply limits forest productivity, the addition of alders to conifer stands increases productivity, as well as levels and availability of N, without decreasing soil pH (Binkley et al., 1992). We observed a small increase in N concentration in black alder leaves with increasing of N in the growth substrate, but not in the tree species that do not fix N₂. Due to a low N retranslocation from leaves, alder litter is rich in this nutrient and mineralises easily

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Table 6

Accumulation of N, P and K in aboveground biomass (B) and in annual biomass production (CAP), N:P:K ratios for aboveground production and N and P use efficiency (NUE, PUE) in the studied plantations.

Species	Age of stand (year)	N _B (kg ha ⁻¹)	P _B (kg ha ⁻¹)	K _B (kg ha ⁻¹)	N _{CAP} (kg ha ⁻¹ yr ⁻¹)	P _{CAP} (kg ha ⁻¹ yr ⁻¹)	K _{CAP} (kg ha ⁻¹ yr ⁻¹)	N:P:K	NUE (kg kg ⁻¹)	PUE (kg kg ⁻¹)
Black alder	2	0.936	0.068	0.203	0.817	0.055	0.178	100: 7: 20	48.3	718
	4	26.432	2.352	8.699	22.449	1.788	6.711	100: 8: 30	61.1	768
	7	36.121	3.010	8.819	27.002	2.008	6.309	100: 7: 23	51.1	687
Silver birch	2	0.141	0.011	0.027	0.131	0.010	0.025	100: 8: 19	39.7	520
	4	0.909	0.124	0.296	0.835	0.110	0.260	100: 13: 31	78.0	592
	7	1.383	0.242	0.543	1.134	0.186	0.415	100: 16: 37	83.3	508
Scots pine	2	0.037	0.004	0.016	0.032	0.003	0.014	100: 9: 44	63.8	680
	4	1.629	0.194	0.913	1.377	0.160	0.740	100: 12: 54	103.0	886
	7	13.891	1.934	7.726	8.848	1.246	5.086	100: 14: 58	125.6	892

(Dawson and Funk, 1981; Löhmus et al., 2002), which improves soil N status. In general, the forest floor under deciduous trees shows high N mineralisation rates (Kanerva and Smolander, 2007; Uri et al., 2008).

Our results showed a decrease of soil pH and P concentration with pedogenesis and increasing age of stands. Thus, P nutrition may improve through the decrease of soil pH. The loss in available P may relate to increasing uptake and assimilation of P by plants during stand development (Šourková et al., 2005). We suggest that the decrease of P in soil might be related with the intensive uptake and assimilation of P by older plants. In older black alder and sil-

ver birch leaves the P concentration was by about 26–34% higher compared with youngest trees, which might be connected with increased microbial activity in soil. It is known that alders increase P availability through the activity of their roots and associated microbial communities (Giardina et al., 1995; Uri et al., 2002), and the interaction of roots and soil microbial communities is especially important in harsh conditions (Löhmus et al., 2006a). Microbial abundance was initially very low in oil shale mining spoil and increased with the age of stands. In the second year after planting, when the survived plants have overcome planting shock, plants support rhizosphere microbial communities massively, but in the

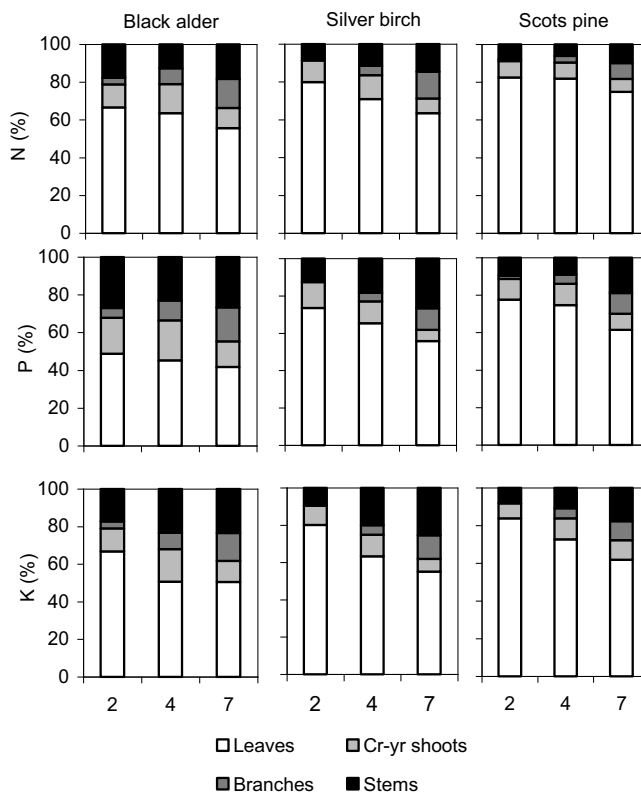


Fig. 4. Distribution of accumulated N, P and K amounts among the aboveground biomass compartments in studied stands (2, 4, 7 – age of stand in years).

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middle-aged stands, in improved soil, the support of rhizosphere communities is less important (Löhmus et al., 2006a, 2007).

In our study we found that the survival and growth varied among tree species. The survival and height of black alder were the highest among the studied tree species. Our findings are in accordance with the results of Oliveira et al. (2005) and Kupka and Dimitrovský (2006), who found that *Alnus glutinosa* had the best adaptation to anthropogenic substrates in the brown coal mining areas.

Our results showed that black alder had the largest absolute biomass and production among the studied species. Many papers report high biomass and production of deciduous species in recultivated abandoned agricultural land and post-mining substrates. So, according to Pregent and Camire (1985), the aboveground biomass of a 4-year-old black alder culture on an abandoned agricultural site could be as high as 15.8 t ha^{-1} and Johansson (2000) found that the aboveground biomass for 4–5-year-old black alder ranges from 2.0 to 13.4 t ha^{-1} . Mean annual increment values found in the literature for 4–12-year-old black alder on agricultural land range from 0.5 to $10.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Wittwer and Stringer, 1985; Johansson, 2000). A relatively high biomass production at $2.3\text{--}8.8 \text{ t ha}^{-1} \text{ yr}^{-1}$ of 4–8-year-old stands of birch was found on agricultural land (Telenius, 1999; Uri et al., 2007; Walle et al., 2007). On clayey–sandy nutrient-poor post-mining substrates the aboveground biomass production of 4-year-old fast-growing poplar, willow and aspen ranges from 5.3 to 19.6 t ha^{-1} (Bungart and Hüttl, 2001). Comparing the results of our study of biomass production for alder and birch stands with the above-presented results, it can be concluded that values found in post-mining areas are smaller than those reported in other studies. However, we should take into account that the period of fast growth of the trees studied in this work is still ahead and their present small biomass may also be due to their slow adaptation to hard growth conditions.

To estimate the nutrition of trees, we compared nutrient concentrations and their ratios with scales of optimum nutrient concentrations. It is known that the interaction of different mineral elements in plant tissues and their balance are of great importance in tree growth and survival under stress conditions (Ingestad and Ågren, 1988; Marschner, 2002; Portsmuth et al., 2005). In our study the N concentration in alder leaves ($2.5\text{--}2.9\%$) was a little lower than in general in Europe ($2.0\text{--}4.0\%$) (Saarsalmi, 1995; Löhmus et al., 1996; Uri et al., 2002; Vares et al., 2004). Also the concentrations of N in the leaves of silver birch and Scots pine were lower than needed for optimum growth (Ingestad, 1962), but the concentration of P was almost optimal in their foliage compared to Ingestad's (1962) scale. Leaf N and P concentrations of black alder and silver birch found in the present study were quite similar to the respective values on abandoned agricultural land (Vares et al., 2004; Uri et al., 2007). Compared to the scale of Ingestad (1962), deficiency of K in Scots pine and silver birch leaves was detected. The lower than optimum K concentration may be related to K availability. It is known that its availability decreases in calcareous environments due to the Ca and K antagonism (Trémolières et al., 1998; Marschner, 2002).

An important parameter in the study of nutrient concentration is the N:P:K ratio. According to nutrition studies (Ingestad, 1987), the optimum N:P:K ratios for silver birch and Scots pine are 100:13:65 and 100:14:45, respectively. For black alder we used the optimal ratio for grey alder 100:18:50 (Ingestad, 1987). Comparing the N:P:K ratios for aboveground production in the present study, it is evident that the relative P and K concentrations in annual production were lower than optimum in black alder. For silver birch and Scots pine the P:N ratio was close to optimum, while K:N in silver birch was twice lower than Ingestad's optimum and the K:N ratio in Scots pine was a little higher than the optimum. So we can conclude that the pines in our plantations were well supplied with these nutrients.

Our findings of higher concentrations of nutrients in leaves and smaller in stems are in the same range as the respective results of other researchers in young silver birch (Uri et al., 2007), black alder (Vares et al., 2004) and Scots pine (Jach et al., 2000) stands. Higher aboveground N, P and K contents were found in black alder than in the other studied species. The nutrient content per unit of dry biomass in 7-year-old black alder in the present study was in a range comparable with the respective values in 8-year-old silver birch stand (Uri et al., 2007) and with 7-year-old hybrid aspen (Tullus et al., 2009) on abandoned agricultural land. Thus, it can be concluded that in the post-mining area the nutrient accumulation of black alder was similar to that in a fertile agricultural land.

Some investigations show that different species growing in the same growth conditions use different amounts of nutrients to produce the same amount of biomass or stemwood (Alban et al., 1978; Alban, 1982; Eriksson and Rosén, 1994). In trees growing on reclaimed oil shale mining areas the N, P and K accumulated in biomass were highest for black alder, which was certainly related to the bigger biomass of the stands. However, the amounts of nutrients needed for producing a unit of aboveground biomass were significantly different between species. It was revealed that in similar growth conditions black alder used more N and silver birch more P for biomass production compared to the other studied species. Scots pine used N and P for biomass production more efficiently than black alder or silver birch. Our data about lower N use efficiency of black alder compared to other studied species confirmed the findings of Binkley et al. (1992), who reported that N_2 -fixing alders have lower N use efficiency than non-fixing tree species. These authors also reported a significant increase in soil N availability under N_2 -fixing tree species such as alder, and nutrient use efficiency should decrease with increasing rates of uptake (Binkley et al., 1984, 1992).

5. Conclusion

Afforestation of alkaline mining spoil with fast-growing trees is the best means to accelerate the development of new forest ecosystems. Deciduous trees should be favoured because they increase soil fertility more and have higher productivity than conifers. The present study revealed changes in soil properties with increasing stand age. Soil pH and P concentration decreased and soil N concentration increased with stand age. The survival and productivity of black alder stands on a reclaimed oil shale mining area were high, and hence it is a promising species for afforestation. Although black alder uses more nutrients for biomass production than the other studied species, the species is efficient in nutrient assimilation and produces a high biomass even in harsh conditions of reclaimed mines. Also, fast-growing black alder may serve for the production of bioenergy on recultivated sites in the future. The suitability and potential of biomass production of these species on reclaimed mining areas need further investigations.

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CHEMICAL AND MORPHOLOGICAL INDICATION OF THE STATE OF LODGEPOLE PINE AND SCOTS PINE IN RESTORED OIL SHALE OPENCAST MINING AREAS IN ESTONIA

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*Experimental comparative investigations of lodgepole pine (*Pinus contorta*) and Scots pine (*Pinus sylvestris*) plantations were carried out on exhausted oil shale opencast sites in Estonia, with the aim to assess the perspectives to avoid monocultures and to broaden the species list in the recultivation of areas destroyed by mining. The levelled detritus of the Narva opencast (59°15' N, 27°48' E) is characterized by rather extreme growth conditions for conifers: very alkaline (pH > 8.0) and stony substrate, lack of N in soil, destroyed water regime etc. The concentrations of nutrients vary in the growth substrate between plots and under different species. The needles of Scots pine contain more P, K, Ca than the needles of lodgepole pine. Comparison of the nutrient composition of two conifer species in 21–23-year-old plantations showed the deficiency of N, P and K and optimal concentrations of Ca and Mg in needles. Research indicated that lodgepole pine and Scots pine differ in their needle and shoot biomass as lodgepole pine formed longer and heavier needles and shorter and thicker shoots than Scots pine. Regardless of unfavourable soil conditions a good growth of stands have developed on levelled opencasts. From a practical point of view and taking into account the aim of the present study, besides the native Scots pine lodgepole pine from the list of introduced tree species for recultivation of oil shale opencast mining areas may be promising.*

Introduction

Vast areas of land all over the world have been rendered unproductive by human activities [1]. Ecosystem destruction by mining for coal, quarrying for minerals, and other processes to meet demands of industries, is an inevit-

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able part of civilization [2]. The increasing human need for these resources will certainly accelerate further degradation of natural habitats, as most of the mining areas are on the land that was previously occupied by forests or agriculture. The mineral extraction process drastically alters the physical and biological nature of a mined area. Strip-mining, commonly practiced to recover coal reserves leads to acceleration of erosion of biological diversity and creation of several other environmental problems [3], destroys vegetation [4], causes extensive soil damage and destruction [5] and alters microbial communities [6].

The goal of restoration is usually to develop a long-term sustainable ecosystem native to the area where mining had occurred [7]. Restoration aims to return the degraded system to some form of cover that is protective, productive, aesthetically pleasing [8] and to establish stable nutrient cycles of plant growth and microbial processes [9]. Plantation is the oldest technology for restoration of lands damaged by human activity [10]. Forest plantations can play a key role in harmonizing long-term rehabilitation of the forest ecosystem [11], in restoring productivity and biological diversity to degraded areas [12]. However, some researchers state that naturally developed vegetation shows as good growth as the vegetation of cultivated areas [4]. Moreover, investigations conducted in recent years have suggested that monocultures may in long-term perspective give negative results in the restoration of vegetation [13].

The choice of plantation species is likely to greatly influence both the rate and the trajectory of rehabilitation processes [14]. The presence of different tree species in a productive system can result in a better structure and increased nutrient availability of soil [15].

The role of exotic or native species in rehabilitation needs careful consideration, because we may have to use species combinations (native, exotic or combination thereof) that are capable of surviving in new conditions [16, 17]. For artificial introduction, use of species that are well adapted to the local environment should be emphasized [18, 19]. Indigenous species are preferable to exotics because they are most likely to fit in with a fully functional ecosystem and to be climatically adapted [20].

A desired species for planting on mine spoils should possess the ability to grow on poor and dry soils, to develop the vegetation cover in a short time and to accumulate biomass rapidly, to bind soil for arresting soil erosion and checking nutrient loss, and to improve the status of soil organic matter and soil microbial biomass, thereby enhancing the supply of nutrients available to plants [21]. In addition, if possible, the species should be also of economic importance.

In Northeast Estonia, until 2005, the area damaged by opencast mining was 12 900 ha, and forest rehabilitation of the skeletal calcareous detritus of oil-shale opencast mining has been carried out in an area of 10 188 ha since 1960.

Technogenically spoiled areas need restoration, but it is important to select tree species suitable for the afforestation of these areas. In the first stage of forest rehabilitation the levelled and skeletal calcareous detritus was initiated with sets of Scots pine [5]. Kaar [22] recommends that in the interests of biodiversity attention should be paid also to other tree species besides Scots pine, which so far prevails among trees planted (86%). A possible species for introduction for afforesting spoil areas is lodgepole pine, which is known as rather tolerant to pH and nutrient deficit in soil [23].

The aims of the present study are (i) to carry out the comparison of two pine species, Scots pine and lodgepole pine growing in plantations established on calcareous spoils of oil shale opencasts, (ii) to estimate the suitability of lodgepole pine for recultivation. The main attention was paid to estimation of the growth and biomass of needles and shoots and content of nutrients. For the interpretation of the status of trees it is necessary to clarify nutrition conditions of the growth substrate on the detritus of the Narva opencast.

Material and methods

Study area

The research was conducted in Narva (59°15' N, 27°48' E) opencast in Northeast Estonia. Two lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) (LP) and two Scots pine (*Pinus sylvestris* L.) (SP) stands planted on the levelled detritus of the Narva opencast were monitored and compared in 2004:

LPI – a LP site planted in 1983,

LPII – a LP site planted in 1982,

SPI – a SP site planted in 1982,

SPII – a SP site planted in 1981.

One sample plot (0.1 ha) was established in each plantation. Overbark diameter at breast height and the height of trees were measured on sample plots.

Main characteristics of the studied pine plantations are presented in Table 1.

Table 1. Main characteristics of the studied pine plantations on Narva oil shale opencast

Sample plot	Age, yr.	Number of trees per ha	Mean diameter at breast height $D_{1.3}$, cm	Mean height H, m	Basal area, $m^2 ha^{-1}$	Growing stock, $m^3 ha^{-1}$
LPI	21	2300	10.9	9.1	21.4	113
LPII	22	2450	9.0	8.8	15.4	81
SPI	22	2040	8.5	7.9	11.7	55
SPII	23	1220	11.5	10.4	12.7	75

Climatically the studied area belongs to the Atlantic-continental region, where the influence of the Baltic Sea is strongly felt. According to the Estonian Meteorological and Hydrological Institute, the annual amount of precipitation in this area for the last ten years was 753 mm, the wettest months of the year in 2004 were June, July and September. The amount of precipitation in 2004, when our studies were carried out, was 820 mm (Jõhvi weather station).

Morphological analysis

For the estimation of the state of the trees morphometric parameters (dry mass of needles and shoots and length of needles and shoots) suggested in relevant handbooks were used [24].

The current-year main shoots and needles of trees were collected in autumn 2004 after the growth had stopped. As trees vary, five shoots were collected from the crowns of 10 trees of each sampling site to get an average sample. From the collected samples dry mass (DM) of 100 needles and dry mass of shoots (g) at constant temperature (70 °C) in a thermostat (n = 50), length of needles (cm) (n = 500) and length of shoots (cm) (n = 50) were determined.

Analysis of soil and plant material

To characterize the growth substrate, in 2004 soil samples were collected from a layer of 30 cm depth taking into consideration that in the case of coniferous trees on average 80% of the roots assimilating nutrients are located in the upper 10–30 cm layer of soil [25, 26]. Five samples were taken from all sites and one average sample for the site was formed for analysis. The samples were dried and sieved (sieve No. 2).

The concentrations of mineral elements available to plants (N, P, K, Ca, Mg) in the soil and in the current-year needles were determined in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

Soil $\text{pH}_{\text{H}_2\text{O}}$ was determined in the laboratory of the Department of Eco-physiology of the Forestry and Rural Engineering Institute of the Estonian University of Life Sciences with a pH meter (Mettler Toledo GmbH, InLab412 electrode, Germany). For the analysis of N in soil the Kjeldahl method was used, for available P, Ca and Mg in soil a Flow Injection Analyser (FiaStar 5000) and for K a Flame Photometer were used.

Determination of N in the needles was carried out according to the Kjeldahl method; determination of P was carried out in Kjeldahl Digest by Fiaster 5000, stannous chloride method, ISO/FDIS15681; determination of Ca in Kjeldahl Digest by Fiaster 5000, *o*-cresolphthalein complexone method ISO3696; Mg was determined by Fiaster 5000, titan yellow method, ADSTN90/92; K was determined by the flame photometric method [27].

Statistical analysis

Average characteristics of the studied pine plantations were calculated in FoxPro.

Means of the samples, standard deviation, and correlations between the parameters (r) were calculated using MS Excel 9.0. Normality of variables was checked; the length and dry mass of shoots were normalized by log-transformation. The data were analysed by analysis of variance (ANOVA) in Systat (SPSS, Chicago, USA). The Bonferroni test was used for the multiple comparison of means.

Results and discussion

Characterization of the growth conditions of trees

Establishment of vegetation on abandoned mined lands is hindered by physical factors such as low availability of soil moisture, stony substrate of an uncertain structure, disturbed conditions of air and nutrition. The upper layers of spoils lack connection with groundwater and their moisture regime depends on meteorological conditions (precipitation, air temperature). It was shown also by Williams et al. [28] that especially in arid areas limited rainfall during the growing season and high surface temperatures often limit plant establishment and growth.

Analysis of the upper soil layers (30 cm) showed that the reaction of the soil samples from all study sites of the Narva opencast was alkaline. In two lodgepole pine sites (LPI, LPII) pH was on average 8.1; in the sites of Scots pine soil pH was 8.0 (SPI) and 8.2 (SPII). Lodgepole pine succeeds in nutrient-poor soils also according to literature data [23] and it is not very demanding about soil pH, although its growth becomes inhibited when soil pH > 8 [29]. Scots pine is likewise relatively tolerant of disbalanced nutrients and relatively high soil pH [30]. Although the soil reaction does not directly limit plant growth, the availability of several nutrients to plants depends on it. It is known that in an alkaline soil the mobility of several nutrient elements necessary for plants decreases and the mineral nutrition of plants becomes complicated [31–33]. It is known that when pH rises over 7, the mineralization processes of N will intensify, and its assimilation by plants will fall [34–36]. Considering the relatively slow decomposition of the litter of conifers [37, 38], it may be an additional reason of the disturbed N cycling and N deficiency in the growth substrate in our study sites. Marschner [26, 33] has accented that soil alkalinity decreases availability of N and P to plants.

The soil analysis confirmed heterogeneity of the substrate in the Narva opencast mining area. Concentrations of major elements in soil were very variable between different species and between sites (Fig. 1). For example, as compared to the lodgepole pine site LPII, the substrate of LPI has almost 22% less N available to plants, 57% less K and 30% less Ca, but the con-

centrations of P and Mg were by 8.6% and 14.5% higher, respectively (Fig. 1). Likewise, in site SPI of Scots pine the concentrations of N, K and Ca were higher while site SPII showed higher concentrations of P and Mg. Analogous results about the variable concentration of elements in opencast spoils have been reported by in earlier studies [39–42]. Also Reintam and Kaar [5] found that pedogenesis of opencast detritus differs in intensity and chemically by regions, depending significantly on tree species and density of vegetation. The level of organic carbon was the highest under deciduous stands, but also under pine with grasses. The poor ground vegetation and the presence of residual kukersite in detritus result in a low accumulation of the organic carbon of plant origin in some high productivity stands. Sparse vegetation growth on abandoned mine soils also results from low content of organic matter, low levels of plant nutrients, particularly P [43], N [44] and K concentrations [45].

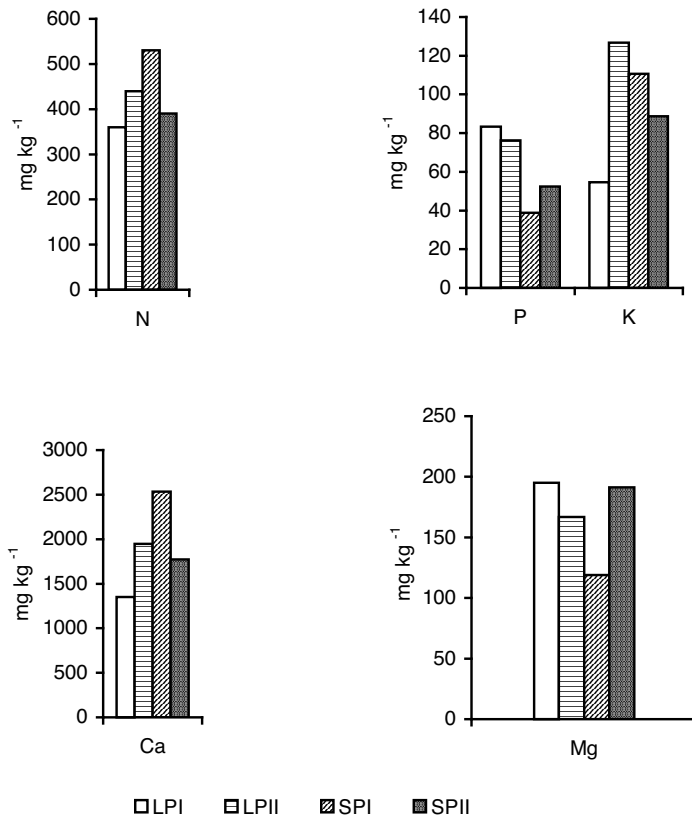


Fig. 1. Chemical composition of growth substrate in the Narva opencast area

From the aspect of mineral nutrition of plants the balance of the concentration of nutrients in soil is considered to be an important factor. Our research results showed that the ratios of the main nutrients differed in the growth substrates of four sites on oil shale opencast spoils. The ratio of N : P : K in the detritus of lodgepole pine was 1 : 0.23 : 0.15 (LPI) and 1 : 0.17 : 0.29 (LPII). The ratio of N : P : K in the detritus of Scots pine was 1 : 0.07 : 0.21 (SPI) and 1 : 0.13 : 0.23 (SPII). The differences in the ratios of nutrients in the substrate should be reflected in the growth and development of trees.

Mineral composition of needles

The needle diagnostic method is one of the possibilities of assessing the status of trees [24] in both in industrial areas and in natural forest ecosystems [25, 32, 41, 46–48].

Considering rather large differences in the concentrations of nutrients available to plants in the detritus of the study sites, rather large variation in the needle analysis could also be expected. Analysis of needle samples collected from different sites indicates not only differences between the two species in the concentrations of nutrients (Fig. 2), but also differences in the chemical composition of the needles of the same species from different sites. It was found that the content of P, K and Ca in Scots pine needles was higher than in the needles of lodgepole pine. No significant differences were observed between nitrogen concentrations in lodgepole pine needles from different sites. However, chemical analysis of Scots pine needles revealed an 11% difference between the two sites with the higher concentration in the site SPI.

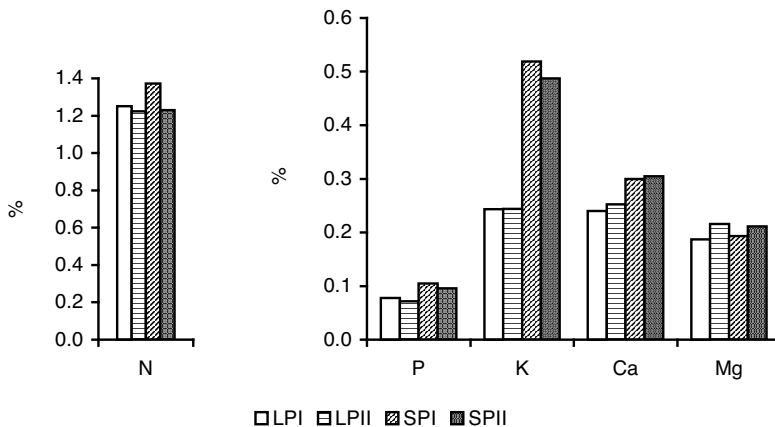


Fig. 2. Concentration of mineral elements in current-year needles of lodgepole pine and Scots pine

For most coniferous trees growth-limiting element is nitrogen [32, 49]. In this study we compared the obtained results with the optimum N concentrations in needles suggested by several authors [50–52] (Table 2) and with figures indicating N deficiency in pine needles [41, 53, 54]. Tests conducted by Raid [54] showed that an especially strong N deficiency (concentration in needles 0.92–1.15%) develops in pine seedlings in *Cladina* and *Calluna* site types. According to Porgasaar [53] the nutrition of Scots pine can be regarded as good if the N concentration in needles at the end of the growing season is 2.0–2.5%, while N shortage is great if its concentration in needles is 1%. Ingestad [50] states that for optimum growth of pine the N concentration in needles has to be 2.4–3.0%. According to Wehrmann [51] 1.8–3.2% is needed. Brække and Salih's [52] data show in current-year needles of Scots pine deficiency when the N concentration is 1.2–1.5%. Considering all these figures we can say that the needle samples collected from trees on opencast spoils in autumn 2004 indicate a severe N deficit. Our data on the deficit of N in the needles of Scots pine confirm the results of Kaar and Raid [41], who found only 0.7–1.03% N in the needles of Scots pine growing on Narva opencast. However, some authors state that Scots pine tolerates N deficiency relatively well, using optimally the nitrogen assimilated from the soil [25]. Most probably Scots pine mobilizes N from old tissues to form new needles if the conditions for N uptake are hard.

Table 2. Concentration of elements in current-year needles of Scots pine in Narva opencast and comparison with optimum scales elaborated by Ingestad [50], Wehrmann [51] and Brække, Salih [52]

Element, %	Ingestad [50]	Wehrmann [51]	Brække, Salih [52]	Narva opencast	
				SPI	SPII
N	2.4–3.0	1.8–3.2	>1,8	1.37	1.23
P	0.15–0.4	0.2–0.3	>0,18	0.11	0.096
K	0.9–1.6	0.55–0.9	>0,6	0.52	0.49
Ca	0.04–0.3	0.05–0.24	>0,07	0.3	0.3
Mg	0.12–0.18	0.06–0.13	>0,08	0.19	0.21

As lodgepole pine is an exotic species in Estonia, we use for the comparison and assessment of its nutrition on opencast detritus the scale of the concentrations of nutrients in the current-year needles presented by Ballard and Carter [55] and Brockley [56], which can help to draw conclusions about the supply of nutrient elements also in the trees growing on opencast detritus. The scale was developed for the lodgepole pine growing in its natural area in North America, and thus the comparison made is conditional. Comparison of our data with the scale of Ballard and Carter [55] (Fig. 3) improved by Brockley [56] (where <1.00% – N severely deficient; 1.00–1.15% – moderately to severely deficient; 1.15–1.35% – slightly to moderately

deficient; $>1.35\%$ – N adequate) allows us to say that lodgepole pines growing on opencast detritus show slight to moderate N deficiency. However, if compared to van den Driessche's [57] results on the lodgepole pine foliar N concentration of 1.63–1.73% dry wt., we can be convinced of the deficit of N on the Narva opencast. Earlier investigations [58] of mineral nutrition of conifers growing on oil shale mine sites have shown that needles of *Pseudotsuga menziesii*, *Pinus contorta* and *Picea pungens* had N and P deficit.

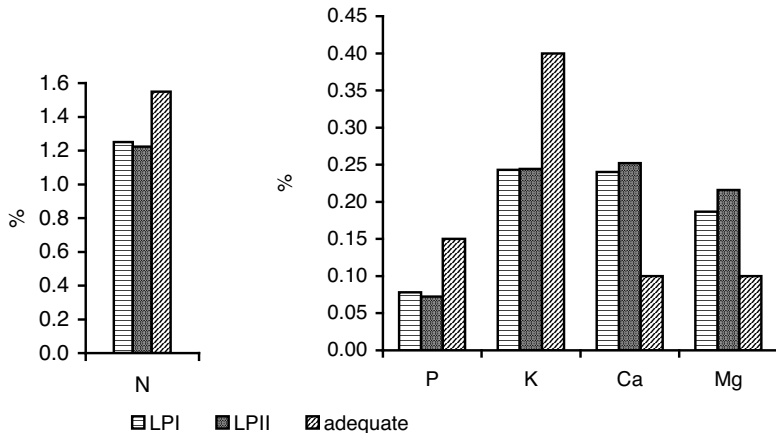


Fig. 3. Adequate macronutrient concentration in lodgepole pine needles in Narva in comparison with the scale elaborated by Ballard and Carter [53]

In the samples collected in 2004 the concentration of phosphorus in the needles of Scots pine in the two sites was 0.11% and 0.096%. Considering the scales of needle P concentrations by Ingestad [50], Wehrmann [51] and Brække, Salih [52] (Table 2), we can say that current-year needles of Scots pine suffer a severe P deficiency. A study by Kaar and Raid [41] also showed that the concentration of P in the needles of Scots pine on the detritus of Narva opencast is not over 0.16%.

The concentration of P in the needles of lodgepole pine growing in the Narva opencast mine was only 0.072% and 0.078% of dry wt. (Fig. 3), which should indicate P deficit in the tissues ($<0.08\%$ P) [56].

Comparison of the two pine species suggests P deficiency in the needles in both of them. The concentrations of P in spoil detritus were not reflected in the P concentrations of needles. Consequently, in alkaline substrate P compounds that are difficult to assimilate by plants are formed. Assimilation of phosphate ions from soil is the most successful when the pH is 6.5–7.5 [59]. As pH of spoil detritus in the study sites is higher (8.0–8.2), the alkalinity of the substrate should be considered the reason for P deficit.

An earlier study by Kaar and Raid [41] showed that the pine plantations were mostly sufficiently supplied with potassium, and the supply of calcium

and magnesium was high in all opencasts. The results of our study indicated a deficiency of K in pines. Compared with the scales of Ingestad [50], Wehrmann [51] and Brække, Salih [52] (Table 2) needles of Scots pine showed K deficiency. According to Brockley [56] the nutrition of lodgepole pine can be regarded as optimum when the K concentration is over 0.40%, while a severe deficiency occurs in case the K concentration in needles is below 0.30%. According to Ballard and Carter [55] the optimum K concentration in needles is 0.40%. Hence, also lodgepole pine plantations suffer rather severe K deficiency on levelled opencast mines (Fig. 3). Data by Kärblane [59] and Marschner [33] show that the supply of plants with K is disturbed at pH 7.5–8.5. Potassium is hard to obtain in arid soil [60]. As K is involved in starch formation, translocation of sugars, development of chlorophyll, protein synthesis, cell division, and growth [61], thus K deficiency may result in many changes in physiology and metabolic processes of trees.

The plantations of Scots pine and lodgepole pine had a sufficient supply of calcium and magnesium. Comparison of our data with the scales of optimum concentrations of elements published by Ingestad [50], Wehrmann [51] and Brække, Salih [52] (Table 2) shows that the current-year needles of Scots pine on the sample plots contained optimum amounts of Ca and Mg. As to lodgepole pine, the concentration of Ca and Mg in the current-year needles was even higher than optimum (Fig.3) at comparison with the scales by Ballard and Carter [55] and Brockley [56] (optimum Ca concentration in needles > 0.10%, Mg > 0.08%). It is known that intensive K accumulation may be accompanied by inhibited accumulation of Ca and its low concentrations in tissues and vice versa [26]. So, at intensive accumulation of Ca into Scots pine needle tissues falling K concentration was observed.

Ratios of different nutrients in tissues promise to be better indicators of plant nutrient status than absolute concentrations [62]. Optimum growth of trees occurs under balanced nutrition conditions [63–65]. It is known that trees can assimilate nutrients in relatively optimum ratios also from rather disbalanced and nutrient-poor soils [26]. The ratios of the nutrients (N : P : K) in the needles of pines in plantations on opencast detritus did not vary significantly between the different sampling plots of lodgepole pine (LPI and LPII) and Scots pine (SPI and SPII). The ratio of N : P : K in the needles of lodgepole pine was 1 : 0.06 : 0.16 (LPI) and 1 : 0.06 : 0.20 (LPII), this ratio in the needles of Scots pine was 1 : 0.09 : 0.38 (SPI) and 1 : 0.08 : 0.39 (SPII).

Comparison of the absolute values of the ratios of nutrients in the needles of lodgepole pine with the scale of ratios suggested by Brockley [56] as important indicators of the status of trees allows us to confirm severe deficiency of P and K and optimum concentration of Mg in the needles of lodgepole pine growing on opencast detritus. According to Brockley [56]:

*N : P > 13 – moderate to severe P deficiency (our analysis: LPI – 16.0, LPII – 17.0);

*N : K > 4.5 – moderate to severe K deficiency (LPI – 5.2, LPII – 5.0);

*N : Mg < 15 – no Mg deficiency (LPI – 5.2, LPII – 4.9).

The nutrient concentrations seemed to be low if compared with defined standards for optimum concentrations based on laboratory experiments with Scots pine seedlings [50, 51] and on Scots pine forest stands in Finland, Sweden and Norway [52]. From the other hand, the indicated concentrations of N and K in the needles of Scots pine growing on opencasts did not differ from these values obtained in *Vaccinium* and *Oxalis-Myrtillus* forest types [32, 66, 67]. Following from that we can suppose that content of elements in the needles of our study area is sufficient for good growth of trees.

Morphological analysis

The morphology of trees is considered in monitoring systems that evaluate the state of trees in areas under human impact [24, 68]. One of the most important tests of tree quality is estimation of the biomass and growth parameters of assimilating organs – leaves or needles.

From the standpoint of tree productivity an important indicator is needle mass, which is affected from photosynthesis, metabolism and growth processes. The better the growth conditions, the heavier are the needles and the more vigorous is tree growth. Various investigations of fertilizer consumption reveal that also the length of needles and the dry mass of 100 needle pairs reflect rather well the soil conditions of forest site types [41]. Results of earlier studies of forest plantations on oil shale opencast sites correspond, as to the needle length and dry mass, mostly to plantations in *Cladina* site type and partly to *Vaccinium vitis-idaea* site types [41].

It is known that besides the quality of the substrate also climatic as well as biotic factors are of importance [69]. According to the literature, in precipitation-rich years pine needles are characterized by elevated length and mass values as well as nitrogen and phosphorus concentrations in needles [59]. In dry years, on the contrary, needles are shorter and lighter, their N and P concentrations are lower, but they are rich in K. The year 2004 was rich in precipitation (yearly precipitation amount 820 mm according to data of the Estonian Meteorological and Hydrological Institute), and it is possible that this favoured the formation of needle mass. Therefore, studies should be continued to clarify problems that cropped up.

Our investigations on Narva opencast showed that the average length of the needles on the main shoots of Scots pine from two sample plots formed in 2004 was 4.3 and 4.7 cm. From investigations in the same climatic conditions in Lahemaa National Park it is known that the average length of the needles on the main shoots was 4.5–5.5 cm in 1991–1994 [70, 71]. Results obtained by us did not differ significantly from the average length of Scots pine needles in Estonia [72] and other measurements in the same climatic zone [70, 71]. However, the dry mass of the needles in two stands on the oil shale opencast was notably smaller (DM of 100 needles was 1.23 and 1.26 g) (Fig. 4) than that of the trees measured in Lahemaa National Park in 1990–

1992 [70]. Still, as compared with the results obtained in a strongly alkalized area (pH of soil 8.1) near Kunda cement plant (DM of 100 needles on the main shoots was 0.91 g) [70], the dry mass of needles of pines growing on the sites of oil shale opencast is on average 34% higher.

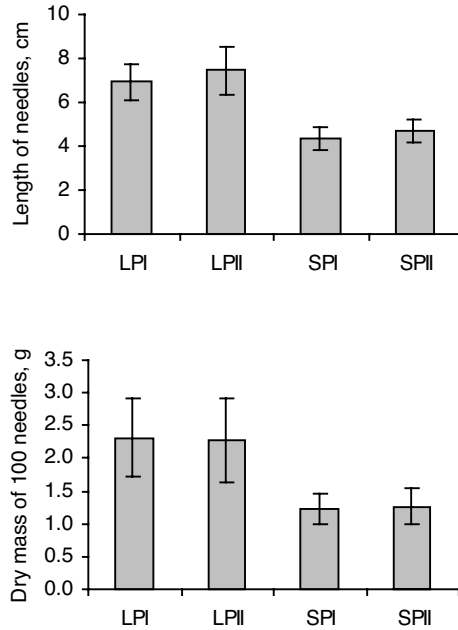


Fig. 4. Length of needles and dry mass of 100 needles (mean±SD) of lodgepole pine and Scots pine in the Narva opencast mine area

Our investigation showed the needles of lodgepole pine to be 1.7 times as long and 1.9 times as heavy as the needles of Scots pine. This can be explained by the difference in the genotype. Kishchenko [73] argues that the annual increment of needles depends on the internal reserves of the organism and intensity of growth rather than on the length of the growing period.

By use the multiple comparison of means the statistically significant differences were found between two sample plots for the length of the needles of lodgepole pine ($p < 0.05$), but not between two sample plots of Scots pine ($p > 0.05$). However, there was a significant difference between two species of pines ($p < 0.05$) in the length of needles (Fig. 4). Dry mass of 100 needles analysis showed that the dry masses of needles of a certain species (both lodgepole pine and Scots pine) in two plots were similar ($p > 0.05$), but dry masses of 100 needles differed significantly between species ($p < 0.05$) (Fig. 4). Correlation analysis revealed a strong relationship between the length and dry mass of the needles of both lodgepole pine

and Scots pine (LPI $r = 0.66$, LPII $r = 0.86$, SPI $r = 0.73$, SPII $r = 0.81$, $p < 0.001$).

We cannot make any particular conclusions from results of ANOVA as we do not know if variability of the mass and length of shoots depends on the sampling point or on tree species. The variability of shoot parameters between sample plots within species was significant. Comparing the mean shoot length of two species we can confirm that the shoots of Scots pine showed a more intensive length increment than lodgepole pine shoots ($p < 0.05$) (Fig. 5). The dry mass of the shoots of the two pine species did not differ significantly ($p > 0.05$), but was somewhat higher in the case of lodgepole pine (Fig. 5).

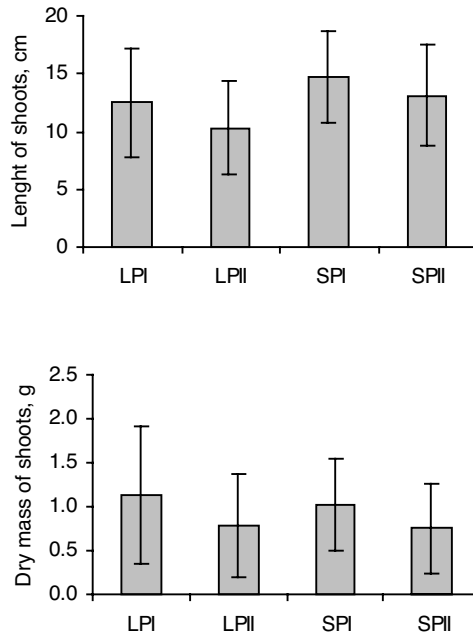


Fig. 5. Length of shoots and dry mass of shoots (mean \pm SD) of lodgepole pine and Scots pine in the Narva opencast mine area

Our investigations showed that lodgepole pine and Scots pine differ in their needle and shoot biomass as lodgepole pine formed longer and heavier needles and shorter and thicker shoots than Scots pine. Possible reasons for the superior growth rate of lodgepole pine compared to Scots pine were investigated in Sweden. Norgren [74] showed that lodgepole pine seedlings had greater mass than those of Scots pine of the same age. The growth analysis showed that the faster relative growth rate in lodgepole pine

seedlings was linked with a higher leaf area and nitrogen use efficiency. From research in Sweden it is known that lodgepole pine is estimated to produce 36% more wood than Scots pine and it survives better in the young stages, but is less stable against wind and snow load after being planted [75]. This higher stemwood production can be achieved through a faster rate of total biomass production or by allocating a larger proportion of the biomass produced to stem growth [74]. Comparison of the mean annual increment of height and diameter of lodgepole pine and Scots pine showed no differences between the studied species ($p > 0.05$).

Conclusions

The levelled and skeletal calcareous detritus of oil shale opencast sites is characterized by unsuitably high $\text{pH} \geq 8$ and disbalanced nutrition substrate for the growth of trees. Extreme growth conditions affect the physiological state of trees, especially mineral nutrition processes. Because of the alkaline pH of the growth substrate elevated amounts of Ca and Mg and deficit of N, P and K developed in the tissues of needles. Differences were revealed between the two species investigated, which were due to differences in the metabolism and demand of nutrients. Scots pine accumulates larger amounts of P, K and Ca than lodgepole pine. The relatively stable ratio of N : P : K in the needles of pines on different sample plots indicated their ability to obtain mineral nutrients from soil in balanced ratios.

Lodgepole pine had greater needle mass and length, shorter and thicker shoots than Scots pine. According to the mean annual increment of height and diameter lodgepole pine and Scots pine did not differ essentially.

In spite of unfavourable soil conditions (stony substrate, too high pH for successful assimilation of phosphorus, low N reserved, disturbed water regime), stands on abandoned levelled opencast mines show good growth. In general we may say that although the reaction of detritus in opencast sites is not suitable for optimum growth of several tree species, Scots pine and lodgepole pine can grow there. From a practical point of view and considering the necessity to avoid Scots pine monocultures in recultivation processes, lodgepole pine may be suitable to grow in post-mining landscapes.

In recent years, interest in rehabilitating the land disturbed by mining activity has grown from the point of species selection. Rehabilitation of degraded landscapes needs research for identification of stress-tolerant plant species having a positive influence on soil fertility and for maximizing ecosystem productivity under a wide range of degraded site conditions. The current research needs to be continued and more investigation is needed for final conclusions.

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Growth, aboveground biomass and nutrient concentration of young Scots pine and lodgepole pine in oil shale post-mining landscapes in Estonia

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Abstract The investigation was carried out in 8-year-old Scots pine (*Pinus sylvestris* L.) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) plantations on post-mining area, Northeast Estonia. The aim of the study was to assess the suitability of lodgepole pine for restoration of degraded lands by comparing the growth, biomass and nutrient concentration of studied species. The height growth of trees was greater in the Scots pine stand, but the tree aboveground biomass was slightly larger in the lodgepole pine stand. The aboveground biomass allocation to the compartments did not differ significantly between species. The vertical distribution of compartments showed that 43.2% of the Scots pine needles were located in the middle layer of the crown, while 58.5% of the lodgepole pine needles were in the lowest layer of the crown. The largest share of the shoots and stem of both species was allocated to the lowest layer of the crown. For both species, the highest NPK concentrations were found in the needles and the lowest in the stems. On the basis of the present study results it can be concluded that the early growth of Scots pine and lodgepole pine on oil shale post-mining landscapes is similar.

Keywords Scots pine · Lodgepole pine · Oil shale mining · Reclamation · Biomass · Mineral nutrition

Introduction

Developing society has increased dependence on fossil fuels and faster evolution requires increasingly more resources. During their existence people have used different raw materials from the bowels of the earth, but inevitably we will be faced with the fact that when mines are exhausted, we are left with huge areas of destroyed soil, fauna and flora. Every year, opencast mining in the Northeast Estonian oil shale field – the largest commercially exploited oil shale deposit in the world (total amount of resources: 7×10^9 tons) (Bauert and Kattai 1997) – creates substantial areas of wasteland. The restoration of post-industrial landscapes is often a challenge regarding multifunctional land use issues. Multifunctionality is important from the point of view of both natural capital and socio-economic values (Haines-Young et al. 2006). On the other hand, restoration provides several opportunities for the optimal use of landscape functions (de Groot 2006). One option to restore these areas is to leave them as they are, hoping that spontaneous succession of vegetation will do its work. However, natural succession on mining areas is a time-consuming process (Wali 1987). A faster alternative is to restore mining areas biologically. The goal of restoration is usually to develop a long-term sustainable ecosystem native to the area where mining occurred (Chambers et al. 1994). However, depending on governmental possibilities and social interests, multidirectional activities could be developed in the recultivated areas. Practice of different countries show that exhausted mining areas could be used for creating sporting facilities, for the recreation areas and parks, for the development of agriculture or reforestation (Stottmeister et al. 2002). Forestry is the dominating land use after oil shale mining in Northeast Estonia. Until 2006 the area damaged by oil shale opencast mining is 13,098 ha and 10,347 ha has been afforested (Kaar and Tomberg 2006), mainly with Scots pine (86%) (Kaar 2002). Because of the large proportion of monocultures of the Scots pine, one of the possible alternatives is to establish parks and green areas, where other tree species including exotic species can be used. Native species are successful in plantations on post-mining areas (Butterfield 1996; Shepherd 1994), but still fast growing exotic species are often preferred (Ang 1994; Shepherd 1994). It is known that, desired species for planting on mine spoils should accumulate biomass rapidly and if possible the species should be of economic importance (Singh and Singh 1999; Singh et al. 2002). Fast-growing exotic species are reported to show faster growth than native species on degraded land during initial couple of years of establishment (Parrotta 1999). Dutta and Agrawal (2003) concluded that exotic species may be recommended for primary rehabilitation on coal mine spoil due to their fast growth and

establishment. Baumann et al. (2006) found that *Pinus nigra* grew better in the mining substrate than *Pinus sylvestris* indicating that *P. nigra* may be a better choice for reforestation of mine overburden containing lignite. For a long time Estonian oil shale mining areas have been “research laboratories”, where large-scale investigations have been conducted to find out most suitable tree species for restoration (Kaar et al. 1971). A total of 52 indigenous and introduced species have been planted to evaluate their growth in extreme conditions on post-mining areas. Among others lodgepole pine has been planted. Investigations in Sweden showed that the fast growth rate of lodgepole pine makes it capable of suppressing slower growing species such as Scots pine and Norway spruce (Despain 2001).

For assessing the suitability of selected plant species for restoration of opencast oil shale mine spoils, the growth and biomass of trees were quantified to test the hypothesis that plants obtaining higher growth and biomass production will be more suitable for speedy restoration of degraded lands. In this study we supposed the better growth of lodgepole pine compared to Scots pine. The aim of this paper was to analyse and compare the growth, aboveground biomass allocation and nutrient concentrations of Scots pine and lodgepole pine used for reclamation of post-mining areas. The study results allow to assess the suitability of lodgepole pine for reclamation of oil shale post-mining areas. The approaches of this study can be used for other regions where alkaline wastelands require reclamation.

Materials and methods

Study area

The study area is located in the Narva (59°15' N, 27°48' E) opencast oil shale mining area in Northeast Estonia. The calcareous quarry detritus of the oil shale opencast area is considered as an unfavourable substrate for the growth of trees. It is alkaline ($\text{pH}_{\text{H}_2\text{O}} = 8.0\text{--}8.2$), heterogeneous and extremely stony, its water and nutrition regimes are disturbed and the concentrations of nitrogen and phosphorus in it are low. Mean N and available P concentrations in plantations were 327 mg kg^{-1} and 48 mg kg^{-1} , respectively. The present study was carried out in Scots pine and lodgepole pine plantations established by planting 2-year-old seedlings in 1998. The planting arrangement was $1.5 \times 1.5 \text{ m}$ (4444 trees per ha) for Scots pine and $2.0 \times 2.0 \text{ m}$ (2,500 trees per ha) for lodgepole pine.

Measurements and data collection

Fieldwork in the studied stands was carried out in August 2006. One sample plot (0.1 ha) was established in each stand. The diameter at root collar (D) with a calliper and the height (H) of all trees with a Suunto clinometer were measured for each sample plot. The aboveground biomass of trees was determined from harvested model trees. The trees growing on sample plots were divided into five height classes and one tree from each height class per plot was randomly selected and felled. The crowns of the model trees were divided into three layers (highest – 1, middle – 2, lowest – 3) to compare the differences of developing of crowns. In each layer, 2 model branches were selected for estimating the growth of needles and shoots. Current-year and 1-year-old main shoots were taken for measurements from model branches. The dry mass of needle (g), the length of 10 needles (cm), the length and thickness (dry mass per length) of shoots (g cm^{-1}) and the density of needles on shoots per each model branch were determined. The harvested trees were divided into aboveground compartments: needles, shoots and stems. Dead shoots were separated. After drying at $70 \text{ }^\circ\text{C}$ until constant weight the dry mass of the compartments was determined. All fractions were weighed to 0.001 g. The aboveground biomass of tree was obtained by sum of needles, shoots and stem biomass.

Chemical analysis

The plant material for analysis was collected from model trees of three growth classes: the lowest, medium and highest per sample plot. The concentrations of nitrogen (N), phosphorus (P) and potassium (K) were determined in different biomass compartments of the model trees (current-year and 1-year-old needles and shoots and stem). The collected plant material was dried and ground. One composite sample per compartment was done from different crowns layers.

Determination of N in the plant material was carried out according to the Kjeldahl method; P was determined in Kjeldahl Digest by Fiastr 5000, Stannous Chloride method, ISO/FDIS 15681; K was determined by the Flame Photometric method (Ruzicka and Hansen 1981). Chemical analyses were made in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

Statistical analysis

The Lilliefors and Shapiro–Wilkinson tests were used to check the normality of variables. Unnormal data were normalized by log- and root-transformation. Throughout the study, the means are presented with standard error of the mean. To perform statistical analysis, Statistica 7.0 and Excel 2003 were used, and the significance level $\alpha = 0.05$ was accepted in all cases. The Tukey HSD test was used for the multiple comparison of means.

Results

Height and diameter

Comparison of the growth of pines on the post-mining areas showed that the mean height of the Scots pine stand was significantly larger than that of the lodgepole pine stand ($P < 0.05$) (Table 1). There was no significant difference in the mean diameter of trees between the two plant species.

Aboveground biomass and biomass allocation

The aboveground biomass allocation to compartments (needles, shoots and stem) within species and between species did not differ significantly (Tukey test, $P > 0.05$) (Fig. 1).

The vertical distribution of compartments of Scots pine between the crown layers showed that the largest proportions of the total needle biomass were located in the middle and lowest layers of the crown, respectively 43.2% and 35.7% (Fig. 2). Of the Scots pine shoot biomass respectively 47.4% and 41.3% gave the lowest and middle part of the crown. The largest share of the Scots pine stem (62.2%) was allocated to the lowest layers of the crown. For lodgepole pine the largest share of needles, shoots and stem was allocated to lowest layers of the crown, respectively 58.5%, 67.7% and 66.5% (Fig. 2). Although there was no statistically significant difference in the mean aboveground biomass between two species, lodgepole pine had a 24% higher aboveground biomass than Scots pine (Table 1).

Table 1 Tree characteristics and biomass of the aboveground compartments of Scots pine and lodgepole pine. Values are given as the mean \pm SE

Species	D, cm	H, cm	Needle, g	Shoot, g	Stem, g	Aboveground biomass, g
Scots pine	3.31 \pm 0.09	152.3 \pm 4.2 ^a	298.9 \pm 117.8	254.8 \pm 124.6	246.9 \pm 129.6	800.7 \pm 370.8
Lodgepole pine	3.28 \pm 0.07	120.0 \pm 2.9 ^b	476.9 \pm 200.4	294.7 \pm 158.8	282.2 \pm 124.1	1053.8 \pm 476.1

Superscript letters indicate a statistically significant difference ($P < 0.05$)

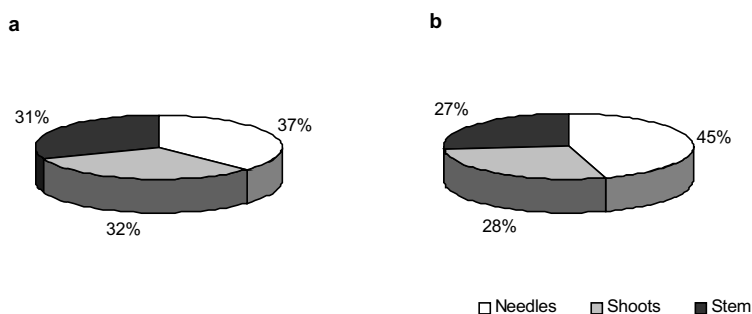


Fig. 1 Relative biomass allocation to the different aboveground compartments for Scots pine (a) and lodgepole pine (b)

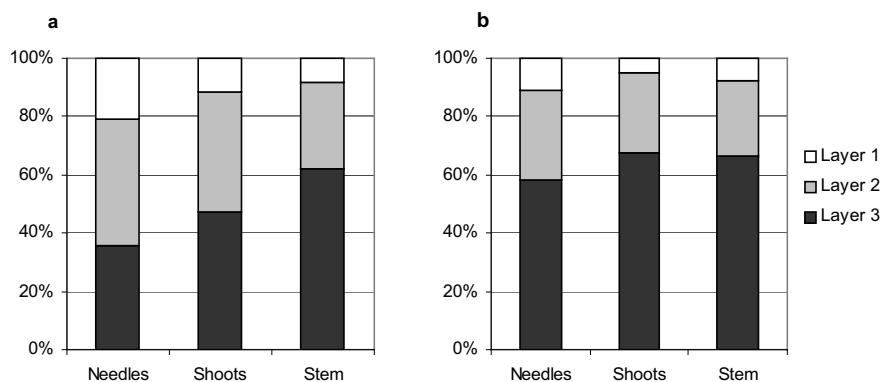


Fig. 2 Vertical distribution of the proportion of needle, shoot and stem biomass in the tree crown for Scots pine (a) and lodgepole pine (b)

Morphological parameters of needles and shoots

The statistically significant differences were found between the crown layers of Scots pine in the current-year dry mass of needles and length and thickness of shoots ($P < 0.05$) (Table 2). Results showed that these parameters were smaller in the lowest layer of the crown. For lodgepole pine, the length and thickness of shoots were slightly smaller in the lowest part of the crown and the density of needles on shoots was slightly bigger, but no statistically significant differences occurred. Other parameters were similar between the crown layers. Parameters of 1-year-old needles and shoots had the same tendency.

Significant differences between the two species were found in the length and dry mass of current-year and 1-year-old needles ($P < 0.05$) (Fig. 3), length and thickness of shoots and density of needles ($P < 0.05$) (Figs 4, 5).

The thickness of the current-year shoots differed significantly between the species, but the thickness of the 1-year-old shoots was similar for both species. The thickness of the current-year shoots of Scots pine was 60% smaller than the thickness of the 1-year-old shoots ($P < 0.05$), for lodgepole pine this difference was 38% ($P < 0.05$).

The density of needles differed significantly between the species in the case of both current-year and 1-year-old shoots ($P < 0.05$). The density of needles on the current-year shoots was larger than on 1-year-old shoots; for Scots pine the difference was 30% and for lodgepole pine, 21% ($P < 0.05$).

Table 2 Variation of parameters of current-year needles and shoots in different crown layers of Scots pine and lodgepole pine. Values are given as the mean \pm SE

Species	Crown layer	Dry mass of needle, mg	Length of needle, mm	Density of needles on shoot, No cm ⁻¹	Length of shoot, cm	Thickness of shoot, g cm ⁻¹
Scots pine	1	0.013 \pm 0.002 ^a	4.3 \pm 0.34	6.1 \pm 1.5	14.5 \pm 4.1 ^a	0.056 \pm 0.012 ^a
	2	0.009 \pm 0.001 ^{ab}	4.0 \pm 0.3	8.0 \pm 0.3	14.0 \pm 2.1 ^a	0.043 \pm 0.006 ^a
	3	0.008 \pm 0.001 ^b	3.8 \pm 0.3	8.4 \pm 0.5	7.8 \pm 0.9 ^b	0.023 \pm 0.002 ^b
Lodgepole pine	1	0.017 \pm 0.003	5.9 \pm 0.4	10.3 \pm 1.6	10.6 \pm 2.4	0.070 \pm 0.010
	2	0.018 \pm 0.005	6.3 \pm 0.6	11.9 \pm 0.9	10.7 \pm 2.4	0.072 \pm 0.021
	3	0.015 \pm 0.003	6.3 \pm 0.5	12.1 \pm 0.9	8.6 \pm 1.8	0.046 \pm 0.008

Superscript letters indicate a statistically significant difference ($P < 0.05$)

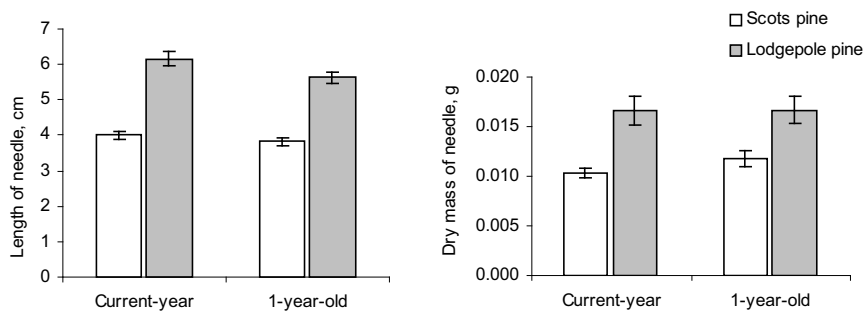


Fig. 3 The length and dry mass of current-year and 1-year-old needles of Scots pine and lodgepole pine

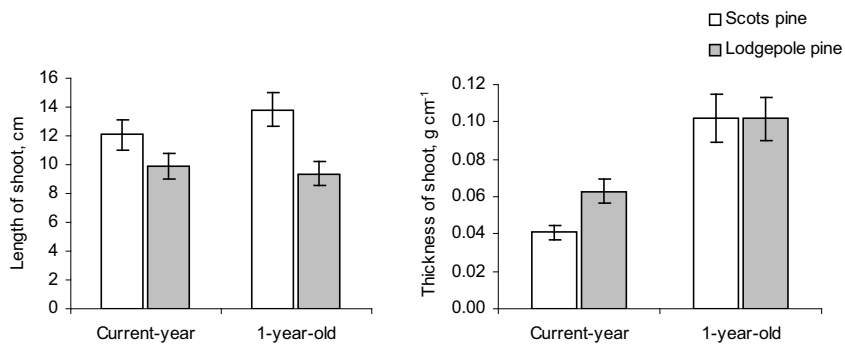


Fig. 4 The length and thickness of current-year and 1-year-old shoots of Scots pine and lodgepole pine



Fig. 5 Density of needles on current-year and 1-year-old shoots of Scots pine and lodgepole pine

Nutrient concentration and allocation

For both species, the highest NPK concentrations were found in the current-year and 1-year-old needles and the lowest in the stems (Table 3). The differences in the concentrations between the fractions were statistically significant both in Scots pine and lodgepole pine stands.

Nitrogen and phosphorus concentrations in the current-year and 1-year-old needles between the two species were not significantly different, but a higher concentration of potassium had Scots pine needles ($P < 0.05$). The NPK concentrations in the shoots revealed no differences between the species, except for the potassium concentration in the current-year shoots of Scots pine, which was significantly higher than the lodgepole pine values ($P < 0.05$). The concentrations of elements in the stems did not differ between the species.

Comparison of the N : P : K ratios, one of the most important parameters in the analysis of nutrient concentrations, was made on the basis of current-year needles. It was revealed that for Scots pine the N : P : K ratio in the needles was 100 : 9.4 : 35.6 and for lodgepole pine 100 : 8.6 : 30.

Table 3 N, P and K concentrations (%) in different tree fractions of Scots pine and lodgepole pine. Values are given as the mean \pm SE

	Scots pine			Lodgepole pine		
	N	P	K	N	P	K
Current-year needles	1.590 \pm 0.027 ^a	0.146 \pm 0.004 ^a	0.567 \pm 0.029 ^a	1.43 \pm 0.086 ^a	0.125 \pm 0.009 ^a	0.420 \pm 0.024 ^a
1-year-old needles	1.382 \pm 0.030 ^b	0.127 \pm 0.004 ^a	0.519 \pm 0.025 ^a	1.200 \pm 0.092 ^a	0.100 \pm 0.010 ^{ab}	0.347 \pm 0.033 ^a
Current-year shoots	0.717 \pm 0.061 ^c	0.102 \pm 0.001 ^a	0.633 \pm 0.041 ^a	0.700 \pm 0.058 ^b	0.099 \pm 0.002 ^{ab}	0.368 \pm 0.005 ^a
1-year-old shoots	0.578 \pm 0.060 ^c	0.065 \pm 0.005 ^b	0.270 \pm 0.014 ^b	0.547 \pm 0.019 ^{bc}	0.077 \pm 0.002 ^b	0.277 \pm 0.008 ^b
Stem	0.340 \pm 0.027 ^d	0.044 \pm 0.004 ^b	0.189 \pm 0.016 ^b	0.284 \pm 0.011 ^c	0.040 \pm 0.003 ^c	0.171 \pm 0.006 ^c

The superscript letters indicate a statistically significant difference ($P < 0.05$)

Discussion

Growth and biomass

Evaluation of the growth and biomass in plants growing on mine spoil is important to assess the suitability of plant species for the reclamation process. From the literature we can find that lodgepole pine has a vastly better height growth than Scots pine, which could be related to the higher relative growth rate of lodgepole pine (Ågren and Knecht 2001; Despain 2001; Ingstad and Kähr 1985; Strand et al. 2006). Based on our results, it can be stated that the average height growth of Scots pine surpassed significantly the height growth of lodgepole pine. So the advantage of lodgepole pine was not revealed on mining spoils. In root collar diameters no significant differences between the species were found; the proportion of stem mass in the aboveground biomass did not differ either.

From the literature we can find different results of Scots pine biomass. Xiao and Ceulemans (2004) found that the average aboveground biomass of 10-year-old trees growing on nutrient rich forest soil is 10.64 kg per tree. Helmisaari et al. (2002) reported that in 15-year-old trees growing in nutrient poor *Vaccinium vitis-idaea* forest site type the average aboveground biomass was 1.5 kg. Our results, 0.8 kg per tree, are more similar to Helmisaari et al. (2002) than to Xiao and Ceulemans (2004).

The average aboveground biomass of lodgepole pine growing on oil shale mining area was 1.1 kg. It is smaller than 4.25 kg for 11-year-old lodgepole pines growing on nutrient poor soil studied by Bothwell et al. (2001), but greater than 0.25 kg, which was found by Turner et al. (2004) for 11-year-old lodgepole pines growing in Yellowstone National Park on dry and nutrient poor soil.

Comparison of the aboveground biomass between Scots pine and lodgepole pine revealed no statistically significant difference; still, lodgepole pine formed 24% more aboveground biomass than Scots pine. This might be caused by lodgepole pine's higher nitrogen use effectiveness (Norgren 1996), so it can form more biomass with the same amount of nutrients than Scots pine. On the basis of the present results it can be concluded that Scots pine and lodgepole pine do not differ significantly in the growth and biomass.

However, we must take into consideration that the stands are young and a period of faster growth for both species is still ahead. Magnani et al. (2000) in their study of Scots pine stands of different age found that maximum aboveground primary production occurs at the age of 14–18 years with the height of trees 7.7–9.9 m. Karu (2005) found that the height, diameter and biomass increment of Scots pine begins to decrease at the age of 25 and at the height of 6–8 m.

Biomass allocation

Our study showed that the biomass of Scots pine was allocated to compartments quite evenly: 37% to needles, 32% to shoots and 31% to the stem. The results of Xiao and Ceulemans (2004) showed that needles constitute 27.6%, shoots 30.9% and the stem 41.5% of the aboveground biomass of Scots pine growing on nutrient rich forest soil. Research made by Helmisaari et al. (2002) in a 15-year-old Scots pine stand revealed that the aboveground biomass is distributed as follows: 12% needles, 45% shoots and 43% the stem. Karu (2005) reported that the aboveground biomass of 16-year-old Scots pine growing in a post-mining area was allocated almost equally between needles, shoots and stems, respectively 36%, 34% and 30%, which was similar to the results of our study. Our results indicated that of the aboveground biomass of lodgepole pine 45% was allocated to needles, 28% to shoots and 27% to the stem. Turner et al. (2004) declared that 44–46% of the aboveground biomass of lodgepole pine is given by needles, 17–22% by shoots and 34–38% by stems, which are similar to our data. Norgren (1996) found that lodgepole pine has a larger proportion of needles in relation to the aboveground biomass than Scots pine. In our results no significant differences in the relative allocation of the aboveground biomass to needles were found between the species; still, lodgepole pine had 8% more needle mass.

Our results indicate that lodgepole pine allocated 27% of the aboveground biomass to the stem and Scots pine 31%; however, the mean stem mass of lodgepole pine was higher than that of Scots pine (respectively 282.2 g and 245.0 g). This is in agreement with the results concerning the aboveground biomass in young and middle-aged Scots pine and lodgepole pine trees obtained by Albrektsen et al. (1995), who reported that lodgepole pine allocates a lower proportion of its aboveground biomass to the stem while still producing a greater total stem mass than Scots pine.

As to the vertical distribution of biomass of the different compartments between the crown layers of the studied species we found that more needles, shoots and stem biomass of lodgepole pine occurred in the lowest part of the crown, but the biomass of needles and shoots of Scots pine was allocated evenly between the middle and lowest part of the crown and the largest share of the stem mass was allocated to the lowest part of the crown. Some authors (Ågren et al. 1980; Mandre and Tullus 2002; Troeng and Linder 1982) argue that the assimilating mass and the photosynthetic productivity of conifers are allocated predominantly in the middle layers of the crown. Xiao and Ceulemans (2004) reported that in a 10-year-old Scots pine stand more branch and needle biomass is in the lower part of the crown than in the higher layers.

Morphological parameters of needles and shoots

We used needle and shoot morphological characteristics to estimate the growth of trees. The length and dry mass of current-year needles and also the length and relative thickness of current-year shoots of Scots pine increased from lower to higher layers of the crown. The same trend was observed in 1-year-old needles and shoots. This observation should mean that needle and shoot growth is limited by the reduced availability of light in the lower part of the crown. Indeed, studying the light impact on Scots pine needles Niinemets et al. (2001) found that needle thickness and width increase with increasing light intensity.

Our results showed that current-year and 1-year-old needles of lodgepole pine were significantly longer and heavier than Scots pine needles. This is in agreement with data of Norgren (1996), who reported that lodgepole pine formed longer and greater in mass current-year needles than Scots pine. The longer needles may be due to the genotype; however, from the literature (Laas 2004) it is known that the length of needles of both species is in the same range (3–9 cm).

The density of needles differed significantly between the species: lodgepole pine produced shorter shoots and had more needles per cm on shoot than Scots pine. This is compatible with the results of Norgren (1996), showing that lodgepole pine has a higher density of needles than Scots pine.

Nutrient concentration and allocation

Some investigations show that different species growing in the same growth conditions use different amounts of nutrients to produce the same amount of biomass or stemwood (Alban et al. 1978; Alban 1982; Eriksson and Rosén 1994). We found that the highest NPK concentrations were in the needles and the lowest in the stems both in Scots pine and lodgepole pine stands. Jach et al. (2000) established that the highest N concentrations occur in Scots pine needles and fine roots and the lowest in branches, bark of the stems and coarse roots.

To assess the nutrient concentrations in photosynthetic tissue we used the scale of optimal nutrients in current-year needles recommended by Ingestad (1962) and Brække and Salih (2002) for Scots pine and Ballard and Carter (1985) and Brockley (2001) for lodgepole pine. Ingestad (1962) states that for optimum growth of pine the concentration of N in needles has to be 2.4–3.0%, that of P 0.15–0.4% and of K 0.9–1.6%. According to Brække and Salih (2002) the respective concentrations are >1.8%, >0.18% and >0.6%. Compared to these scales, our findings suggest N, P and K deficiency in Scots pine needles. Compared to the scale of Brockley (2001), the concentrations of N, P and K in lodgepole pine needles were at an optimal level (Table 3). These results indicate that the current-year needles of lodgepole pine are better supplied with nutrients than Scots pine needles.

Ratios of different nutrients in tissues promise to be a better indicator of plant nutrient status than absolute concentrations (Perry 1994). According to Ingestad (1979), the optimum N : P : K ratio of nutrients in pine needles is 100 : 14 : 45. Comparison of these ratios to the ratios we established suggests that the proportion of phosphorus and potassium in the needles of both species was clearly below the optimum.

A lower N concentration in lodgepole pine needles compared to Scots pine has earlier been reported (Albrektsen et al. 1995; Alriksson and Eriksson 1998; Ingestad and Kähr 1985; Norgren and Elfving 1994), but the concentrations in woody components are similar (Alriksson and Eriksson 1998). This fact allows us to state that lodgepole pine is able to form a larger needle area with a lower concentration of N than Scots pine, which can be due to the higher N use efficiency of lodgepole pine. Norgren (1996) reported that the higher N use efficiency of lodgepole compared to Scots pine is achieved through a lower investment in N per unit biomass. This can be one reason why lodgepole pine has a larger needle area in boreal forest ecosystems where N is a limiting factor for growth.

Conclusion

On the basis of the results of the present study it can be concluded that Scots pine and lodgepole pine growing in oil shale post-mining landscapes do not differ significantly in the growth, biomass and biomass allocation pattern. Taking into consideration that the plantations studied are in a developing stage, it is important to observe the further growth and biomass production in different stages of stand development. The study of the suitability of different tree species for reclamation of post-mining areas in Estonia should be continued to reduce the large proportion of Scots pine monoculture. In Estonia, at this moment, lodgepole pine has no economic importance, but it can be used for establishing the parks and green areas for restoration of degraded areas.

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A comparison of the growth of Scots pine (*Pinus sylvestris* L.) in a reclaimed oil shale post-mining area and in a *Calluna* site in Estonia

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Abstract The growth of Scots pine and its suitability for afforestation of post-mining landscapes in Northeast Estonia were assessed in comparative analytical studies by using morphological parameters and mineral nutrition characteristics. The growth and nutrient uptake of Scots pine growing on post-mining substrate were compared with the characteristics of pines of the same age (22–23 years) in a *Calluna* forest site type predominant in North Estonia in similar climatic zone. Results of the analyses of soil upper layers showed that the concentration of N and P in soil did not differ between the opencast spoil and *Calluna* site, but significantly higher pH of soil and concentrations of K, Ca, and Mg were found in mine spoil. The concentrations of K and Mg in needles were significantly higher in the post-mining area, but the concentrations of N, P, and Ca did not differ significantly. Comparison of the needle nutrient concentration with the standard for optimum concentrations revealed P deficit in the post-mining area and P and K deficit in the

Calluna site. Scots pine formed longer and thinner needles and shoots in the post-mining substrate than in the *Calluna* site. It was assumed that in the post-mining area the growth of pines is predominantly dependent on K and Ca concentrations in their tissues as the biomass of needles was strongly correlated with the K/Ca ratio, whereas the biomass in the *Calluna* site was correlated with the N/P ratio. The height and diameter of trees were significantly larger in the post-mining area.

Keywords Oil shale post-mining area · Reclamation · Scots pine · Biomass accumulation · Nutrient concentration

Introduction

Oil shale is the most important mineral resource in Estonia. As a result of oil shale opencast mining in Northeast Estonia, large areas of land are degraded and require restoration. Afforestation is the most suitable way of restoring mine sites. In Northeast Estonia, the area damaged by oil shale opencast mining until 2006 was 13,098 ha, from which 10,347 ha was afforested (Kaar and Tomberg 2006).

In recent years, interest in rehabilitating lands disturbed by mining activity has grown, especially from the point of species selection. Until

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recent years, a large proportion of trees planted were conifers (>90%), mainly Scots pine (86%; Kaar 2002). As a result of mining, the relief is rugged, and the soil heterogeneous and extremely stony. Oil shale mining spoil is very alkaline ($\text{pH}_{\text{KCl}} = 8.0$), and initial N and organic content is low (Kaar and Raid 1996; Lõhmus et al. 2006). The pedogenesis and geological aspects have been thoroughly studied after oil shale mining (Reintam and Kaar 1999; Reintam 2001; Reintam et al. 2002), but there is still lack of knowledge and information about the suitable tree species and methods for afforestation. Due to the actuality of restoration oil shale opencast mining areas in Estonia, there are already some studies carried out related to selection of suitable introduced tree species for afforestation (Kaar 2002; Kuznetsova and Pärn 2004). It is of great interest to study the ecological potential of Scots pine (*Pinus sylvestris* L.), the predominating tree species in Estonia although information about the tolerance of Scots pine to growth conditions prevailing in mining areas is still controversial. The study of Baumann et al. (2006) showed that growth of *P. sylvestris* seedlings during their first year was reduced in lignite-containing substrate compared to sandy soil from a natural forest, suggesting that *P. sylvestris* is not well adapted to the mining substrate. Kaar (2002) discussed, that besides *P. sylvestris*, *Pinus contorta*, *Larix decidua*, and *Larix kurilensis* might be suitable for open sites and stony substrate of opencast mines. Several authors suggested for afforestation of abandoned mining areas not at all with coniferous but with deciduous trees. Kupka and Dimitrovský (2006) indicated that the best adaptation to anthropogenic substrates in the brown coal mining areas had *Alnus glutinosa*. According to efficient adaptive strategies, the survival and productivity of *A. glutinosa* stands on oil shale mining areas are high, and hence, this species might be a perspective for the afforestation of these areas (Lõhmus et al. 2006).

This paper describes the one part of the study: analysis of the growth of trees in post-mining area in comparison with the growth of trees on different forest site types in Estonia. The aim of this study is to analyze and compare the growth

of Scots pine established on reclaimed oil shale post-mining areas and in *Calluna* site type, which is widespread and typical for North Estonia.

The specific objectives of this study were to estimate the growth and biomass of trees and mineral composition of the needles on reclaimed oil shale post-mining area 20 years after plantation and assess the trees vitality for afforestation of these alkaline and stony areas. The practical value of this investigation is to make recommendations concerning the suitability of Scots pine for recultivation of exhausted oil shale opencast mines.

Materials and methods

Study area

The research was carried out in Scots pine stands in Narva oil shale post-mining area (59°15' N, 27°48' E) and in natural forest *Calluna* site type, near Tallinn (59°18' N, 24°43' E; Fig. 1). The plantations were established in 1981–1982 with planting density of 1.25×1.5 m.

Morphological measurements

Fieldwork was carried out in 2004–2006. Three sample plots in Scots pine stands in the post-mining area and three sample plots in the *Calluna* site type were established, and average values per study area were presented (Table 1). In each sample plot (0.05 ha), the stem diameter at breast height (D) and the height (H) of trees were measured. The sturdiness quotient (height/diameter ratio, H/D), which should reflect the stocky or spindly nature of the trees and describe the survival or growth of trees in the field (Thompson 1985), was calculated. Main characteristics of the studied pine stands are presented in Table 1.

For morphological measurements 50 current-year main shoots per each sample plot in the post-mining area and in the *Calluna* site were collected from the middle part of the tree crowns, considering that the assimilating mass and the photosynthetic productivity of conifers are allocated predominantly in the middle layers of the canopy (Mandre and Tullus 2002). Collected needles and

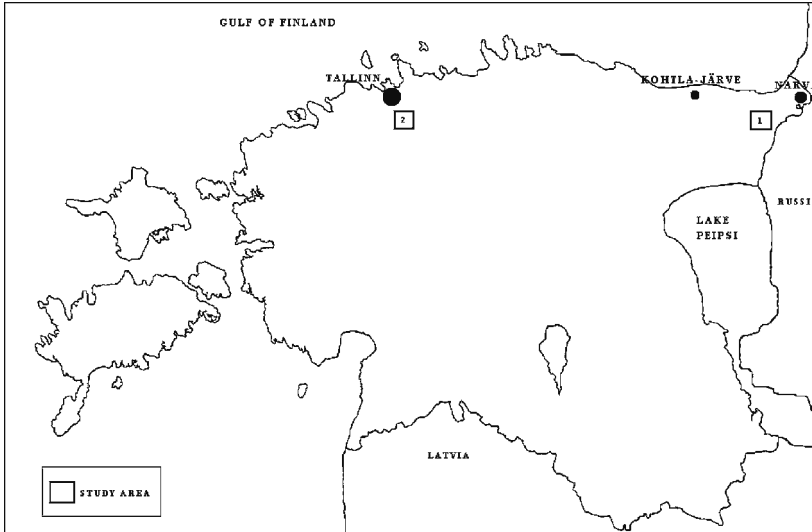


Fig. 1 Location of study areas in Estonia (1 post-mining area, 2 *Calluna* site)

shoots were dried at 70°C in a thermostat and the dry mass was weighed (gram). From the collected samples, the length of needles (centimeter) and shoots (centimeter) was determined and the thickness (dry mass per length) of needles (milligram per centimeter) and shoots (gram per centimeter) was calculated.

Soil analysis

Soil samples were collected in September 2004 from depths of 30 cm, as approximately 80% of the roots assimilating nutrients are located at a

depth of 10–30 cm of soil (Orlov and Koshel'kov 1971; Marschner 2002). Three samples per each sample plot were taken and one average sample per sample plot was formed for analysis. The samples were dried and sieved. The concentrations of elements available to plants (N, P, K, Ca, Mg) in the soil of each sample plot were analyzed in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

The soil pH_{H2O} was determined in the laboratory of the Department of Ecophysiology of the Forestry and Rural Engineering Institute of the Estonian University of Life Sciences with a

Table 1 Main characteristics of the studied pine stands in 2004

Study site	Age, years	Number of trees per hectare	<i>D</i>	<i>H</i>	<i>H/D</i>	<i>G</i>	<i>M</i>
Post-mining area	22–23	2,000	10.5 ± 4.4 ^a	8.7 ± 1.9 ^a	0.94 ^a	13.6	73
<i>Calluna</i> site	22	5,000	7.3 ± 1.1 ^b	4.9 ± 0.6 ^b	0.68 ^b	20.9	69

D mean diameter at breast height (centimeter), *H* mean height (meter), *G* basal area (square meter per hectare), *M* growing stock (cubic meter per hectare)

Superscript letters indicate a statistically significant difference

Table 2 Mean (\pm SD, $n = 3$) element concentrations (milligram per kilogram) of growth substrate in the post-mining area and in the *Calluna* site

Study site	pH	N	P	K	Ca	Mg
Post-mining area	8.1	436.7 \pm 80.8	42.5 \pm 8.7	86.5 \pm 25.2 ^a	2,222.3 \pm 399.5 ^a	114.7 \pm 78.9 ^a
<i>Calluna</i> site	5.6	450.0 \pm 60.0	33.3 \pm 8.5	4.2 \pm 1.8 ^b	85.3 \pm 0.6 ^b	9.5 \pm 1.5 ^b

Superscript letters indicate a statistically significant difference

pH meter (Mettler Toledo GmbH, InLab412 electrode). For the analysis of N in soil, the Kjeldahl method was used. Available P, Ca, and Mg in soil measured by flow injection analysis (FiaStar 5000). Available K was determined by flame photometric method.

Chemical analysis of needles

Current-year needles for chemical analysis were collected from each sample plot in late autumn 2006 after growth was stopped; they were cleaned and dried and the average sample per sample plot was created. The concentrations of mineral elements (N, P, K, Ca, Mg) were determined in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

Determination of N in the needles was carried out according to the Kjeldahl method; P was determined in Kjeldahl Digest by Fiaster 5000, Stannous Chloride method, ISO/FDIS15681; Ca was determined in Kjeldahl Digest by Fiaster 5000, o-Cresolphtalein Complexone method ISO3696; Mg was determined by Fiastar 5000, titan yellow method, ADSTN90/92; K was determined by flame photometric method (Ruzicka and Hansen 1981). To estimate the balance of nutrients, the ratios of elements (N/P/K; N/P; N/K) were calculated.

Statistical analysis

The average values of the studied stands were calculated using FoxPro software. Means of the samples, standard deviation, and linear correlations between the parameters (r) were calculated. The normal distribution of variables was checked; the length and dry mass of shoots were normalized by log transformation. The data were analyzed by analysis of variance (ANOVA) and t test. Statisti-

cal calculations were performed with Systat 10 and Excel 2003.

Results

Chemical composition of growth substrate

The chemical conditions of anthropogenic substrate and natural forest soil are given in Table 2. Compared to the opencast spoil, the substrate of *Calluna* site has almost 22% less plant available P, 95% less K, 96% less Ca, and 92% less Mg (Table 2). High concentrations of Ca, K, and Mg were associated with high pH in the topsoil, which was about twice as high as in the sample plots of *Calluna* site. It was found that the pH of oil shale mine detritus was alkaline (pH 8.1), while the soil pH in the *Calluna* site type was optimal for Scots pine (pH 5.6). Analysis of nutrients in the upper soil layers revealed differences between the two studied areas (Table 2). Results of the t test showed that the concentration of N and P did not differ between opencast spoil and the *Calluna*

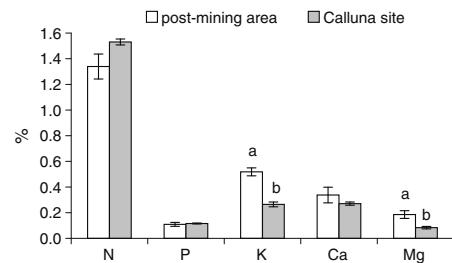


Fig. 2 Mean (\pm SD, $n = 3$) element concentrations of Scots pine needles in the post-mining area and in the *Calluna* site. Values with a different letter differ significantly from each other ($p < 0.05$)

Table 3 The ratios of the nutrients in the current-year needles of Scots pine in the post-mining area and in the *Calluna* site

Study site	N/P	N/K	N/P/K
Post-mining area	12.4	2.6 ^b	100/8/39
<i>Calluna</i> site	13.2	5.8 ^b	100/8/18

Superscript letters indicate a statistically significant difference

site, but significant differences were found in the concentrations of K ($p = 0.03$), Ca ($p = 0.01$), and Mg ($p = 0.01$).

Analysis of plant material

Comparison of the mean values of elements in Scots pine needles of the opencast area and the *Calluna* site showed that the needles from the oil shale opencast area contained over two times more K, 1.3 times more Ca, and 2.2 times more Mg than the needles from the *Calluna* site (Fig. 2). By using the *t* test, the statistically significant differences were found between the post-mining area and the *Calluna* site for the concentration of K ($p = 0.001$) and Mg ($p = 0.03$) in needles, but the concentrations of N, P, and Ca did not differ significantly ($p > 0.05$). The N/P ratio was similar in the two studied types of areas ($p = 0.25$), but the N/K ratio differed significantly ($p = 0.003$; Table 3).

Morphological analysis of trees

The survival and growth of Scots pine are variable, and high mortality of trees might be related to the extreme heterogeneity of the post-mining substrate. But trees that survive show good growth. Our results showed that the height increment of trees growing in the post-mining area essentially exceeded the growth in the *Calluna* site: the mean annual height increment in the post-mining area was 36–45 cm, in the *Calluna* site 23 cm per year. Also the *H* and *D* of trees and the ratio *H/D* was higher in the post-mining area ($p < 0.01$; Table 1), than in the *Calluna* site.

Results of ANOVA showed that the needles of trees growing in the spoil area of opencast

mines were essentially longer and the thickness of needles (milligram per centimeter) was smaller than in the *Calluna* site (Fig. 3). The length of shoots did not differ between the pines of the areas compared, but the thickness of shoots (gram per centimeter) in the post-mining area was significantly lower than in the *Calluna* site ($p < 0.05$; Fig. 3).

Relationships between nutrients and growth parameters of trees

Our study revealed a significant correlation between the dry mass of needles and K/Ca ($r = 0.99$; $p = 0.045$) in needles and a correlation between the dry mass ($r = 0.99$; $p = 0.03$) and length ($r = 1.00$; $p = 0.004$) of shoots and N concentration in the needles from the post-mining area. In the *Calluna* site, the dry mass of pine needles was correlated with the N/P ratio in needles ($r = 1.00$; $p = 0.002$), and shoot length was correlated with the Ca concentration ($r = 0.99$; $p = 0.03$) in needles.

Discussion

The growth of trees is determined by habitat resources (light, temperature, water, nutrients availability) and species specificity (e.g., nutrients and water use efficiency, morphological variability). Earlier studies have shown that the substrate in the opencast area is heterogeneous with a great variability of the mechanical structure (Raid and Vaus 1971; Kuznetsova and Mandre 2005, 2006). The present study revealed that soil pH in opencast areas is strongly alkaline. It is well known that the soil pH is a major factor in determining the availability of nutrients in soil. In alkaline soil, the mobility of several nutrient elements necessary for plants decreases and the mineral nutrition of plants becomes complicated (Keren et al. 1981; Mandre 1995; Marschner 2002). Our earlier research with exotic conifers showed that in the post-mining area assimilation of N and P by plants is hindered by the alkaline reaction of

the substrate and the composition of nutrients is disbalanced (Mandre and Kuznetsova 2004).

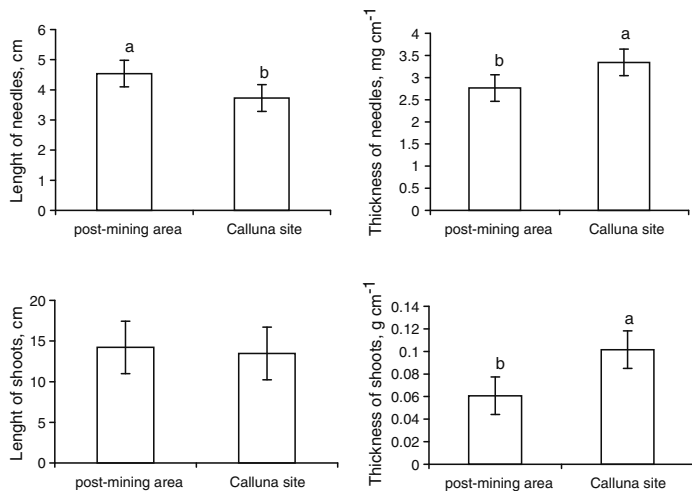
Results of our study showed that the concentrations of N and P did not differ between studied substrates, but significantly higher concentrations of K, Ca, and Mg were associated with high soil pH in the post-mining area. Our data demonstrate the low content of N and P in the post-mining area and in the *Calluna* site. Several authors (Bradshaw 1983; Piha et al. 1995) confirm that plant growth in post-mining landscapes is obviously limited by N and P deficiencies.

Literature data (Raid and Vaus 1971) showed that loams predominate in the Narva mine area. The investigations of Limstrom (1960) on the survival and growth of tree species in exhausted mining areas in the USA showed that most of them grow better on clayey soil and worse on sandy soils depending on differences in moisture conditions. It was shown that technogenic soils are fed by surface waters (Kaar and Raid 1996). According to Raid (1972) there is enough water in stony loamy substrate in post-mining areas, but in dry periods, moisture deficit may limit the growth of trees.

Calluna site type is characterized by sandy soils with poor nutrient conditions, which is the main cause of the moderate growth of trees in this site type. Mandre et al. (2006) confirmed that the concentrations of extractable nutrients in the soil of *Calluna* site type areas are low. Besides the insufficiency of nutrients, a limiting factor for tree growth in this site type may be the unfavorable moisture conditions. From Raitio (1990), it is known that the survival of heath forest is altered by low soil water-holding capacity and plant vulnerability to stresses. So, it may be assumed that moisture conditions for the growth of Scots pine in the loamy substrate of abandoned opencast mines may be better than in *Calluna* sites.

For estimating and comparing the nutrient levels in trees in the spoil area of opencast mining and the *Calluna* site, we used the scale of optimal nutrients in current-year needles recommended by Brække and Salih (2002), which was worked out in Scots pine stands in Scandinavia. According to this scale, N deficiency occurs if needles contain 1.2–1.5% N. Compared to this scale, the pines in the post-mining substrates grow in N-deficit conditions, but in the needles of pines in

Fig. 3 Morphological characteristics of Scots pine needles and shoots in the post-mining area and in the *Calluna* site. Values are given as mean \pm SD ($n = 150$). Values with a different letter differ significantly from each other ($p < 0.05$)



the *Calluna* site type, the level of N was almost optimal. As Brække and Salih (2002) indicate that the P concentration in needles $>0.18\%$ is necessary for an optimum growth of Scots pine, our data demonstrated that the P concentration in pine needles in the post-mining area and the *Calluna* site suggest P deficiency. According to Brække and Salih (2002), the deficiency of K occurs if its concentration in needles is $<0.35\%$. In the post-mining area, the concentration of K in the needles is at almost pre-optimum level, but in the *Calluna* site a great deficiency of K in needles was detected. Compared to the scale of Brække and Salih (2002), the concentration of Ca and Mg was in both sites at an optimal level.

Besides the absolute concentration of nutrients, their balance is important for plant growth. According to steady-state nutrition studies (Ingestad 1987), the optimum N/P/K ratio for Scots pine needles is 100:14:45. Investigations of Ingestad (1979) show that maximization of plant growth rates requires a balanced supply of both nitrogen and phosphorus. According to the studies of Raid (1996), the optimal ratio of N and P should be (10 to 11:1). In the study of Ingestad and Ågren (1988), the ratio of nitrogen to phosphorus remains constant (8 to 10:1), when plants receive nutrients in a ratio similar to that in their tissues. When terrestrial plants deviate from the 10:1 N/P ratio, this generally reflects a similar nutritional imbalance caused by reduced uptake of the growth-limiting nutrient (Koerselman and Meuleman 1996). Our results showed that in the needles of pines growing in exhausted opencast mines and in the *Calluna* site the ratios of nutrient elements were mostly unbalanced. It is evident that the N/P ratio was similar in the two studied site types, but the N/K ratio differed significantly. According to the scale of Ingestad (1987), in our study the N/P ratio was lower than optimum. The N/K ratio was pre-optimum in the post-mining area, while the N/K ratio in the *Calluna* site was more than twice lower than optimum. The results of the present study confirm that the growth of Scots pine is limited by the concentration of P in the post-mining area and by the concentrations of P and K in the *Calluna* site. However, the

concentrations of N and K in the needles of Scots pine growing in the post-mining area did not differ from the values obtained for *Oxalis-Myrtillus* (Mandre 1995; Ots 2002) and *Vaccinium* site type stands (Pensa and Sellin 2002) in North Estonia.

Different nutrient conditions and accumulation affect the growth of trees and morphological parameters of needles and shoots. The poorer tree growth at the *Calluna* site may be also due to bigger plant competition for resources. The tree density at the *Calluna* site is higher than the post-mining site. The smaller tree density in the post-mining area was caused relatively by bad tree survival related to the heterogeneity of post-mining substrate. The height growth of survived Scots pine and the ratio of *H/D* were essentially larger in the post-mining area than at the *Calluna* site, indicating the relatively better *H* growth compared to *D* growth in the post-mining area. The deficiency of K in soil may have caused the decrease in height growth at the *Calluna* site. It is known that the deficiency in K (Kärblane 1996) and N (Miidla 1989) leads to inhibition of plant growth. According to the studies with seedlings (Raid 1979), in the conditions of N and P deficiency, the stems remain thin, while under K deficiency, the stems are shorter. Comparison of growing stock of studied stands showed that both stands are similar although there is a smaller density of trees in the post-mining area. According to Estonian classification of site quality classes (Directive of Forest Management 2006), growing stock of studied stands corresponds to quality class II. An increase in growing stock usually means higher quality forests, whereas a decrease in growing stock generally indicates degrading forest conditions. Our studies confirm the results obtained by Reintam et al. (2002) that the mean annual increase in height of Scots pine in the first three decades in the post-mining area is 25–40 cm. In our case, the mean values of the length of needles and shoots were lower in the *Calluna* site than in the post-mining area, which may be caused by N/K imbalance and K deficiency in needles.

In earlier studies with exotic species in the post-mining areas, we found correlations between

needle biomass and the content of K and ratios of N/K and K/Ca in needles (Kuznetsova 2004). In this study, the dry mass of Scots pine needles was strongly correlated with the ratio of K/Ca in needles in the post-mining area and the ratio of N/P in the *Calluna* site. It may be assumed that morphological parameters of pine are influenced by different nutrients and their ratios.

Conclusions

Our results indicated different morphological adaptations of Scots pine to growth conditions in the oil shale post-mining area and in the *Calluna* site. Pines in the post-mining area form longer and thinner needles and shoots than pines in the *Calluna* site type stand. In the oil shale post-mining area and in the *Calluna* site, the growth of needles and shoots depends on concentrations of different mineral elements. Results of analyses showed that despite the heterogeneity of the post-mining substrate, which affects the survival of Scots pine, the growth of Scots pine is relatively good. We can suppose that oil shale mining detritus seems to be a better environment for the growth and nutrition of Scots pine compared to *Calluna* site. Compared Scots pine stands were similar by growing stock, but mean values of height and diameter were significantly higher in the post-mining area. Thus, Scots pine may be considered as a species that is well adapted to the mining substrate and is promising for the reclamation of post-mining landscapes.

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The Growth of Lodgepole Pine (*Pinus contorta* var. *latifolia* Engelm.) in a Reclaimed Oil Shale Mining Area, Abandoned Agricultural Land and Forestland

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Abstract

The main objective of the study was to analyse lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) growth in relation to soil nutrients in a reclaimed oil shale mining area (ROSMA), abandoned agricultural land (AAL) and forestland (FL). The growth–soil interactions and soil–needle chemical relationships were analysed and compared in lodgepole pine plantations at various sites. The impact of soil conditions on tree growth was significant; the height and diameter of trees were different between the studied sites. Despite the higher P and K concentrations in the soil in ROSMA, the concentrations of these elements in needles were lower compared to the AAL and FL. This may be caused by the high value of soil pH and K / Ca antagonism. Although the concentrations of the elements in the needles were lower in ROSMA, the needles were longer and heavier. This was possibly due to the higher N and P use efficiency in the lodgepole pine plantation in the ROSMA. The growth of lodgepole pine was better in more fertile environments, in our study the AAL or on the clay substrates of ROSMA compared to the FL.

Key words: lodgepole pine, growth, biomass, nutrient concentration, soil type

Introduction

Every year opencast oil shale mining in Estonia creates substantial areas of alkaline wasteland that require recultivation. As of 2006 exhausted oil shale mines covered 13,098 ha of land, of which 10,347 ha had been forested (Kaar and Tomberg 2006). In Eastern Europe, including Estonia, there is a clear tendency of increase in abandoned agricultural areas, brought about by drastic changes in the political and economic situation (Mander and Jongman 2000). During the last decade, more than 400,000 ha of agricultural land was abandoned in Estonia (Uri et al. 2007). Afforestation of these areas is a sustainable land use to reduce CO₂ emission and improve soil fertility. Sequestration of carbon in plant biomass and in soil is an important environmental effect of afforestation of disturbed and abandoned agricultural lands.

In the present study, we analyse the growth of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in Estonian conditions. According to the Estonian Nature Conservation Act (2004), distributing exotic species in nature is not encouraged. However, lodgepole

pine is a promising species for cultivation in park forests and green areas in Estonia. Also, lodgepole pine can be used as a suitable species besides native species for afforestation of reclaimed oil shale mining areas (ROSMA) and abandoned agricultural lands (AAL).

Lodgepole pine is a native North American tree species that occupies large territories there. Among the North American conifers it has the widest ecological range. Lodgepole pine has been found to grow well on nutritionally poor soils (Weetman et al. 1985), where it has advantages over other species (Despain 2001). Lodgepole pine is also adaptive to soil pH variability (Koch 1996). Commonly, the roots of this species are deeply distributed in sandy nutritionally poor soils (Laas 1987, Cohen et al. 1990). Young lodgepole pines grow fast and tolerate well severe climate conditions; therefore in northern Europe, it is cultivated for forestry purposes more widely than other non-indigenous pine species (Laas 2004).

Lodgepole pine has been used in forest plantations in different climate zones and on different types of soil. It has been reported that lodgepole pine has been planted on climatically harsh, exposed, nutrient-poor

peat soils in Scotland (Lines 1996) and Ireland (Gallagher et al. 1987); on poor, dry, out-washed sand-fields in Denmark (Larsen 1980); and on subalpine or cold climate sites in New Zealand (Miller and Ecroyd 1987, Ledgard 1993, 2001). Lodgepole pine has also been used in plantations in Finland (Weissenberg 1972, Ruotsalainen and Velling 1993), Sweden (Rosvall et al. 1998, Knight et al. 2001) and Iceland (Sigurgeirsson 1988).

It is known that the exotic coniferous species have frequently higher productivity than *Pinus sylvestris* or native broad-leaved trees (Peterken 2001). *Pinus contorta* var. *latifolia* has been widely used in forest plantations in northern Sweden due to its high productivity (von Segebaden 1993). The clearest example of successful introductions of nonindigenous species is *Pinus contorta* var. *latifolia*, which is clearly superior to local *Pinus sylvestris* in productivity (Varmola et al. 2000). In Sweden, lodgepole pine is regarded as a more competitive species compared to Scots pine (Norgren 1996). Besides, from research conducted in Sweden it is known that lodgepole pine wood production is 36% higher compared to Scots pine (Elfving et al. 2001). In Lithuania, about 20 species of *Pinus* were introduced; however, only some of them in forests (Navasaitis 2004). *Pinus contorta* was found to be a promising species for Lithuania. This species may be planted there especially in areas unsuitable for farming, because it is resistant to *Heterobasidion annosum* (Žiogas 2006).

It has been suggested that in the reclamation of degraded landscapes, some fast-growing exotic species show better growth in the first years than native species (Parrotta 1999). The results from Lusatian lignite mining region in Germany indicate that black pine (*Pinus nigra*) grows better in the mining substrate than Scots pine (*P. sylvestris*), indicating that black pine may be a better choice for reforestation of post-mining landscapes than Scots pine (Baumann et al. 2006). Dutta and Agrawal (2003) concluded that exotic species may be recommended for preliminary rehabilitation of the coal mine spoil due to their fast growth and development.

Experimental cultures of lodgepole pine have been planted on different sites in Estonia. The total area of stands where lodgepole pine is dominant is 7 ha in Estonia (Laas 2004). The first experiments of the lodgepole pine cultivation were made at the present Järvselja Training and Experimental Forest District in 1908 (Kasesalu 2000). Kasesalu (2000) concluded that the growth of lodgepole pine and Scots pine is approximately the same in *Myrtillus* site type at Järvselja, and that lodgepole pine has better prospects mainly in park forests and green areas in Estonia.

In 1977, the Estonian Forest Institute had an opportunity to order seeds of various trees through the

IUFRO seed bank catalogue. Lodgepole pine seedlings from seeds of different provenances of North America and from seeds collected in Estonia (Luunja, Kambja) were planted to Sõe Arboretum and Narva ROSMA. Earlier observations indicated that the best growth is demonstrated by trees grown from local seeds (Luunja) in Sõe Arboretum (Erik 1999) and the Narva ROSMA (Kuznetsova and Mandre 2005). These two areas were selected for this study.

The main objective of the study was to analyse lodgepole pine growth in relation to soil nutrients in the ROSMA, AAL and forestland (FL). To assess the growth of lodgepole pine and to find the suitable growth conditions for the studied species, the growth, biomass and nutrients were qualified considering that the trees obtaining higher growth and biomass would be more suitable for cultivation in these soil conditions. Analysis of the chemical composition of the soil and morphological and chemical characteristics of assimilative organs of trees serve as a foundation for understanding the status of trees and a forest site. Different authors have tried to evaluate the success of the restoration of the damaged areas with the help of growth and biomass production of various plants (Kumar et al. 1995, Singh and Singh 1999). The morphology of trees is used in monitoring to evaluate the state of trees in areas under human impact (Schubert 1985, Innes 1993, Озолинчюс 1996). Needle analysis has often been used as a diagnostic method of describing the nutritional status of trees (Brække 1996) as well as their biomass increment and growth conditions (Niinemets et al. 2002). The thickness of shoots (Duryea 1984) and density of needles on the shoots have been used as an indicator of tree vitality (Pensa 2000). Optimal uptake and concentration of nutrients in tissues ensure balanced physiological processes and bioproduction (Aerts and Chapin 2000, Niinemets and Kull 2003, Niinemets and Lukjanova 2003).

The hypothesis of our study was that the AAL and ROSMA can offer better growth conditions for lodgepole pine compared to the FL. It was assumed that at a higher nutrient concentration in soil the growth of trees would be better.

The objectives of our study were: (i) to analyse the growth of trees in relation to soil nutrients in the ROSMA, AAL and FL, and (ii) to define the most suitable growth conditions for lodgepole pine from the studied areas.

Materials and methods

Study area

The study was carried out in three small experimental lodgepole pine plantations established in the Narva ROSMA, in Sõe Arboretum (AAL) and at Luige

(*Calluna* forest site type) (FL) (Table 1, Figure 1). Considering that lodgepole pine is not a native species in Estonia and it was difficult to find similar stands to do replicates, this is a pilot study without replicates. The plantations at Narva and Sõe were established in 1979 with 2-year-old seedlings. The planting arrangement was 3 × 3 m in Narva with 113 plants planted. In Sõe the planting arrangement was 2 × 2 m and 64 plants were planted. The seeds of lodgepole pine originated from Luunja in these two plantations. The share of survived trees was 76.6% in Sõe in 1997 (Erik 1999). Our monitoring of Narva plantation in 2001 showed that the share of survived trees there was 53%. The reason for trees dying on these sites could be heterogeneity of the substrate of the post-mining area and frost damage of trees in Sõe. No information could be found about the origin of the seeds at Luige. The plantation at Luige was established in 1982. It is a plantation where lodgepole pines (50 trees) grow among Scots pines. The arrangement of trees is approximately 2 × 2 m.

Table 1. Plantations studied

Plantation	Location	Site	Soil type
Narva	59°16' N, 27°47' E	Reclaimed oil shale mining area (RO SMA)	<i>Spolic Anthrosol</i>
Sõe	58°38' N, 26°21' E	Abandoned agricultural land (AAL)	<i>Gleyic Cambisol</i>
Luige	59°18' N, 24°43' E	Forestland (FL)	<i>Arenosol</i>

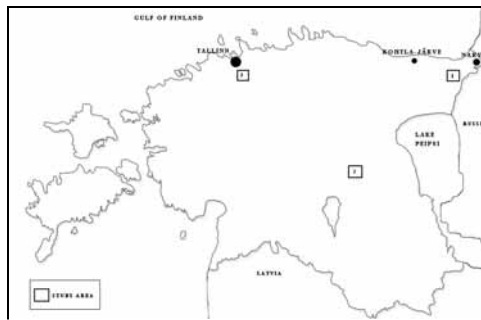


Figure 1. Location of study plantations in Estonia (1 – Narva, 2 – Sõe, 3 – Luige)

Morphological measurements

Fieldwork was carried out in the studied plantations in September 2005. Considering that plantations are small (60 trees at Narva, 50 trees at Sõe and Luige), no sample plots were established. The stem diameter at breast height (DBH) and the height (H) of all trees for each plantation were measured. The diameter of

trees was measured to the nearest 0.1 cm with a caliper. The height of trees was measured to the nearest 0.1 m using a Suunto clinometer.

For the estimation of the state of trees in study areas, parameters of the morphometric evaluation system used in Central Europe (Manual for Integrated Monitoring 1993) were used. Considering that the assimilating mass and the photosynthetic productivity of conifers is allocated predominantly in the middle layers of the canopy (Mandre and Tullus 2002), for morphological measurements current-year needles and shoots were collected from the middle part of the tree crowns. Three model current-year shoots per tree were collected randomly from the crowns of 5 trees per each plantation. The collected needles and shoots were dried at 70°C in a thermostat and weighed (g). From the collected samples, the length of needles (*n* = 150) and shoots (*n* = 15) was measured; the dry mass of 100 needles and shoots (*n* = 15) was weighed and the density of needles on shoots (needle number per unit shoot length) (*n* = 15) was calculated.

Laboratory analyses

Soil analysis

In all plantations, one soil pit was dug. The soil type was determined according to the FAO-UNESCO (1994) classification (Table 1). Three samples from the 0–20 cm soil layer were taken per plantation in September 2005. The soil samples were dried and sieved. The soil pH_{H2O} was measured with a pH meter (Mettler Toledo GmbH, InLab412 electrode, Germany). For the analysis of the soil total N the Kjeldahl method was used. Available phosphorus and potassium were determined by the flame photometric method. All soil samples were analysed in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

Chemical analysis of needles

Three samples of current-year needles per plantation were collected for chemical analysis in September 2005. The collected needles were cleaned, dried and ground.

Determination of N in the needles was carried out according to the Kjeldahl method; P was determined in Kjeldahl Digest by FIAstar 5000, Stannous Chloride method, ISO/FDIS 15681; K was determined by the flame photometric method (Růžička and Hansen 1981). The concentrations of nutrients (N, P, K) were determined in the Laboratory of Plant Biochemistry of the Estonian University of Life Sciences.

Statistical analyses

Normality of variables was checked by the Kolmogorov–Smirnov, Lilliefors and Shapiro–Wilk’s tests.

The dry mass of shoots was normalised by using a log-transformation. The data were analysed by one-way analysis of variance (ANOVA). The Tukey test was used for the multiple comparison of the mean. Correlations (*r*) between the growth parameters and nutrients were calculated. Throughout the study, the means are presented with the standard error of the mean (\pm SE). Statistical analyses were carried out with software STATISTICA 7.0 and the level of significance $\alpha = 0.05$ was accepted in all cases.

Results

Soil characteristics

Significant differences were observed in the concentrations of macronutrients (NPK) and in the pH of the upper layer of Narva soil and soils of Söe and Luige (Table 2). The soil pH was statistically significantly the highest at Narva compared to the other soils. The analysis of soil nutrients showed that N concentrations in the Narva and Söe plantations were similar and more than three times higher compared to Luige. The available P and K concentrations were significantly higher in the Narva plantation compared to Söe and Luige plantations (Table 2).

Table 2. Soil characteristics in 0–20 cm soil layer: pH, and N, P and K concentrations

Plantation	pH	N (%)	P (mg kg ⁻¹)	K (mg kg ⁻¹)
Narva	7.0 \pm 0.01 ^a	0.16 \pm 0.009 ^a	47.3 \pm 4.1 ^a	207.3 \pm 4.9 ^a
Söe	6.1 \pm 0.003 ^b	0.18 \pm 0.008 ^a	13.6 \pm 2.9 ^c	83.3 \pm 3.9 ^b
Luige	5.5 \pm 0.09 ^b	0.05 \pm 0.001 ^b	33.3 \pm 2.4 ^b	5.1 \pm 0.9 ^c

Values are given as the mean \pm SE. ^{abc} letters indicate a statistically significant difference in the Tukey test at $p = 0.05$.

Tree measures: height and DBH in the plantations

Comparisons of the main growth characteristics between the studied stands are provided in Table 3. Comparative analysis showed a statistically significant difference in tree heights between stands. Although initial densities of Narva and Söe stands differed, the DBHs of lodgepole pine in these stands were similar. Despite the unfavourable soil conditions during the

Table 3. Comparison of tree height (H) and tree diameter at breast height (DBH) in the lodgepole pine plantations

Plantation	H (m)	DBH (cm)
Narva	9.1 \pm 0.4 ^b	14.5 \pm 0.7 ^a
Söe	11.5 \pm 0.6 ^a	15.1 \pm 0.9 ^a
Luige	5.9 \pm 0.1 ^c	8.7 \pm 0.3 ^b

Values are given as the mean \pm SE. ^{abc} letters indicate a statistically significant difference in the Tukey test at $p = 0.05$.

first years after the recultivation of oil shale mining spoil, the height and DBH of 25-year-old lodgepole pine in Narva was comparable to the results from Söe rather than to Luige.

Needles and shoots

The length of needles of lodgepole pine was significantly higher in the Narva plantation than in the other two sites (Figure 2). Lodgepole pine had a greater dry mass of 100 needles in the Narva site, but there was no significant difference in needle dry mass between the Narva and Söe sites. The length and dry mass of shoots were similar on the Narva and Söe sites, but they were significantly lower compared to the Luige site. The shorter shoots of lodgepole pine in the Narva and Söe sites had a higher needle density (Figure 2).

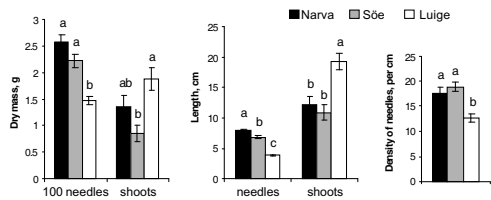


Figure 2. Morphological characteristics of lodgepole pine needles and shoots in a reclaimed oil shale mining area, abandoned agricultural land and forestland. Values are given as the mean \pm SE. Different letters indicate a statistically significant difference (Tukey test, $p = 0.05$)

Nutrient concentration in needles

The concentrations of main mineral nutrients (NPK) in needles differed significantly between the Narva and the other two studied plantations (Söe, Luige) (Table 4). The lowest NPK concentrations in lodgepole pine needles were observed in the Narva plantation, although the concentrations of these elements in the Narva soil were higher compared to the other studied soils. The N / P ratio in needles was similar for the Söe and Luige plantations. For the Narva plantation, the N / P ratio was found to be higher. The N / K ratio was similar for all plantations.

Table 4. NPK concentrations and N / P, and N / K ratios in needles in the lodgepole pine plantations

Plantation	N	P	K	N / P	N / K
	%				
Narva	1.1 \pm 0.03 ^c	0.06 \pm 0.006 ^b	0.34 \pm 0.04 ^b	18.8 ^a	3.3
Söe	1.6 \pm 0.06 ^a	0.13 \pm 0.02 ^a	0.49 \pm 0.06 ^a	12.4 ^b	3.3
Luige	1.5 \pm 0.03 ^a	0.13 \pm 0.03 ^a	0.54 \pm 0.04 ^a	11.8 ^b	2.9

Values are given as the mean \pm SE. ^{abc} letters indicate a statistically significant difference in the Tukey test at $p = 0.05$.

Relationships between growth parameters of trees and soil nutrient concentrations

The correlation between soil nutrients and growth parameters of trees was estimated including the data of all three plantations. The analysis showed that soil nutrients had a significant influence on many growth parameters of trees. The H and DBH of trees were positively correlated with the soil N concentration ($r = 0.72$, $r = 0.89$, $p < 0.05$, respectively). A strong positive correlation was found between the dry mass of needles and the soil N concentration ($r = 0.83$, $p < 0.05$). The length of needles was positively correlated with soil N ($r = 0.96$, $p < 0.05$) and K concentrations ($r = 0.73$, $p < 0.05$). The dry mass and length of shoots were negatively correlated with the soil N concentration ($r = -0.90$, $r = -0.92$, $p < 0.05$, respectively).

Discussion and conclusions

Results of our study showed that the impact of soil nutrients on the growth of lodgepole pine was significant; the height and diameter of trees were different between the studied sites. The soils differed in nutrient concentrations as well as pH. The initial site conditions were most unfavourable in the Narva stand. As a result of mining, the relief is rugged, and the soil is heterogeneous and extremely stony. Oil shale mining spoil is very alkaline ($\text{pH}_{\text{KCl}} = 8.0$), the initial N and organic content are low (Kaar and Raid 1996, Löhmus et al. 2006, 2007), and in young stands a significant proportion of the organic matter is formed from oil shale mining residues (Reintam et al. 2002). Comparing our data of soil analyses with earlier data about initial soil conditions (Kaar and Raid 1996, Löhmus et al. 2006, 2007) we may conclude that the soil improvement during the first 25 years was remarkable. We can see that with the formation and development of soil the content of N increased and the soil pH decreased by 1 unit during the first 25 years. Our results are in accordance with the results reported by Löhmus et al. (2007), who found that the soil pH decreased by 1 unit during the first 26 years in black alder and Scots pine plantations in a ROSMA. Despite the decrease of the soil pH in the Narva ROSMA, the soil pH is still slightly alkaline and significantly higher compared to the AAL and FL soils.

Plant nutrition depends on many factors: soil properties, climatic factors and physiological status of trees. The nutrients are dependent on one another and can interact with other elements. Also the pH value of soil affects the uptake of nutrients (Marschner 2002). It is known that alkalinisation of soil inhibits the availability of several nutrients, causing serious deviations in the mineral composition of plants

(Marschner 2002). Considering that in alkaline soils the mobility of P is limited (Marschner 2002), we can expect that for the lodgepole pine growth conditions on AAL and FL soils were quite favourable compared to the calcareous soil of the ROSMA. Apparently the alkaline soil at Narva opencast complicates the uptake of P and its deficiency can limit the growth of trees. Our results showed that the P concentration in soil was higher in the Narva ROSMA compared to the AAL and FL soils; however the P concentration in needles was smaller at Narva than on other studied soils. Several authors have also reported that N (Singh et al. 2002) and P (Fitter and Bradshaw 1974, Bloomfield et al. 1982) limit plant growth on abandoned coal mine soils. Ninemets and Kull (2003) suggested that plant productivity in calcareous wooded meadows is limited by both N and P. It is known that N and P depend more on the organic matter content of soil, while K is more related to the clay minerals (Piho 1967). This explains the higher concentration of K in the loamy soils of the Narva ROSMA. Although the available K concentration of soil was higher in the Narva ROSMA compared to the other sites, higher K concentrations in needles were observed in the AAL and FL soils with lower soil pH values. Its availability decreases in calcareous environments due to the Ca / K antagonism (Trémolières et al. 1998, Marschner 2002).

Many authors have emphasised that the interaction of different mineral elements in plant tissues and the balance of mineral elements are of great importance in tree growth and survival under stress conditions (Ingestad and Ågren 1988, Marschner 2002, Portsmouth et al. 2005). The scale of optimum nutrient concentrations and their ratios in the current-year needles have been found for lodgepole pine, growing in its natural area in North America (Brockley 2001). A comparison of the N / P and N / K ratios in the needles of lodgepole pine (Table 4) with the scale of ratios suggested by Brockley (2001) permitted us to conclude that there was a considerable deficiency of P ($\text{N} / \text{P} > 13$ – moderate to severe P deficiency) in the needles of lodgepole pine growing in the Narva ROSMA; but there was an optimum concentration of K in needles of all studied plantations ($\text{N} / \text{K} > 4.5$ – moderate to severe K deficiency).

Different adaptive strategies of lodgepole pine growth related to soil type have been reported earlier. Thus Pearson et al. (1984) and Landsberg (1986) found that the formation of the crown and biomass accumulation vary between different growth conditions. Our study revealed different relationships between soil nutrients and growth parameters of trees. The H and DBH of trees were increasing with increasing soil N concentration. The dry mass and length

of needles were increasing with increasing soil N and K concentrations, although the dry mass and length of shoots were increasing with the decreasing of soil N concentration. Taking into account the results of the analysis described above, it can be concluded that the growth of trees was better in the ROSMA and AAL in the areas with a higher concentration of N in the soil. The growth of lodgepole pine in the FL was possibly limited by the low nutrient concentration in the soil. This could explain the lower forest productivity in this area.

We found that the dry mass and length of needles were superior in the Narva ROSMA and AAL compared to the FL. The density of needles on shoots differed significantly between sites: lodgepole pine produced shorter and lighter shoots with a greater needle number per unit shoot length in the Narva ROSMA and AAL compared to the FL. However, shoot length and needles number per unit shoot length did not correlate. Niinemets and Kull (1995) also did not find any correlation between shoot length and needle number per unit shoot length. However, Metslaid et al. (2005) found that the length of the shoot and the number of needles on the shoot, and also the length of the shoot and the needle mass of the shoot were the best correlated shoot variables in trees that had been growing in a variable understorey environment. Larger needles and greater density of needles on shoots found in the ROSMA and AAL, the areas with the highest concentration of N and K in the soil are among several factors influencing the crown architecture, which may contribute to the competitive success in trees. In the FL, the area with the smallest N concentration in the soil, we found longer and heavier shoots, which may also contribute to the resistance of the tree crowns to the winds, and other unfavourable factors. On the basis of the results of the study of morphological parameters it may be concluded that lodgepole pine uses different adaptive strategies of growth related to soil conditions.

Our results showed that the needles were significantly longer and heavier in the plantation in the Narva ROSMA compared to plantations on the AAL and FL soils, yet the concentrations of elements in needles were lower. This can be related to the higher nutrient use efficiency. It means that lodgepole pine growing in the ROSMA may need fewer nutrients for biomass production. Norgren (1996) reported that the higher N use efficiency of lodgepole pine compared to Scots pine is achieved through its low N investment per unit biomass. In the study realised in black alder Vares et al. (2004) found the highest N use efficiency in the ROSMA and the smallest one on AAL. Therefore we believe that having higher N use effi-

ciency is an advantage for lodgepole pine growth on nitrogen-poor post-mining soil.

Generally, post-mining soils because of their unfavourable chemical and physical properties are a less desirable growth environment compared to native soils (Singh et al. 2006). Nevertheless, Reintam *et al.* (2002) argued that ROSMAs in Estonia have a high potential for forestry. Thus it was found that some exotic species, for example, larches (*Larix decidua*, *L. sibirica*) grow well in the ROSMA (Kaar 2002, Kuznetsova and Pärn 2004). Previous studies in ROSMA reported positive results of lodgepole pine cultivation in clayey areas (Kaar and Raid 1996) and similar growth of lodgepole pine and Scots pine in calcareous soils (Kuznetsova and Mandre 2006). An experiment in Finland confirmed that lodgepole pine has especially great advantages over Scots pine on strongly clayey soils (Tigerstedt 1986). This study showed that the growth of lodgepole pine in the Narva ROSMA was higher compared to the FL soil. Also, lodgepole pine growth in the Narva ROSMA showed more similarities with its growth on the AAL. This may indicate that lodgepole pine is not well adapted to the nutritionally poor sandy FL, and requires more favourable growth conditions similar to those in the AAL or in clay substrates of the ROSMA.

In conclusion, it may be said that lodgepole pine uses different growth adaptive strategies in relation to soil conditions. We cannot encourage the cultivation of lodgepole pine as a foreign species in forest, but on the basis of the results of the current study the use of this species for recultivation of the AAL and ROSMA may be recommended. Also the results of this study can be used as an example for other regions, where lodgepole pine is a common tree species and for areas subjected to restoration.

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РОСТ СОСНЫ СКРУЧЕННОЙ (*PINUS CONTORTA* VAR. *LATIFOLIA* ENGELM.) НА РЕКУЛЬТИВИРОВАННЫХ ОТВАЛАХ СЛАНЦЕВЫХ КАРЬЕРОВ, ЗАБРОШЕННЫХ СЕЛЬСКОХОЗЯЙСТВЕННЫХ УГОДЬЯХ И В ЛЕСОПОСАДКАХ

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Резюме

Основная цель работы заключалась в анализе роста сосны скрученной, произрастающей на разных типах почвы, и выявлении наиболее подходящего места произрастания для данного вида сосны.

Взаимодействие между ростом деревьев и почвы, а также химическая взаимосвязь между почвой и хвоей были проанализированы в насаждениях сосны скрученной в разных условиях произрастания.

Было установлено существенное влияние почвы на рост сосны. Деревья из разных насаждений отличались по высоте и диаметру. Несмотря на то, что концентрации Р и К в почве рекультивированных отвалов сланцевых карьеров (РОСК) были выше, содержание этих элементов в хвое были ниже, чем в хвое в заброшенных сельскохозяйственных угодьях (ЗСУ) и лесопосадках (Л). Это может зависеть от высокой щелочности почвы и К/Са антагонизма. Хотя содержание элементов в хвое было ниже на РОСК, хвоя здесь была длиннее и тяжелее, что может быть связано с более высокой эффективностью использования N и P сосной скрученной на РОСК.

Полученные результаты показали, что сосна скрученная растет лучше на ЗСУ и глиняных субстратах РОСК; худший рост наблюдался на бедной питательными веществами лесной песчаной почве.

Ключевые слова: скрученная сосна, рост, биомасса, питательные вещества, тип почвы

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Keelteoskus: vene, eesti, saksa, inglise

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APPROBATION

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Visual presentations

29.06–03.07.2009. **Kuznetsova, T.**, Rosenvald, K., Lõhmus, K., Ostonen, I., Lukjanova, A., Mandre, M. 2009. Early growth, biomass production and root characteristics of silver birch, black alder and Scots pine on a reclaimed oil shale mining area. 6th Int. Symp. Ecosystem Behaviour BIOGEOMON 2009. Helsinki, Finland.

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27.–29.06.2006. **Kuznetsova, T.**, Mandre, M., Lukjanova, A. Morphology and nutrition of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and Scots pine (*Pinus sylvestris* L.) on oil shale post-mining landscapes in Northeast Estonia. The VI International Youth Environmental Forum ECOBALTICA 2006. St. Petersburg, Russia.

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Local conferences and meetings

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06.10.2005. **Kuznetsova, T.** Põlevkivikarjääride rekultiveerimistulemustest Ida-Virumaal. EPMÜ Metsandus- ja maaehitusinstituudi ja Harjumaa Keskkonnateenistuse seminar "Tööstusheitmete mõjust metsale". RMK, Tallinn.

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VIIS VIIMAST KAITSMIST

ANNE MUST

THERMO- AND HYGRORECEPTION IN GROUND BEETLES

(*COLEOPTERA: CARABIDAE*)

JOOKSIKLASTE (*COLEOPTERA: CARABIDAE*)

TERMO- JA HÜGRORETSEPTSIOON

Vanemteadur **Enno Merivee**

27. oktoober 2010

THEA KULL

REPRODUCTION ECOLOGY AND GENETIC DIVERSITY OF

DECLINING SEDGE (*CAREX*) SPECIES

VÄHENEVA ARVUKUSEGA TARNALIIKIDE (*CAREX*)

PALJUNEMISÖKOLOOGIA JA GENEETILINE MITMEKESISUS

Prof. **Tiiu Kull**, vanemteadur **Tatjana Oja**

23. november 2010

MARGIT HEINLAAN

ECOTOXICOLOGICAL EVALUATION OF SYNTHETIC

NANOPARTICLES AND PARTICULATE ENVIRONMENTAL SAMPLES

SÜNTEETILISTE NANOOSAKESTE JA TAHKETE

KESKKONNAPROOVIDE ÖKOTOXIKOLOOGILINE HINDAMINE

Prof. **Kalev Sepp**, juhtivteadur **Anne Kahru**

14. detsember 2010

REIN DRENKHAN

EPIDEMIOLOGICAL INVESTIGATION OF PINE FOLIAGE DISEASES

BY THE USE OF THE NEEDLE TRACE METHOD

OKKAJÄLJEMEETODI KASUTAMISEST MÄNNI OKKAHAIGUSTE

EPIDEMIOLOOGILISES UURIMISTÖÖS

Teadur **Märt Hanso**

13. jaanuar 2011

MIHKEL KIVISTE

CONDITION AND RESIDUAL BEARING CAPACITY OF

EXISTING REINFORCED CONCRETE STRUCTURES

OLEMASOLEVATE RAUDBETOONTARINDITE

SEISUND JA JÄÄKKANDEVÕIME

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