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ORIGINAL PAPER

Growth development and plant–soil relations in midterm silver birch (*Betula pendula* Roth) plantations on previous agricultural lands in hemiboreal Estonia

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Abstract The first silver birch (*Betula pendula* Roth) plantations aimed at short-rotation forestry (SRF) management were established in Estonia in 1999 on former arable land, as experimental and demonstration areas of this novel land use and silvicultural system. Growth and plant–soil relations in such silver birch plantations have more often been studied at a young age (<10 years), while studies covering the later stages of the rotation period are rare. We used repeated monitoring of soil properties and tree growth in 11 midterm (15-year-old) SRF silver birch plantations to evaluate: (1) growth rate and productivity, (2) impact of soil physico-chemical properties on tree growth and (3) changes in the topsoil chemistry between young and midterm plantations. Growth and yield of midterm silver birch SRF plantations exceeded the best local birch forest yield table values by a factor of about 2. The best growth was observed on former agricultural soils corresponding to *Oxalis* and *Oxalis-Myrtillus* forest site types. Available water content in the topsoil layer (0–25 cm) had a significant positive effect on the growth rate of birches, with competitively dominant and medium trees more affected. The topsoil pH_{KCl} (range 3.7–7.1) level had a negative effect on growth rate, especially in suppressed trees. The A-horizon of former agricultural soils had provided sufficient nutrients to ensure high productivity of the trees. During the 13 years between the two monitorings, concentrations of the topsoil total N and available P had remained at the same level, while available K and pH_{KCl} had decreased significantly.

Keywords Silver birch · Short-rotation forestry · Plantation forestry · Former agricultural soil · Soil acidity · Available water content

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Introduction

There has been increasing interest in alternative wood sources in order to supply the rising demand for industrial wood and to reduce the timber harvest from natural forests, where the productivity is relatively low. One possibility is to practise short-rotation forestry (SRF) on abandoned arable lands, an intensive forest management practice that has spread to Northern Europe during the past decades (Weih 2004; Tullus et al. 2012a). Since the 1990s, large areas of agricultural land have been abandoned in Northern and Eastern Europe (Wall and Hytönen 2005; Prishchepov et al. 2013), including Estonia (Peterson and Aunap 1998). Several deciduous plantations were established on previous agricultural lands in Estonia in 1999 with silver birch and with hybrid aspen (Vares et al. 2001; Tullus et al. 2007) to gain experience with this novel land use.

Silver birch (*Betula pendula* Roth) is regarded as a suitable tree species for SRF practice in hemiboreal conditions on previous agricultural soils. Birches (*B. pendula* and *B. pubescens*) are the most important commercial deciduous tree species for Northern and Eastern European forestry (Hynynen et al. 2010). The area of birch forests in Estonia makes up approximately 31 % of the total forest land (Yearbook Forest 2013). Silver birch is characterized by fast growth at a young age on previous agricultural soils (Telenius 1999; Vares et al. 2001, 2003; Daugaviete et al. 2003; Jõgiste et al. 2003; Uri et al. 2007; Kund et al. 2010) and higher wood density compared to other fast-growing deciduous trees (Repola 2006; Johansson 2007; Liepinš and Rieksts-Riekstinš 2014). An economic study of silver birch plantations on previous agricultural soils showed that based on financial maturity, the potential rotation period could be around 35 years on the best sites (Tullus et al. 2012b), which is about half of that used for traditional birch management in Estonia.

Although growth and development of young (<10 years) birch plantations on former arable land has been recorded in several studies (Telenius 1999; Vares et al. 2001, 2003; Daugaviete et al. 2003; Jõgiste et al. 2003; Uri et al. 2007; Kund et al. 2010), there exist only few empirical studies from the mid-rotation period (Johansson 1999, 2007; Saramäki and Hytönen 2004; Hytönen et al. 2014) and none of them compares growth of birch plantations on previous agricultural land with forestland stands growing on similar soil types. In Estonia, silver birch yield tables have been compiled for naturally regenerated forestland stands (Henno 1980; Kiviste 1997). The potential growth and productivity of silver birch plantations on previous agricultural soils, which have somewhat different physical and chemical properties compared to forest soils in the hemiboreal region (Alriksson and Olsson 1995; Messing et al. 1997; Wall and Heiskanen 2003; Wall and Hytönen 2005), are still quite poorly studied. Previous agricultural soils are usually nutrient rich, well drained and generally homogenous in the humus horizon, which is a result of previous and long-term fertilization, ploughing and tilling.

Acquisition of different resources by trees is depending on resources supply, which in turn depends on site characteristics such as soil physico-chemical properties and biological activity. However, resources are not equally available to all trees in the stand (Binkley et al. 2013), and hence, competition will cause differentiation in tree size and their access to available resources, with dominant trees being more advantaged than suppressed trees in this respect (Binkley et al. 2010; Otto et al. 2014). Generally, birches are relatively sensitive to soil physico-chemical properties (Perala and Alm 1990) and also to within-stand competition due to their low shade tolerance (Hynynen et al. 2010). Thus, it is important to clarify what factors are mainly limiting tree-level productivity in silver birch plantations on previous arable land, as this topic is not well studied in the region.

We should consider that afforestation is a land-use change, the effects of which on the environment or on ecosystem productivity are not always unequivocal. Silver birch can ameliorate unfavourable site conditions through nutritious litter fall and microbiological activity around the root system in the soil (Perala and Alm 1990; Carnol and Bazgir 2013). In order to retain high productivity in fast-growing silver birch plantations on abandoned agricultural lands, it is also important to understand the dynamics and changes in nutrient concentrations and pH_{KCl} levels in the topsoil, whereby it is possible to predict the need for fertilization. Knowledge of soil nutrient dynamics and balance is also important when the site is to be re-used for agricultural purposes in the future. Generally, in plantation forestry, fast-growing trees may deplete soil nutrients very intensively and fertilization is needed to maintain productivity (Ericsson 1994; Berthrong et al. 2009; Liao et al. 2012). The general findings of mutual relations between forest plantations and soil fertility are in contradiction with the results from Northern Europe, where afforested agricultural soils have higher soil fertility compared to continuously forested soils (Wall and Hytönen 2005). SRF plantations can even use nutrients more efficiently in the long term, preventing their loss through leaching or runoff with water on arable lands (Kahle et al. 2010). Even though the area of forest plantations has rapidly expanded in Northern Europe, there is still a lack of information about how this novel land use will influence soil properties on previous agricultural lands in the long term, especially on the basis of repeated measurements. Impact of former land use on chemical properties of soil can be long lasting. For example, it has been found that the high content of macronutrients (NPK) may persist for decades after the agricultural land use ceases (Wall and Hytönen 2005; Falkengren-Grerup et al. 2006). Also N mineralization rate (often characterized through C:N ratio) could remain relatively unchanged after afforestation (Ritter et al. 2003), depending also on exact type of previous agricultural land use (Vladychenskii et al. 2013). After agricultural land afforestation, acidification is usually taking place, which has been observed with many tree species (Ritter et al. 2003; Vladychenskii et al. 2009; Uri et al. 2011; De Schrijver et al. 2012b), but we were not able to find any long-term studies on changes in soil pH_{KCl} after the afforestation of former agricultural land with silver birch in the hemiboreal region.

The aim of our study was to estimate tree growth, impact of soil physico-chemical properties on tree growth, changes in topsoil macronutrient concentrations, organic C, C:N ratio and pH_{KCl} on previous agricultural soils in midterm SRF silver birch plantations during the first half of the rotation period. Based on results, practical management implications are provided. Hypotheses are: (1) silver birch plantations' growth and yield at the end of 15th growing season is exceeding birch stands on similar forest soils, (2) concentration of macronutrients in previous agricultural soils is not limiting the growth of trees, (3) the topsoil macronutrients (NPK) concentration and C:N ratio remained unchanged and pH_{KCl} decreased after the first 15 years of growth on former field soils.

Materials and methods

Studied plantations

The study was carried out in 11 midterm silver birch plantations on mineral abandoned arable soils (Table 1) in Estonia (Fig. 1). Estonia is situated in the hemiboreal vegetation zone (Ahti et al. 1968) within a transition zone from maritime to continental climate. The weather in Estonia is considerably milder than the continental climate characteristic of the same latitude. The mean annual temperature during the study period (2010–2013) was 5.9 °C, and the mean precipitation was 733 mm according to nearest weather stations to the studied plantations (The Estonian Environment Agency).

Plantations one hectare in size were planted with 1-year-old bare-rooted seedlings (Vares et al. 2001). Planting density varied between 2500 and 3300 trees per hectare (Kund et al. 2010). Usually, birch seedlings were planted on a ploughed soil, except in Läänemaa, Tartumaa and Valgamaa plantations, where strip ploughing for the establishment of planting rows was used (Vares et al. 2001). Weeding and hay-mowing were carried out during the first years after planting to ensure higher survival of the young seedlings. All plantations were fenced against possible damage from game browsing.

Based on soil type, we tentatively divided plantations into different forest site types (Table 1) according to the Estonian classification of natural forest site types (Lõhmus 1974): *Hepatica, Oxalis* and *Oxalis-Myrtillus*. *Hepatica* site type is located on draught-sensitive soils with a stoney A-horizon and slightly alkaline B-horizon. *Oxalis* site type prevails on well-drained automorphic soils where clay enrichment occurs in the B-horizon. *Oxalis* site type is one of the most common site types where natural regeneration of birch occurs on former field soils in Estonia. *Oxalis-Myrtillus* site type is usually formed on hydromorphic sandy soils with moister conditions compared to *Oxalis*.

Tree growth measurements

The long-term permanent rectangular experimental plots with a size of 0.1 ha (as an exception, 0.08 ha in the Läänemaa plantation), where all trees have unique identification numbers, were monitored in each plantation to estimate above-ground growth and yield of the trees. Repeated growth measurements were carried out annually at the end of the vegetation period between the ages from 12 to 15 years (2010–2013).

The stem diameter at breast height (DBH, cm) over bark was recorded for every single tree using the millimetre scale of a standard forest calliper. The height of every fifth tree was measured with Vertex IV (Haglöf Sweden AB) with 0.1 m resolution. Altogether, ca 2000 trees were measured in each study year, and average growth characteristics after 15 years of growth are presented in Table 2.

In order to characterize the stem size of single trees, stem volume index (DBH^2H) was used.

The total standing volume was calculated for each plantation by using the equation for birch stands from the Estonian forest planning guidelines (2009):

Table 1 General characteristics of the studied silver birch plantations: geographical locations, previous land use (Tullus et al. 2013), tentative forest site types, density and basal area at the age of 15 years

Plantation	Location		Previous land use	Tentative forest site type	Density, trees (ha^{-1})	Basal area (m^2 ha^{-1})
Hiiumaa	58°59′N	22°32′E	Crop field	*Hepatica*	1510	3.5
Võrumaa	57°51′N	26°38′E	Grassland	*Hepatica*	1720	15.2
Järvamaa	58°50′N	26°03′E	Grassland	*Oxalis*	1670	16.5
Põlvamaa	58°05′N	27°26′E	Crop field	*Oxalis*	1930	16.8
Raplamaa	58°54′N	24°54′E	Crop field	*Oxalis*	2430	20.1
Tartumaa	58°26′N	26°45′E	Crop field	*Oxalis*	1090	11.2
Valgamaa	57°52′N	26°12′E	Crop field	*Oxalis*	1710	11.1
Ida-Virumaa	59°05′N	27°20′E	Grassland	*Oxalis-Myrtillus*	2330	19.8
Läänemaa	58°53′N	24°06′E	Grassland	*Oxalis-Myrtillus*	1188	18.5
Pärnumaa	58°39′N	24°51′E	Crop field	*Oxalis-Myrtillus*	1430	11.1
Viljandimaa	58°09′N	25°32′E	Grassland	*Oxalis-Myrtillus*	1550	11.7

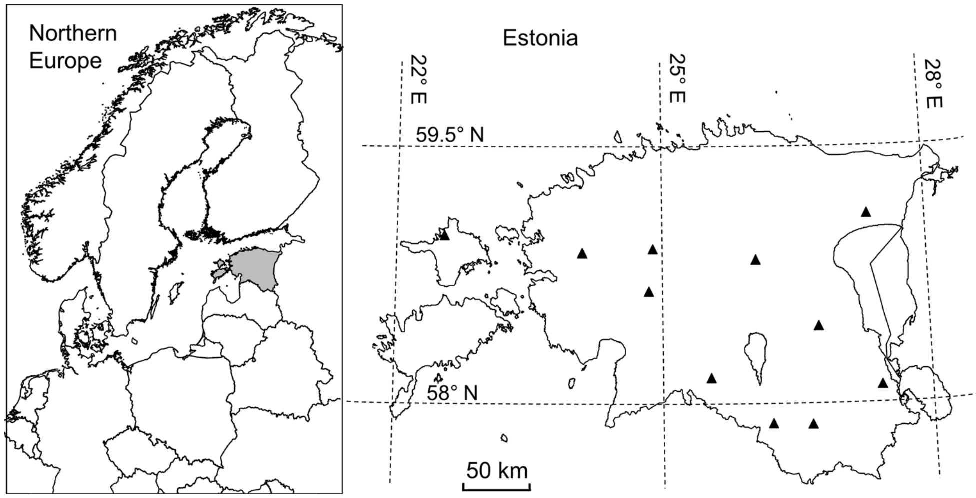

Fig. 1 Locations of the studied silver birch plantations ($n = 11$, marked as *black triangles*)

Table 2 Growth characteristics (H_{mean} mean height, H_{dom} mean height of the dominant trees (i.e. trees exceeding the upper quartile of DBH in the given stand), DBH_{mean} mean stem diameter at breast height, DBH^2H_{mean} mean stem volume index) in the studied silver birch plantations at the age 15 years (±SE)

Plantation	H_{mean} ± SE (m)	H_{dom} ± SE (m)	DBH_{mean} ± SE (cm)	DBH^2H_{mean} ± SE (dm^3)
Hiiumaa	5.2 ± 0.39^{a}	7.8 ± 0.29^{a}	5.0 ± 0.19^{a}	17.0 ± 3.41^{a}
Võrumaa	13.0 ± 0.27^{bc}	14.6 ± 0.11^{b}	10.1 ± 0.24^{cde}	142.7 ± 13.25^{c}
Järvamaa	13.9 ± 0.44^{ce}	16.3 ± 0.11^{cd}	10.8 ± 0.16^{cf}	188.3 ± 19.43^{def}
Põlvamaa	15.4 ± 0.25^{f}	17.0 ± 0.19^{de}	10.3 ± 0.16^{cde}	159.3 ± 12.37^{ce}
Raplamaa	14.9 ± 0.26^{def}	16.9 ± 0.08^{de}	9.9 ± 0.18^{cd}	171.5 ± 13.69^{ce}
Tartumaa	13.8 ± 0.43^{bde}	16.1 ± 0.13^{cd}	11.1 ± 0.26^{df}	159.5 ± 17.34^{def}
Valgamaa	12.4 ± 0.35^{b}	14.8 ± 0.33^{b}	8.6 ± 0.23^{b}	100.6 ± 11.37^{b}
Ida-Virumaa	13.8 ± 0.29 ^{cd}	15.9 ± 0.19^{c}	9.8 ± 0.23^{c}	179.1 ± 16.84^{cd}
Läänemaa	16.3 ± 0.19^{f}	17.7 ± 0.20^{e}	13.9 ± 0.24^{g}	327.8 ± 17.72^{g}
Pärnumaa	15.3 ± 0.24^{ef}	16.7 ± 0.13^{cd}	11.1 ± 0.20^{ef}	201.8 ± 15.43^{ef}
Viljandimaa	15.0 ± 0.21^{def}	16.4 ± 0.17^{cd}	11.7 ± 0.18^{f}	203.4 ± 13.23^{f}
Mean	13.7 ± 0.16	15.6 ± 0.24	10.0 ± 0.08	168.8 ± 5.52

Lowercase letters denote significant (p value < 0.05) differences between groups according to Tukey's LSD test

$$M = G \cdot H \cdot F \tag{1}$$

where M is total stem volume (m^3 ha^{-1}), G is stand basal area (m^2 ha^{-1}), H is average height of plantation (m) and F is stand form factor.

In order to estimate the influence of stand density on tree growth, stand sparsity index (L) was calculated for every stand according to Nilson's (2006) equation:

$$L = 100 \cdot n^{-0.5} \tag{2}$$

where L is average distance between the trees (m) and n is number of trees per hectare.

Soil analysis

Soil sampling was carried out in the final study year when plantations were 15 years old (Table 3). A 1-m-deep soil pit was dug in the centre of each experimental plot, and soil type was determined according to the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB 2014; Table 1). Soil samples for chemical analyses were taken from each soil horizon in the revealed profile. For the soil pH_{KCl} measurement, 1 M KCl suspension at 10 g: 25 ml ratio was used. The total nitrogen (N) was determined according to Kjeldahl (Tecator ASN 3313 AOAC). The available phosphorus (P) (ammonium lactate extractable) was determined by flow injection analysis and the available potassium (K) by the flame photometric method. Organic matter (Corg) was determined as loss on ignition (LOI, %) at 360 °C. All the soil chemical analyses were performed in the Laboratory of Plant Biochemistry, Estonian University of Life Sciences.

Soil bulk density (BD, g cm^{-3}) was determined with undisturbed core samples using a steel cylinder (50 cm^3). The samples were taken from the middle of each soil

Table 3 The studied silver birch plantations' soil types according to WRB classification (IUSS Working Group WRB 2014) and soil A- and B-horizon properties: texture, bulk density (BD, g cm^3), acidity (pH_{KCl}), total N (%), available P (mg kg^{-1}), available K (mg kg^{-1}), Corg (%) and Corg:Ntotal ratio (C:N) after the 15th growing season

Plantation	Soil type	Soil horizon	Textural class	BD	pH_{KCl}	N	P	K	Corg	C:N
Hiiumaa	*Calcaric Skeletic Regosol*	A	Sandy loam	1.30	7.1	0.25	41	96	2.35	9.3
		B	Sandy loam	1.30	7.6	0.04	0	47		
Võrumaa	*Eutric Regosol*	A	Sandy loam	1.36	6.5	0.08	58	144	1.14	14.1
		B	Sand	1.27	7.4	0.01	25	23		
Järvamaa	*Endocalcaric Luvisol*	A	Sandy loam	1.25	5.6	0.14	13	88	1.85	13.1
		B	Sandy loam	1.53	7.7	0.02	1	31		
Põlvamaa	*Stagni Fragic Retisol*	A	Sandy loam	1.38	5.3	0.07	27	62	0.97	13.7
		B	Sandy loam	1.71	5.1	0.03	27	53		
Raplamaa	*Endocalcaric Cambisol*	A	Sandy loam	1.25	5.8	0.16	61	247	2.10	13.0
		B	Sandy loam	1.29	6.3	0.05	25	72		
Tartumaa	*Dystri Glossi Fragic*	A	Sandy loam	1.26	4.4	0.11	50	38	1.30	12.2
	Retisol	B	Sandy loam	1.59	4.3	0.02	29	50		
Valgamaa	*Dystri Glossi Fragic*	A	Loam	1.39	4.8	0.11	1	31	1.92	17.6
	Retisol	B	Loam	1.50	5.8	0.03	23	74		
Ida-Virumaa	*Endogleyic Umbrisol*	A	Silt loam	1.02	5.0	0.12	3	57	1.44	11.6
		B	Silt loam	1.30	4.3	0.01	32	12		
Läänemaa	*Gleyic Albic Podzol*	A	Sand	1.11	3.7	0.13	57	7	2.20	16.7
		B	Sand	1.42	4.9	0.01	110	5		
Pärnumaa	*Mollic Gleysol*	A	Sandy loam	1.06	6.8	0.25	360	177	2.65	10.7
		B	Sandy loam	1.38	7.0	0.02	11	115		
Viljandimaa	*Dystri Glossic Retisol*	A	Loam	1.18	5.0	0.14	6	63	1.60	11.1
		B	Sandy loam	1.48	4.8	0.04	21	47		

horizon in three replications and then oven-dried at 105 °C to constant weight in the laboratory.

Samples for determining soil specific surface area (SSA, m^2 g^{-1}) and soil texture were taken from the middle of all soil horizons. For the soil texture analysis, sand (soil particles with diameter >0.063 mm) was excluded by sieving. Clay (<0.002 mm) and silt (0.002–0.063 mm) fractions were determined by the pipette method (FAO 2006). The relative proportions of these fractions gave the textural class.

SSA of soil samples taken from each horizon up to a depth of 75 cm was determined by adsorption of water vapour on 10 g dry soil surface (Puri and Murari 1964).

Available water content (AWC) is the amount of water available for plants, i.e. the difference between water content at field capacity and water content at permanent wilting point in the soil. We estimated AWC to 75 cm soil depth, assuming that the root systems of birches of this age are mostly located in this layer (Varik et al. 2013). We did not consider actual water content, but the soil's potential to store it. AWC as a static soil property was calculated as a function of BD and SSA, using the pedotransfer equations (Eqs. 3, 4, 5) developed for top horizons of agricultural soils in Estonia (Kitse 1978). The volume of gravel was subtracted from the estimate, similarly to the earlier study performed with hybrid aspen on former arable soils (Tullus et al. 2010):

$$\mathrm{AWC}_{\mathrm{A-horizon}} = \mathrm{BD} \cdot (47.7 - 18.2 \cdot \mathrm{BD} - 0.04 \cdot \mathrm{SSA} - 72/\mathrm{SSA}) \cdot L \cdot (1 - \mathrm{Gr}) \quad (3)$$

$$\mathrm{AWC}_{\mathrm{E-horizon}} = \mathrm{BD} \cdot (44.3 - 18.0 \cdot \mathrm{BD} - 0.08 \cdot \mathrm{SSA} - 41/\mathrm{SSA}) \cdot L \cdot (1 - \mathrm{Gr}) \quad (4)$$

$$\mathrm{AWC}_{\mathrm{B(C)-horizon}} = \mathrm{BD} \cdot (46.5 - 19.1 \cdot \mathrm{BD} - 0.05 \cdot \mathrm{SSA} - 64/\mathrm{SSA}) \cdot L \cdot (1 - \mathrm{Gr}) \quad (5)$$

where AWC is the available water content in the soil (mm), BD is the bulk density (g cm^{-3}), SSA is the soil specific surface area (m^2 g^{-1}), L is the thickness of the layer (mm) and Gr is the portion of gravel (soil particles with diameter more than 2 mm).

Statistical analyses

The Shapiro–Wilk test was used to check the normality of the variables. The pairwise Student's t test was used to determine the significance of the changes in the topsoil nutrient concentrations, organic C, C:N ratio and pH_{KCl} between the first soil sampling in 2000 (Vares et al. 2001) and repeated soil sampling in 2013. Differences in growth characteristics between site-type groups and between plantations were tested with the Tukey's LSD test.

In order to evaluate the influence of site type, the soil's physical and chemical properties and stand sparsity on individual trees' growth and to also consider the size-dependent effects from intraspecific competition, all the trees were assigned a size class (suppressed, medium, dominant) according to their presumable competitive position in the plantation at the end of the final study year (age 15). The tree was considered to be suppressed if its DBH $\leq$ lower quartile, medium when lower quartile < DBH < upper quartile or dominant if its DBH $\geq$ upper quartile of all recorded DBHs in the plantation. After the classification of trees, the significance of soil characteristics for the trees' growth was tested with the linear mixed (random intercept) model with the R Statistics function lmer in package lme4 (Bates et al. 2014), where plantation was treated as a random effect. All the variables were scaled in order to compare the magnitude of effects.

In the model, mean annual increment (MAI) and current annual increment (CAI) of *H* and DBH were used as response variables in order to distinguish between long-term (reflected in MAI) and recently emerged (reflected in CAI) effects from growth factors. MAI was estimated based on tree dimensions in the final study year (MAI = growth characteristic/15). CAI (change in growth between last and current year) was estimated as the average of the last three years: $CAI = AVG(CAI_{13}; CAI_{14}; CAI_{15})$, thus reducing the growth fluctuations arising from other non-soil-related factors (e.g. weather conditions).

When analysing the effect of soil characteristics and stand sparsity on growth, interaction with tree size class was also tested. Thus, we analysed whether the given explanatory variable affected tree growth and whether this effect depended on competitive status (size class) of the tree.

Although the number of observations of response variables was high, most of the explanatory variables, except tree size class, varied only at stand level. Therefore, the effect of each explanatory variable was tested separately.

The model assumptions were checked from residual distributions and Q–Q plots.

The Hiiumaa plantation was excluded from the total N assessment array, since we considered that the poor growth of the trees was not related to a high concentration of total N, but to the stony and shallow soil in the mentioned plantation. In addition, we excluded the Pärnumaa plantation from the total N assessment array as well, as we considered that excessive moisture and high total N in *Gleysol* do not favour growth in the early and late phases of the vegetation period.

Mean values are presented with standard error. Level of significance $\alpha = 0.05$ was used to reject null hypothesis after statistical tests. All statistical analyses were carried out using R Statistics software (R Core Team 2014).

Results

Growth and yield

Height growth in the studied silver birch plantations was relatively homogeneous, and the mean height varied between 12.4 and 16.3 m, with the exception of the Hiiumaa plantation (5.2 m). The mean height after the 15th growing season did not differ ($p = 0.785$) between plantations representing *Oxalis* (14.2 ± 0.17 m) and *Oxalis-Myrtillus* (14.9 ± 0.15 m) site types (Fig. 2). The mean height in *Hepatica* site type (9.5 ± 0.53 m) was significantly lower than in *Oxalis* ($p = 0.019$) and in *Oxalis-Myrtillus* ($p = 0.005$) site types. The mean height of the dominant trees (H_{dom}) should reflect site quality better than the mean height of all trees, since it is less influenced by stand density, competition between the trees and other potential negative growth factors. Significantly higher H_{dom} was recorded in *Oxalis* (16.3 ± 0.13 m, $p = 0.002$) and in *Oxalis-Myrtillus* (16.6 ± 0.14, $p = 0.001$) site types compared to the *Hepatica* site type (11.4 ± 0.86 m).

The mean DBH after the 15th growing season varied from 5.0 to 13.9 cm between plantations. The lowest mean DBH was recorded in the *Hepatica* site type (7.7 ± 0.21 cm), which differed significantly from the *Oxalis-Myrtillus* site type (11.2 ± 0.12 cm, $p = 0.008$), but not from the *Oxalis* site type (10.0 ± 0.10 cm, $p = 0.238$). We found that, at single-tree level, plantation sparsity had started to significantly ($p = 0.040$) limit the suppressed trees' current year diameter growth (Fig. 5c), while no significant effect was observed on mean annual growth rate yet (Table 4). The impact of sparsity on the diameter growth of medium trees was negligible ($p = 0.052$). Sparsity had no impact on the dominant trees' current annual diameter growth ($p = 0.334$).

Even though in the *Oxalis* site type the mean stem volume index (DBH^2H) of the trees (158.3 ± 7.04 dm^3) was almost two times higher than in the *Hepatica*, it did not differ significantly ($p = 0.238$). The mean DBH^2H in the *Hepatica* site type was 86.4 ± 10.69 dm^3, being significantly lower compared to the *Oxalis-Myrtillus* (219.8 ± 9.31 dm^3, $p = 0.008$) site type.

The mean stem volume estimated at plantation level was 104.0 ± 11.96 $m^3\ ha^{-1}$, exceeding 140 $m^3\ ha^{-1}$ in the best plantations after the 15th growing season. Higher stem

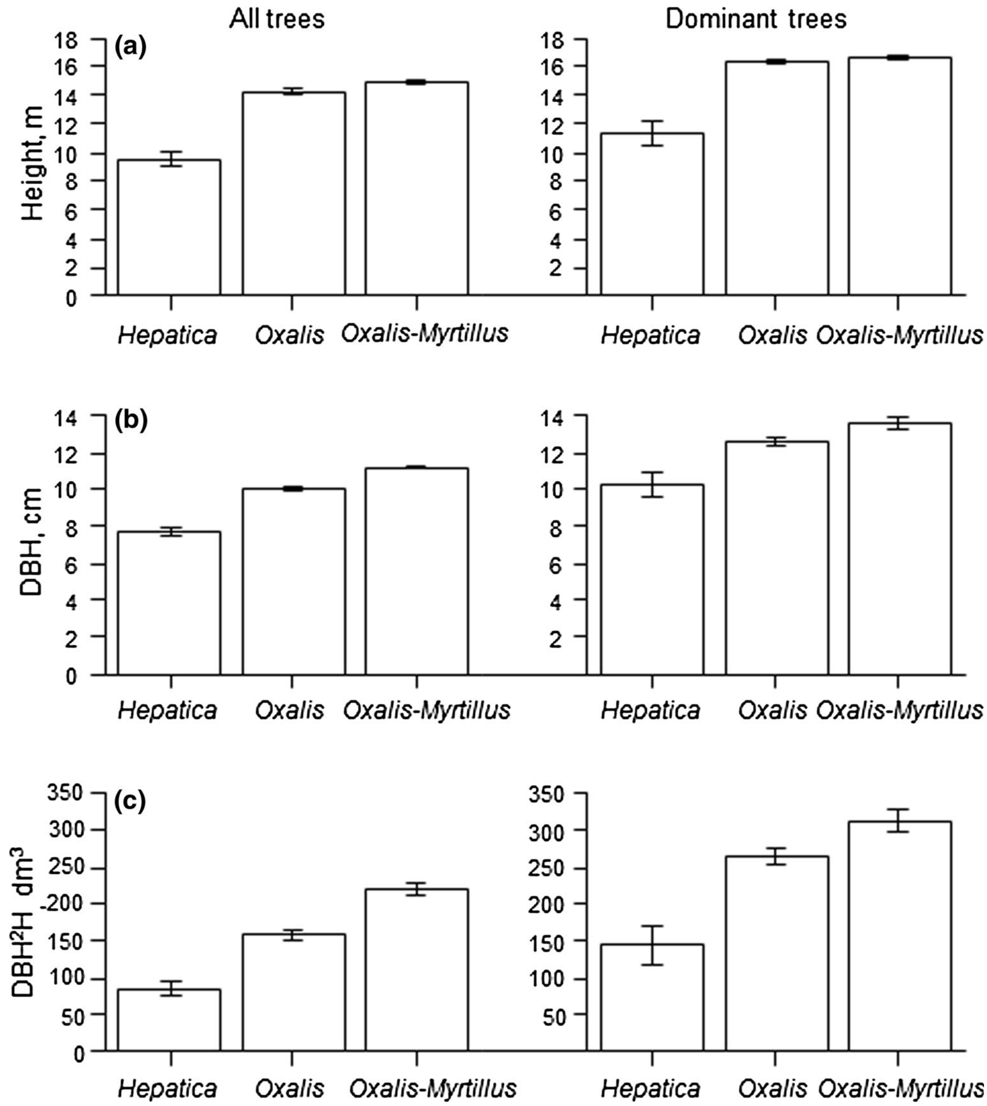

Fig. 2 Average growth characteristics [height (**a**), DBH (**b**) and DBH^2H (**c**)] of silver birches in different site types. *Whiskers* denote standard error for the mean of the site type

volume was estimated in the *Oxalis* (106.6 m^3 ha^{-1}) and in the *Oxalis-Myrtillus* (125.8 m^3 ha^{-1}) compared to the *Hepatica* (54.0 m^3 ha^{-1}) site type. The mean CAI of stem volume during the 15th growing season was the highest in the *Oxalis-Myrtillus* site type (23.0 m^3 ha^{-1} $year^{-1}$), while in the *Oxalis* site type, it was 19.2 m^3 ha^{-1} $year^{-1}$, and in the *Hepatica* site type, it was 12.1 m^3 ha^{-1} $year^{-1}$.

The height and DBH growth of the studied silver birch plantations exceed almost twofold the values of the traditional growth and yield tables of Estonian natural birch forests (Fig. 3). Henno (1980) predicts for *Oxalis* forestland that the average height will be 8.0 m, DBH 6.0 cm and stem volume 57 m^3 ha^{-1}, and Kiviste (1997) respective values are 8.2 m, 6.5 cm and 49 m^3 ha^{-1}, at the age 15, which is two times less than we found in our study for *Oxalis* and *Oxalis-Myrtillus* growth (Figs. 2, 3). Even though the growth of plantations in the *Hepatica* site type has been poor compared to the *Oxalis* and *Oxalis-Myrtillus* site types, it still exceeds that of *Oxalis* and *Oxalis-Myrtillus* (Henno 1980; Kiviste 1997) on forestland (Fig. 3) at the age 15.

Plant–soil relations

The effects of soil physico-chemical properties on the growth of the trees were analysed at a single-tree level, considering also the competitive status of the tree (suppressed, medium and dominant trees) in the plantation (Table 4; Fig. 5).

Growth of the trees was most significantly as well as most strongly affected by soil available water content (AWC), especially AWC in the upper soil layer (0–25 cm), while the impact decreased when we tested deeper soil layers. The amount of AWC in the topsoil decreased with depth: 40 % of AWC was located in the upper 25 cm soil layer, 32 % was in at a depth of 25–50 cm and 28 % was between 50 and 75 cm (Fig. 4).

Table 4 The fixed effects (standardized coefficients and *p* values) of stand sparsity and soil variables on individual tree growth characteristics in silver birch plantations (*DBH MAI* mean annual increment of diameter at breast height; *DBH CAI* current annual increment of diameter at breast height; *H MAI* mean annual increment of height; *H CAI* current annual increment of height) according to single-tree size classes (*D* dominant trees, *M* medium trees, *S* suppressed trees)

Variable	Size	DBH MAI		DBH CAI		*H* MAI		*H* CAI	
		Estimate	*p* value	Estimate	*p* value	Estimate	*p* value	Estimate	*p* value
Sparsity	D			0.10^{a}	0.334				
	M			0.22^{b}	0.052				
	S			0.23^{b}	0.040				
$AWC_{0\text{-}75cm}$	D					0.51^{a}	0.023		
	M					0.51^{a}	0.023		
	S					0.32^{b}	0.125		
$AWC_{0\text{-}25cm}$	D	0.41^{a}	0.004			0.59^{ab}	<0.0001	0.43^{a}	0.005
	M	0.40^{a}	0.004			0.66^{a}	<0.0001	0.32^{a}	0.007
	S	0.28^{b}	0.027			0.56^{b}	<0.0001	0.20^{b}	0.190
A-horizon pH_{KCl}	D	-0.33^{a}	0.017			-0.31^{a}	0.140		
	M	-0.41^{b}	0.005			-0.44^{b}	0.045		
	S	-0.42^{b}	0.005			-0.56^{c}	0.016		
B-horizon available P	D					0.22^{a}	0.286		
	M					0.32^{b}	0.174		
	S					0.50^{c}	0.032		

Superscript letters denote significant (p value < 0.05) differences between tree size classes; effects are shown only if a significant effect was observed in at least one size class

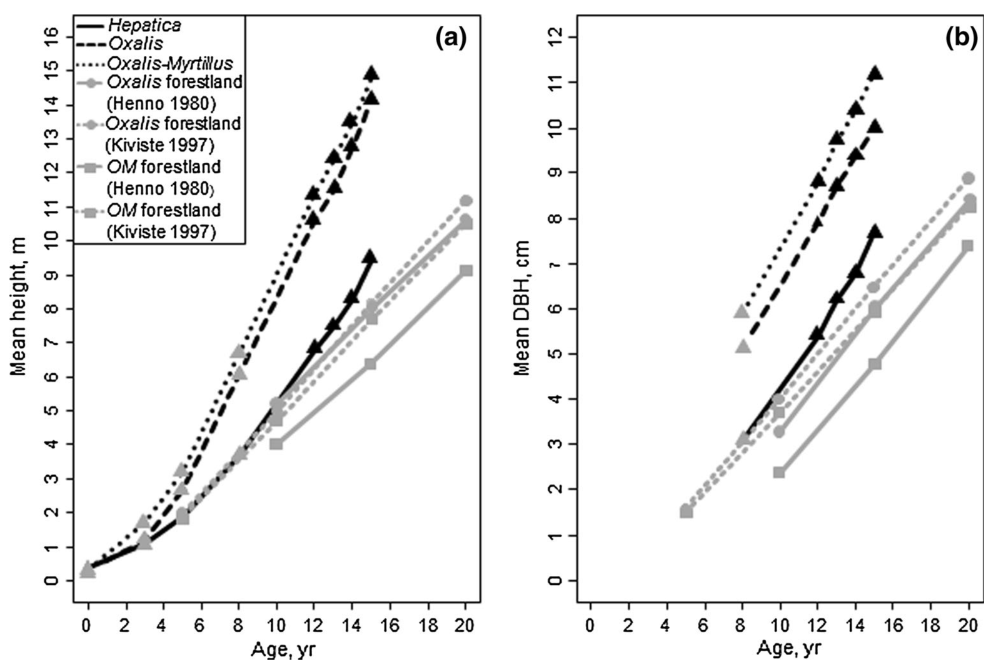

Fig. 3 Height (**a**) and DBH (**b**) development of silver birch plantations on previous agricultural lands in three tentatively assigned site types, based on the current study (*black triangles*) and earlier surveys of the same plots (*grey triangles*, data from Vares et al. 2001; Jõgiste et al. 2003; Vares 2005; Kund et al. 2010) compared to local birch yield tables for *Oxalis* and *Oxalis-Myrtillus* (*OM*) site types on forestland (Henno 1980; Kiviste 1997)

$AWC_{0–25}$ had positive effect on the mean annual increment (MAI) of height in all tree size classes ($p < 0.0001$ in all cases) (Table 4; Fig. 5a). Regarding CAI of height, the strongest impact of $AWC_{0–25}$ was observed with dominant ($p = 0.005$) and medium ($p = 0.007$) trees. No significant relationship between birch growth and AWC in the 25–50 cm or 50–75 cm soil layer was detected. Nevertheless, total water availability in the whole of the 75 cm soil layer had a significant relationship with MAI of height of dominant ($p = 0.023$) and medium ($p = 0.023$) trees.

A-horizon pH_{KCl} had a significant negative effect on the MAI of height and DBH, while the impact of pH_{KCl} on CAI was not important. The most significant impact of A-horizon pH_{KCl} on the MAI of height and DBH was detected in suppressed ($p = 0.016$; $p = 0.005$, respectively) and medium trees ($p = 0.045$; $p = 0.005$, respectively). For dominant trees, a significant impact of A-horizon pH_{KCl} was observed only for the MAI of DBH ($p = 0.017$). Soil B-horizon pH_{KCl} did not have significant influence on the growth of the trees.

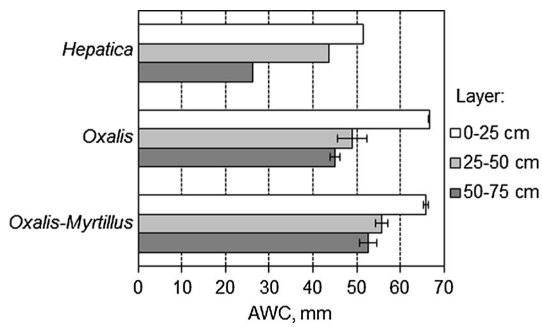

Fig. 4 Distribution of AWC through 75 cm soil profile in different site types; whiskers denote standard error (not shown for *Hepatica* with 2 samples)

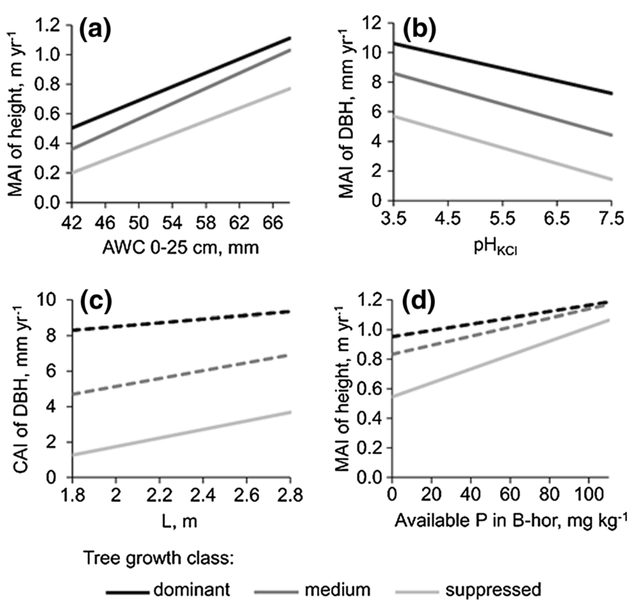

Fig. 5 Graphical representation of linear relationships between growth variables (*MAI* mean annual increment, *CAI* current annual increment, *DBH* stem diameter at breast height) and fixed factors (*AWC* available water content of soil, *L* stand sparsity index) based on the growth soil analyses (Table 4). *Broken lines* represent insignificant relations

The concentrations of soil A- and B-horizon macronutrients (NPK) did not have a significant impact on tree growth in any size class, except for the significant positive effect of available P concentration in the B-horizon on the MAI of height of suppressed trees ($p = 0.032$).

Changes in the topsoil pH_{KCl} and nutrient concentrations

The comparison of topsoil macronutrient (NPK) concentrations and pH_{KCl} between 2-year-old and midterm (15-year-old) plantations revealed that the mean topsoil acidity had decreased by 0.5 units from 5.9 to 5.4. However, for all 11 plantations together, this change was just marginally significant ($p = 0.052$). There was only one plantation (Ida-Virumaa) where the topsoil pH_{KCl} had increased, by 0.7 units (from 4.3 to 5.0). If this plantation was excluded, the decrease in mean topsoil acidity would be highly significant ($p = 0.019$) by 0.6 units from 6.1 to 5.5 (Fig. 6a). Mean concentration of available K had decreased significantly ($p = 0.018$), by about 30 % from 132 to 92 mg kg^{-1} (Fig. 6d). Concentrations of total N, extractable P and Corg, as well as C:N ratio in the topsoil had remained at the same level as the initial status (Fig. 6).

The number of plantations in site-type groups was too low to make statistically sound comparisons of the changes in macronutrients and acidity in the topsoil layer between site-type groups; therefore, we can only describe some trends. The highest drop in pH_{KCl} was in the *Oxalis* site type, where it decreased 0.8 units (6.0–5.2). The level of pH_{KCl} decreased by 0.4 units (5.5–5.1) in the *Oxalis*-

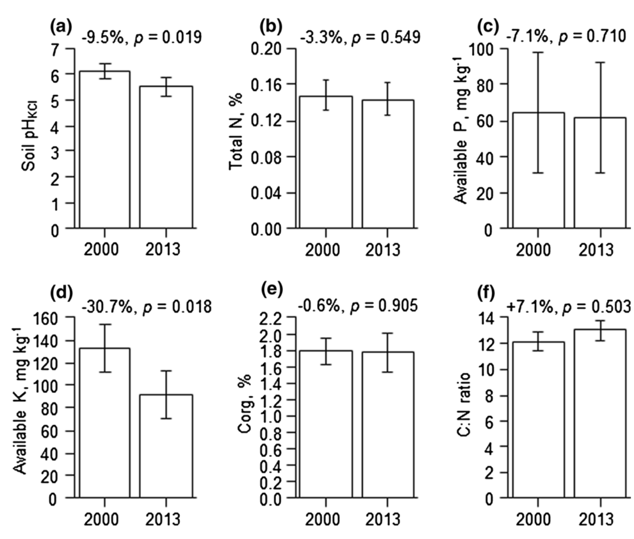

Fig. 6 Comparison of acidity (pH_{KCl}) (**a**), concentrations of macronutrients (NPK) (**b**, **c**, **d**), organic carbon (Corg) (**e**) and C:N ratio (**f**) in soil A-horizon between recently established (2000, Vares et al. 2001) and midterm (2013) silver birch plantations; *whiskers* denote standard error

Myrtillus site type (excluding Ida-Virumaa) and by 0.3 units (7.1–6.8) in the *Hepatica* group. Total N concentration in the topsoil has generally remained at same level as the initial status: there has been little increase in the *Hepatica* (+15 %) and decreases in the *Oxalis* (−14 %) and *Oxalis-Myrtillus* (−4 %) site types. Available P concentration has decreased by 10 % in both *Hepatica* and in *Oxalis* site types and has remained unchanged in the *Oxalis-Myrtillus* group. Available K has decreased more in the *Hepatica* (−33 %) and in the *Oxalis* (−34 %) than in the *Oxalis-Myrtillus* (−21 %) site type. The topsoil Corg concentrations decreased in both *Hepatica* (−18 %) and *Oxalis-Myrtillus* (−8 %) site types, while there was an increase by 18 % in the *Oxalis* site type. C:N ratio in the topsoil layer had slightly decreased in the *Oxalis-Myrtillus* (−5 %) and *Hepatica* (−12 %) site types. *Oxalis* site-type C:N ratio had increased from 11 to 14 (+27 %).

Discussion

Growth and yield of silver birch plantations

The growth and yield of the studied midterm SRF silver birch plantations on abandoned agricultural lands (AAL) are noticeably exceeding the values of the growth and yield tables (Henno 1980; Kiviste 1997) of fertile forestlands (*Oxalis* and *Oxalis-Myrtillus* sites) (Fig. 3). Official growth and yield tables for forestland silver birch stands in Estonia are more than 30 years old and rely on data from even earlier time, whereas a recent study in Estonian natural birch forests also showed their increased productivity compared to classical yield tables (Uri et al. 2012), which was partly attributed to climate change. Exceptionally fast growth of birch plantations, observed in the current study, could be explained by breeding activity (Koski and Rousi 2005; Ruotsalainen 2014), elevated atmospheric CO_2 concentration and extended growing season (Kellomäki et al. 1997; Linder et al. 2010), and long-lasting nutrient supply from previous agricultural land use (Wall and Hytönen 2005). This means that the growth and yield predictions of silver birch plantations on fertile AAL under changing climate conditions would likely be underestimated on the basis of birch growth on forestland, and future monitoring is needed. Growth simulation and economic analysis of silver birch plantations on AAL revealed that the financial maturity age could be around 34–45 years depending on site quality and management scenario (Tullus et al. 2012b). This is almost two times shorter than the legal rotation period for silver birch stands on forest land in Estonia, which depending on site quality varies between 60 and 70 years (Forest Act 2006). However, rotation length can be determined also on the basis of stem breast-height target diameter, which for birch at the best sites is 24–26 cm in Estonia. The growth characteristics of the studied silver birch plantations on AAL are also exceeding those from similar plantations in Sweden (Johansson 1999, 2007) and Finland (Saramäki and Hytönen 2004; Hytönen et al. 2014). More comparable results to our study can be found from Latvia, where mean height in 14-year-old silver birch plantations on well-drained mineral agricultural soils was 13.7 and 14.7 m, and volume was about 120–140 m^3 ha^{-1} (Liepiņš 2011).

Tree growth relations with physical properties of soil

Most of the soils in the current study are well drained and not influenced by ground water supply; therefore, their water conditions depend upon soil water-holding capacity that was estimated in the current study as available water content in soil (AWC). The high water-table level associated with the predomination of fine pores in the soil leads to potential risk of restricted aeration and reduced forest growth (Wall and Heiskanen 2003). In our selection, light-textured soils are prevailing (Table 1), where most of the soil water storage capacity is provided by organic matter. The influence of the organic matter is more pronounced regarding horizon depth, i.e. stock, than content, which was almost similar among soils.

We found that AWC is one of the most important growth factors in fast-growing silver birch plantations on previous mineral agricultural soils during the first 15 growing years. In the current study, the best height growth and yield was achieved in the *Oxalis-Myrtillus* site type, where AWC in all soil layers was higher compared to *Hepatica* and *Oxalis* site types (Fig. 4). This can be explained by higher Corg content and lower bulk density in *Oxalis-Myrtillus* soils compared to *Hepatica* and *Oxalis* soils, as AWC was calculated on the basis of bulk density. Poor growth of the trees in the *Hepatica* site type can be explained by poor soil water-holding capacity due to the large share of limestone rocks in the soil. In western part of Estonia, where most of Estonian *Hepatica* site types are located, droughts appear mostly in the first half of summer (Tammets and Jaagus 2013), thus in the time of vigorous tree growth. Often, early summer precipitation in Estonia does not contribute sufficient additions to soil water storage. In eastern Estonia (with *Oxalis-Myrtillus* prevalence), droughts are usually observed during the second half of summer, thus in time when the annual growth peak of trees has already passed. Pritchett and Fischer (1979) mentioned water usage of 75 000 litres per hectare by trees on sunny summer days, which means 7.5 mm per day. As the $AWC_{0–75\ cm}$ of the studied soils ranges between 116 and 180 mm (mean 159 mm), it means that without precipitation support, soil water reserves could be exhausted during 15–24 days. According to a recent overview (Tammets and Jaagus 2013), in the time period 1957–2009, the frequency of droughts has not changed, although two extremely dry years (2002, 2006) were placed at end of the data series. Our results showed that the influence of AWC on mean annual height and DBH increment was most important when AWC in the upper topsoil layer (0–25 cm) was considered, and this influence decreased in deeper soil layers. These results are logical because the amount of water retained in the soil depends primarily on pore size distribution, which, in turn, depends on textural layering and different morphological make-up (eluvial–illuvial) of studied soils. During early summer, transpiration leads to a decrease in soil water storage, first of all in the topsoil. Thus, the actual water content during summer is more variable in the topsoil than in the deeper soil layers. Our findings differ from the results recorded in fast-growing young hybrid aspen plantations on previous agricultural soils, where growth of the trees was more affected by water supply from deeper soil layers (Tullus et al. 2010). At the same time, water properties of deeper soil layers cannot be neglected as well in silver birch plantations, as $AWC_{0–75\ cm}$ also impacted the mean annual height increment of the medium and dominant trees. Thus, stronger trees exploited water from whole soil volume and developed more evenly distributed root system. However, the subsoil layer holds less water than the upper layers, but corrects gradual discordance caused from middle layer. Probably in drought periods, AWC in deeper and denser soil horizons (B-horizon) could be decisive for maintaining the productivity of the trees. Layering of coarse-textured soils can provide more AWC and support a higher maximum sustainable leaf area index than homogeneous soils of a similar texture (Huang et al. 2011).

Changes in the topsoil chemistry and tree growth relations with chemical properties of soil

Afforestation of AAL with birch seems to have significantly decreased the pH_{KCl} in the soil and noticeably in the transitional pH_{KCl} range, i.e. in slightly acid soils in the *Oxalis* site type. Acidification is quite common after arable soil afforestation for many tree species (Ritter et al. 2003; Vladychenskii et al. 2009; Uri et al. 2011; De Schrijver et al. 2012b). Optimum pH_{KCl} for birch is slightly acidic from 4 to 5 (Perala and Alm 1990) and for birch seedlings from 4.0 to 6.8 (Ingestad 1979). Almost all studied stands belong to the optimum range, except the neutral Hiiuma plantation (7.1) and the acidic Läänemaa plantation (3.7). The neutral pH_{KCl} level in the Hiiumaa plantation will probably remain in the future due to the thin topsoil above limestone parent material and the small dimensions of the trees, which are not able to alter soil conditions sufficiently. Soil pH_{KCl} level after afforestation is in the early stages more strongly influenced by the parent material of the soil than by tree species (Augusto et al. 1998). The primary explanation for the more rapid decrease of pH_{KCl} in the *Oxalis* site type could be liming during pervious agricultural activity, as most of the plantations in the *Oxalis* group are located in Southern Estonia, where soil pH_{KCl} level is naturally more acidic. The same tendency appeared also in afforested AAL on luvisolic soil types in Latvia, where pH_{KCl} decreases not only in the Ap soil horizon, but also in the deeper horizons and intensified podzolization (Nikodemus et al. 2013). It seems that a drop in pH_{KCl} is a natural process on previously limed agricultural soils where birch is forming a more optimal growth environment, and in the future, the pH_{KCl} level will probably stabilize. Nevertheless, birch is capable of growing in quite a wide pH_{KCl} range (Perala and Alm 1990; Ingestad 1979).

The negative impact of topsoil pH_{KCl} on growth was stronger in suppressed and medium trees. Suppressed trees are more sensitive to competition in the stand, and they are not able to adapt and spread their root system to obtain sufficient nutrition and water supply compared to dominant trees. As nutrient uptake depends on soil pH_{KCl} and root activity, a study in young birch stands on AAL reported that preferable soil pH_{KCl} for rhizosphere processes could be around 4.3 (Rosenvald et al. 2011).

The net nitrogen mineralization rate depends on the initial mineral N concentration and the C concentration, and the N and C cycles are strongly interrelated (Van Cleve et al. 1993; Vervaet et al. 2002). In our experiment, the total N varied from 0.07 to 0.25 %. The mean total N and organic C in the topsoil under silver birch plantations had not changed compared to the initial concentration. C:N ratio (mean = 13.0, range 9.3–17.6) in silver birch plantations is close to optimal N mineralization value and has remained at the same level compared with the initial status. Similar tendency was also observed in naturally regenerated birch stands on arable land in the taiga zone of the European part of Russia, where C:N ratios showed no alterations after 17 years from afforestation (Kalinina et al. 2013). The dissonance of the soil organic matter (SOM), or the C and N quantity produced, during 13 years in our study sites shows that SOM has not achieved an equilibrium level specific to the given soil type. Indirect evidence for transition stage is that continuous litter layer had not formed yet on the studied soils; however, there existed sporadic thin leaf litter layer, where about 1 ton of dry matter had accumulated per hectare (Tullus et al. 2013). In soils with high C:N ratios, any initial increase in microbial activity may become limited by nitrogen availability, whereas in soils with low C:N ratios, this does not occur (Persson et al. 1990; Nohrstedt 2001). The previous findings about the influence of birches on organic matter mineralization are controversial. Birches can increase biological activity in acid forest soils, especially in the uppermost 10 cm of soil under the litter (Priha and Smolander 1997; Vervaet et al. 2002). In a laboratory experiment, Saetre (1998) found that although the rate of C mineralization in soil from a birch stand was higher than that of an adjacent Norway spruce stand, this did not result in a higher rate of N mineralization in the birch soil. Afforestation of AAL within the temperate region may induce soil C loss during the first decades, followed by a recovery phase of yet unknown duration (Bárcena et al. 2014). After 15 years of tree growth, we can conclude that the afforested AAL soils were still more similar to arable than to pristine forest soils with respect to total N (Wall and Hytönen 2005).

During the first 15 years of growth, we did not notice significant changes in mean extractable P. Previous agricultural land fertilization has increased P pools in the topsoil, and P is quite stable and long lasting (McLauchlan 2006). The mean degree of phosphorus saturation in the upper soil layers of agricultural and similar type soils was approximately twice as high as that of deciduous forest soils at corresponding depths (Rubæk et al. 2013). Kahle et al. (2007) reported a decrease in P in poplar and willow SRF plantations on AAL from the 6th to the 12th growing year. According to the Latvian experience, afforestation of AAL affects the migration of total P, resulting in diminishing total P in the topsoil and an increase in P in the deeper Bt horizon of *Luvisols* and *Albeluvisols* (Nikodemus et al. 2013). Bioavailability of P depends on soil pH_{KCl} (Hinsinger 2001), and in agricultural land use, it is improved with liming to bring it into the range of 6 to 7. A decrease of pH_{KCl} after afforestation could mean that available P is converted into other P fractions that are not directly available to trees (De Schrijver et al. 2012a). Birch is considered to be quite sensitive to soil P (Perala and Alm 1990), and therefore, future monitoring is needed to analyse P concentration changes and possible impact on growth, even though the concentrations of P in the studied plantations are close to average or higher than the P concentrations of fertile agricultural lands in Estonia. So far, availability of P has not been a limiting factor for silver birch growth on previous agricultural soils; however, a positive relation between the growth rate of suppressed trees and the concentration of P in the B-horizon was found, indicating that under competitive stress, P availability had started to limit growth.

Concentration of available K decreased significantly, by about 30 % in silver birch plantations in this study. However, we did not find significant relations between growth traits and K, and we could conclude that plant supply of K is still sufficient to secure productivity. Kahle et al. (2007) reported a decrease in available K concentrations in SRF poplar and willow plantations on arable soils from the 6th to the 12th growing year. Previous agricultural lands are usually K rich, but afforestation could decrease K concentration in the long run (Wall and Hytönen 2005). Obviously, a certain amount of K was relocated into the trees' biomass, whereas in 27-year-old stands on AAL in NE Sweden, from among five different tree species, birches accumulated the highest amounts of Mg, K, P and N in their stems (Alriksson and Eriksson 1998).

Management implications

Our result that dominant trees are more affected by AWC in soil could just indicate to their larger water consumption. At the same time, Otto et al. (2014) observed that despite higher water uptake, dominant trees in a *Eucalyptus* plantation had higher water-use efficiency compared to smaller trees of the same clone and suggest that manipulating with stand density, i.e. thinnings could increase resource-use efficiency and growth potential.

Thinnings are a silvicultural treatment to change forest structure and redistribute available resources, including soil water (Jiménez et al. 2008). Bréda et al. (1995) studied individual tree water balance and growth in a *Quercus petraea* stand after thinning treatment and found that thinning increased water availability and that dominant trees benefited more from thinning than other trees in the stand. The positive effect of thinnings on tree growth could be especially high during dry years, when the improved water condition after thinning can maintain transpiration (Lagergren et al. 2008; Sohn et al. 2013; Otto et al. 2014). Climate models for Estonia generally predict an increase in precipitation, especially during winter time, but in some cases, precipitation could decrease during the mid-summers (Jaagus and Mändla 2014) and drought could suppress tree growth. Drought risk is higher on sandy soils, but this is offset by the fact that sandy soils will warm up earlier in the spring, providing a growth advantage due to the longer vegetation period. We should also consider the fact that birches are using water inefficiently (Perala and Alm 1990), and birch transpiration rates are higher than those of other commercial tree species in the boreal region (Grossiord et al. 2013).

Although plantation density (transformed into sparsity index in statistical analyses to linearize its effect) had not started to affect mean annual growth and current annual increment of dominant and medium trees, its negative effect was already observed on the current annual increment of suppressed trees. This indicates the need for thinning in these stands for competitive release of faster-growing trees and is in agreement with their basal area (Table 1), which exceeds lower thinning limits of natural birch forests in

Estonia. In Estonia, traditional silver birch silvicultural treatments have been developed for naturally regenerated birch stands, which have high number of trees at an early age and where self-thinning is usually taking place. We suggest that traditional birch forest silviculture systems are not directly transferable to high productivity silver birch plantations on AAL in Estonia where thinnings should be more intensive at an early age. For example, yield tables for silver birch plantations in Finland suggest that stand density should be less than 1400 trees per ha at the age of 15 years (Oikarinen 1983), while in the current study, the average density was about 1700 trees ha^{-1} (Table 1). In order to maintain dominant and medium trees' productivity, as well as stand productivity in the studied young silver birch plantations, it is important to apply early and rather strong pre-commercial thinning where, in the first order, suppressed trees are harvested in order to redistribute available resources for more efficient use.

After the end of the 15th growing season, we can conclude that generally SRF silver birch plantations have not depleted total N and available P concentration in previous agricultural soils. Available K concentration has decreased, but K pools are still high and previous agricultural soils provide sufficient supply for fast growth of silver birch. So far, the studied plantations do not need additional fertilization. In the longer term, there could be a need for K fertilization in order to ensure high productivity in the next forest generations. At the same time, to avoid fertilizing costs and possible environmental damage, logging residuals such as twigs and branches should be left on site to decompose, at the same time enhancing biodiversity.

Conclusions

The growth and yield of midterm silver birch SRF plantations on previous agricultural soils is exceeding local birch yield table values for the best forest soil about twofold in hemiboreal Estonia. The highest productivity was achieved in *Oxalis* and in *Oxalis-Myrtillus* site types, which we consider to be the best sites for establishing intensively managed plantation with silver birch. The most decisive factor for silver birch plantation growth rate in the first 15 years after establishment was available water content in the upper layer (0–25 cm) of previous mineral agricultural soils. The dominant trees were more affected by soil water availability than suppressed and medium trees, and thus, thinnings are needed to secure plantation productivity. The topsoil pH_{KCl} has become significantly more acidic after 13 years of afforestation with silver birch, but growth rate was generally faster in more acidic soils within our study range (A-horizon pH_{KCl} 3.7–7.1). The concentrations of total N and available P had remained at the same level, and the concentration of available K had decreased significantly. At the same time, the concentrations of macronutrients were not limiting the growth rate of the birches. Regarding nutrients, the effect of previous agricultural land-use practice on fast-growing silver birch plantations was still evident and the need for fertilization had not emerged in the middle of the commercial rotation period. Repeated soil and growth monitoring in the future is necessary to draw conclusions based on the entire rotation period.

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