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Development of bioavailable pools of base cations and P after afforestation of volcanic soils in Iceland

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ABSTRACT

Few long-term studies have been conducted on changes in soil nutrients after afforestation in Iceland, a country with a young history of forest management. While fertilization was shown to improve survival of seedlings in the first years after planting on the nutrient limited soils, knowledge about the nutrients status of the soils that develop under maturing forest stands is still scarce. In a chronosequence study, the development of base cations and Olsen-phosphorus (Olsen-P) in the mineral soil was followed in six forest stands of two different tree species of increasing age (14–97 years): native birch (*Betula pubescens*) and introduced Siberian larch (*Larix sibirica*). A treeless heathland was included to present soil conditions prior to forest establishment. The sites are part of the largest forest area in Iceland, located in the east of the country. Results revealed an effect of stand age on all soil nutrients investigated except for potassium (K). Olsen-P increased in 0–10 cm depth of the mineral soil, indicating a better availability and thus improved P supply in maturing forest stands. Calcium (Ca) and magnesium (Mg) concentrations decreased with stand age in 0–10 and 10–20 cm soil depth, while sodium (Na) decreased only in the upper soil layer. Only Olsen-P and K concentrations were higher in the upper soil layer as compared to 10–20 cm depth. This indicates a higher biotic control as opposed to the geochemical control of the other base cations.

1. Introduction

It has been estimated that 15–30% of Iceland had been covered with forests before the time of settlement (c. AD 874) (Blöndal, 1993). After the settlement, deforestation started as a result of the agrarian lifestyle of the settlers, and within less than 200 years human beings had removed the original forest cover almost completely. With the loss of forests, soil erosion increased, causing the loss of valuable fertile land. Soil protection and carbon (C) sequestration must therefore be considered the main goal of afforestation in Iceland. However, it was not before the year 1899 that organised forestry took place in Iceland. A 100 years later, the Regional Afforestation Project Act announced that the aim for regional afforestation projects should be to afforest 5% of the area below 400 m a.s.l. within the next 40 years (Regional Afforestation Project Act no 56/1999). About 80% of the afforestation is carried out by farmers in cooperation with state-run Regional Afforestation Projects, while the remaining 20% is performed by forestry societies, individuals and state agencies (Gunnarsson, 2004). Forests of downy birch (*Betula pubescens*), the only native forest forming tree species left after succeeding glaciations, cover about 1.2% of the land area, and afforestation with exotic tree species adds another 0.3% (Sigurdsson et al., 2005a). From 1990 to 2005, afforestation areas have increased by ca. 215 km^2 to a total area of 289 km^2 according to estimates from the number of seedlings planted annually (Sigurdsson et al., 2005a). However, the survival of these seedlings is poor, so the actual increase in forest cover must be assumed to be much less.

Low average temperatures, short vegetation periods, strong winds, frost heaving in winter, and damages by grazing sheep and horses are all factors that are detriment to the survival of seedlings and hamper the successful establishment of forests. In addition to this, soil nutrient supply is restricted: Icelandic ecosystems are generally nitrogen (N) limited, and phosphorus (P) availability is poor owing to the high P fixation capacity of the volcanic soils (Arnalds et al., 1995). In contrast, the base cations potassium (K), magnesium (Mg) and calcium (Ca) are generally abundant in Icelandic soils (Johannesson, 1960). However, these studies do not directly address the relation between forest growth and soil nutrients, although it is acknowledged that not only N and P, but also soil base cations are essential for a healthy development of forests. There is general concordance among studies that K plays a critical role in many plant physiological processes, and it is assumed that K is a regulation factor in the symbiosis between tree roots and mycorrhizal fungi (van Hees et al., 2006). Similarly, the importance of Ca in metabolic processes and in the control of the

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structure and function of forest ecosystems has been emphasised (McLaughlin and Wimmer, 1999).

Due to the relatively young age of Icelandic afforestation, research on the effect of afforestation on soil properties is still in the beginning. Most soil related studies focus on C sequestration in forest stands (Jónsson and Óskarsson, 1996; Sigurdsson et al., 2005b), the survival of seedlings (Óskarsson and Sigurgeirsson, 2001; Óskarsson et al., 2006), or soil protection by the establishment of vegetation other than trees (Pálmason et al., 1992; Elmarsdóttir et al., 2003; Gretarsdóttir et al., 2004). Similar to international afforestation studies, a positive effect on C sequestration could be recorded in Icelandic forest stands, however with longer time horizons (Sigurdsson et al., 2005b). The fertilization study by Óskarsson et al. (2006) showed that seedling survival and growth was improved by NPK + micronutrients fertilizers applied at the time of planting. However, this study followed tree development only over a period of 6 years, and more studies on the long-term effect of afforestation on a variety of soil nutrient is needed in Iceland.

Studies in other environments and on non-volcanic soils have shown that afforestation can result in a decrease in soil pH and thus a depletion of base cations (Andersen et al., 2002). Sequestration of C in afforestation sites occurs especially in the forest floor biomass and can be affected by previous land-use, climate and type of forest established (Paul et al., 2002). On Allophanic Brown Soils in New Zealand with a high annual rainfall (1400 mm), Chen et al. (2003) studied the effect of afforestation with pine on former grassland. They reported better soil moisture and temperature regimes, a higher release of P through microbial biomass, but a lower level of soil organic carbon, total N and organic P fractions in the forest stands. They emphasised the importance of the forest floor in P cycling. Stevenson (2004) detected in allophanic soils in New Zealand higher contents of P compounds and base cations in forest fragments adjacent to managed pastures than reference forests that were not receiving fertiliser additions. For volcanic soils in Hawaii, Resh et al. (2002) reported higher C sequestration under N-fixing than non-N-fixing trees planted on fields with previous C4 land-use. A similar positive effect of afforestation of sugarcane fields with *Eucalyptus* species in Hawaii was found by Bashkin and Binkley (1998).

The special soil and climatic conditions in Iceland, i.e. volcanic soils in a maritime cool temperate climate, make a comparison with studies in other regions of the world difficult. It is therefore important to carry out field studies in Iceland in order to understand how the soil nutrient status and thus the nutrient supply to trees is changing after afforestation in the Icelandic environment. A better knowledge is required for forest management to improve the success of the highly needed afforestation. The aim of the present study is therefore to investigate the long-term development of the soil nutrient status in forest stands of increasing age in Iceland. The present paper will focus on changes in Ca, Mg, K, sodium (Na), and Olsen-phosphorus in two different soil depths in up to 97-year-old forest stands. Further results of the same study are published by Ritter (2007): they reveal only minor changes in total C, N and P in the soil with stand age. The C content in 0–10 cm soil depth was significantly higher in forest stands older than 30 years than in heath land and the younger forests stands, but changes in the soil C pool were generally less than found in other Icelandic studies on land reclamation with grass. This was partly attributed to the fact that the present soils were already on a moderate C level prior to forest establishment compared to other Icelandic Andosols. Concentrations of N and total P in the mineral soil were not affected by stand age at all. An effect of tree species was only found for the N content in foliar tissue, with higher values for larch than for birch. However, there was no correlation of foliar N content with soil N concentrations or total P in the soil (Ritter, 2007).

2. Materials and methods

2.1. Study site and sampling

The study was carried out as a chronosequence study in six forest stands and a treeless heathland in Fljótsdalshérad in east Iceland (14°44′W, 65°5′N). The study area is part of the largest forest area in Iceland. It is located on the western side of the river Lagarfljót where the river forms a c. 30 km long and 2.5 km wide lake. Study plots were located within a c. 15 km long belt along the lake shore, in an average height of up to 100 m a.s.l. at the foot of a mountain range that reaches a height of 700 m a.s.l. Climate data were obtained from the weather station at Hallormstaður, located within the study area. The average annual precipitation is 735 mm, and the average annual temperature is 3.4 °C. The maximum monthly temperature in summer is 13.4 °C in July, and the minimum monthly temperature is 1.4 °C in January (Icelandic Meteorological Office, average of yearly values 1961–1989). The soils are Andosols developed from basaltic parent material (Upper Tertiary) and the rhyolitic volcanic ash that had been deposited from the eruption of Mt Askja in the year 1875. Owing to the andic properties, bulk density in the plots is rather low.

Plot sizes were between 3.2 and 7.4 ha. The study plots comprise four stands of Siberian larch (*Larix sibirica*) that were planted as part of an afforestation programme, and two stands of native downy birch (*B. pubescens*) that have developed from natural regeneration after the areas had been fenced to avoid grazing of sheep. The initial land use had been similar in all plots, i.e. grazing of free ranging sheep on the unfenced heathland. The larch stands were planted 14, 21, 39, and 53 years before sampling, respectively (plot L14, L21, L39 and L53). The two birch stands were fenced 26 and 97 years ago (plot B26 and B97). Stand ages assigned to the study plots represent the period between planting or fencing and the year of sampling, respectively, and may not correspond to the true age of the trees (Table 1). All stands had reached canopy closure except for the 14-year-old larch and the

Table 1
Description of the vegetation, area, and soil pH in the seven study plots. Larch trees were planted, while birch came up naturally after fencing the area to avoid grazing by sheep.

Plot	Vegetation	Year of planting/fencing[a]	Age (years)	Area (ha)[b]	Mean dominant height (m)[b]	Soil pH[b]	Canopy closure
H0	Heathland	–	0	7.4	–	7.1	Treeless area
L14	Larch	1991	14	4.6	3.9	7.1	Open forest
L21	Larch	1984	21	7.2	6.5	6.7	Closed canopy
L39	Larch	1966	39	3.2	10.4	6.6	Closed canopy
L53	Larch	1952	53	7.3	14.7	6.9	Closed canopy
B26	Birch	1979	26	5.1	3.4	6.8	Open forest
B97	Birch	1908	97	6.1	7.8	6.6	Closed canopy

[a] Data from Elmarsdóttir et al. (2003).
[b] Data from Sigurdsson et al. (2005b), pH measurements for 0–30 depth.