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TREE GROWTH AND THE FACTORS AFFECTING IT IN YOUNG HYBRID ASPEN PLANTATIONS

PUUDE KASV JA SEDA MÕJUTAVAD TEGURID NOORTES HÜBRIIDHAAVAISTANDIKES

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following papers, which are referred to by the Roman numerals in the text. The papers are reproduced with the kind permission of the publishers.

I **Tullus, A.**, Tullus, H., Vares, A., Kanal, A. 2007. Early growth of hybrid aspen (*Populus* x *wettsteinii* Hämet-Ahti) plantations on former agricultural lands in Estonia. Forest Ecology and Management, 245, 118–129.

II **Tullus, A.**, Kanal, A., Soo, T., Tullus, H. 2010. The impact of available water content in previous agricultural soils on tree growth and nutritional status in young hybrid aspen plantations in Estonia. Plant and Soil, doi.: 10.1007/s11104-010-0330-5.

III **Tullus, A.**, Tullus, H., Soo, T., Pärn, L. 2009. Above-ground biomass characteristics of young hybrid aspen (*Populus tremula* L. x *P. tremuloides* Michx.) plantations on former agricultural land in Estonia. Biomass and Bioenergy, 33, 1617–1625.

IV **Tullus, A.**, Soo, T., Tullus, H., Vares, A., Kanal, A., Roosaluste, E. 2008. Early growth and floristic diversity of hybrid aspen (*Populus* x *wettsteinii* Hämet-Ahti) plantations on a reclaimed opencast oil shale quarry in North-East Estonia. Oil Shale, 25, 57–73.

The contributions from the authors to the papers were as follows:

	I	II	III	IV
Original idea	All	AT, AK	AT, HT	All
Study design	All	AT, AK	AT, HT	All
Data collection	AT, AV, AK	AT, AK, TS	AT, TS, LP	AT, TS, ER, AV, AK
Data analysis	AT	AT	AT	AT, TS, ER
Preparation of the manuscript	All	AT, AK, HT	AT	All

AV – Aivo Vares, AK – Arno Kanal, AT – Arvo Tullus, ER – Elle Roosaluste, HT – Hardi Tullus, LP – Linnar Pärn, TS – Tea Soo, All – all authors of the paper

ABBREVIATIONS

ALB	Above-ground leafless biomass
AWC	Available water content in soil
BA	Basal area of the plantation
H	Tree height
HLC	Height of the beginning of the living crown
DBH	Diameter of the stem at breast height
DC	Diameter of the tree crown
DM	Dry matter
LWA	Leaf dry weight per area
SRF	Short-rotation forestry
Z	Height increment of the tree

1. INTRODUCTION

For hemiboreal Estonia, with forest cover of 50.6% (Yearbook Forest, 2009), short-rotation plantation forestry (SRF) is a new silvicultural concept that has received more attention during the last two decades for several reasons. Firstly, the demand for industrial timber, including wood fibres for pulp and paper, has been rising almost continuously (FAOSTAT, 2010) and forest plantations provide an opportunity to reduce the timber harvest from natural forests. Secondly, due to political, economic and social changes, one third of the arable land in Estonia was abandoned at the beginning of 1990s (Peterson and Aunap, 1998) and the decrease in the area of arable land has also continued in the 21st century (Astover *et al.*, 2006). Establishment of SRF plantations is one alternative land use for these areas. Thirdly, being a member of European Union, Estonia has to follow EU energy policy and raise the share of energy from renewable sources to 20% by 2020 (DIRECTIVE 2009/28/EC); woody biomass from SRF plantations is an option for reaching that goal.

A suitable tree species for SRF in a boreal climate should combine fast growth with frost hardiness. At an early age, deciduous trees tend to exceed conifers in biomass productivity in the boreal region; in particular poplars, aspens and willows are considered the most suitable species for SRF here (Karacic *et al.*, 2003; Weih, 2004). Among them, a hybrid between *Populus tremula* L. and *P. tremuloides* Michx., known as hybrid aspen, has proved to be one of the fastest growing deciduous trees in the region. In Estonia more than 700 ha of hybrid aspen plantations have been established since 1999, mostly on abandoned agricultural lands but also for the reclamation of an exhausted oil shale quarry (**I**; **IV**). In 2004 hybrid aspen was included in the list of exotic tree species that may legally be grown on forest land in Estonia (Eestis metsapuudena…, 2004). However, considering the possible environmental impacts of monospecific plantations with exotic tree species, cultivation of hybrid aspen is not recommended on traditional forest lands in Estonia (Tullus, 2005a).

Hybrid aspen is a new deciduous tree for Estonian forestry and experience from other countries also barely extends over half a century. Its growth, productivity and site preferences have mainly been studied in small-scale experimental plantations, whereas knowledge from large-scale commercial plantations is scanty. Besides this, it is difficult to predict how previous agricultural soils will meet the site requirements of aspens, which are known as nutrient and water demanding trees. The large area of abandoned agricultural lands comprises a variety of soil types and for the optimization of the outcome of possible afforestation, soil-crop suitability analysis is crucial (Kukk *et al.*, 2010). Although a large share of abandoned agricultural lands comprise of less fertile soil types (Astover *et al.*, 2006), which are generally not recommended for SRF, fertile sites have also been abandoned. Due to long-term tillage and fertilization the physico-chemical properties of field soils are somewhat different from the equivalent forest soils. Cultivation creates a sharp plough layer boundary between the top- and subsoil, decreases organic matter content and degrades soil structure, and some compaction problems can even occur on fields. After more than 30 years of tree growth, the soil humus horizon properties can still be more similar to arable soil than to pristine forest soil with respect to organic carbon and phosphorus content (De Keersmaeker *et al.*, 2004; Smal and Olszewska, 2008). In general, previous agricultural land use increases soil fertility and the impact of previous use is long lasting (Wall and Heiskanen, 2003; Wall and Hytönen, 2005).

In addition to abandoned agricultural lands, in the north-eastern part of Estonia underground and surface mining of oil shale has degraded large areas. Estonian opencast oil shale quarries are usually reclaimed as forest lands, a few areas also as agricultural lands. Most of the reclaimed areas have been afforested with Scots pine (*Pinus sylvestris* L.) due to its successful establishment and adaptation under harsh conditions (Kaar, 2002). On the other hand it can be argued that large monocultural pine stands present a high fire hazard and they are threatened by pests. The wider use of deciduous trees is recommended for such areas, but knowledge about the adaptation of different deciduous tree species under such extreme conditions is still patchy.

An important issue in SRF systems is nutrient removal from the ecosystem with the harvested biomass, especially when successive rotations are very short, and the consequent need for fertilization (Heilman and Norby, 1998; Weih, 2004; Dickmann, 2006). Nutrient concentrations in biomass as well as allocation and calorific value of biomass are important characteristics of SRF crops and may vary significantly between different species, rotation length and aims of the plantations. For example, bark content in biomass is important for woody energy production, and the share of branches and stems, for bigger dimensional assortments.

In order to evaluate the growth and suitability of hybrid aspen in Estonian conditions and to investigate ecological and silvicultural aspects of hybrid aspen plantations on abandoned agricultural sites, a long-term research program has been initiated. The current thesis will summarise the preliminary results of this program, with the main emphasis on site–growth relations at an early age (five to seven years). Although this constitutes less than one third of the predicted rotation period, knowledge about site properties that help trees overcome planting stress more quickly and in which the hybrid vigour is expressed sooner could be decisive in short-rotation aspen plantations. The plantations established with less optimal site conditions could eventually catch up in annual productivity, but the total yield will be higher in those where early growth acceleration has been more rapid.

2. REVIEW OF THE LITERATURE

2.1. Biology of hybrid aspen

The parental species of hybrid aspen are *Populus tremula* L. (known as common, European or Eurasian aspen) and *P. tremuloides* Michx. (quaking or trembling aspen). They both belong to the family Salicaceae, genus *Populus* (divided into 6 sections), section *Populus* (formerly *Leuce*, aspens and white poplars). Both species have large natural distribution ranges, *P. tremula* being one of the most widely distributed trees in the world and *P. tremuloides* being the most widely distributed tree species indigenous to North America (Dickmann and Kuzovkina, 2008). *P. tremula* and *P. tremuloides* are dioecious, usually medium-sized trees, however they may reach 35–40 m in height and 1 m in DBH, or they can be rather small-dimensioned in stressful sites. They are both economically important tree species, being at the same time genetically very variable with several geographic races and forms, offering diverse material for breeding and selection. They are disturbance-adapted species – often principal colonisers of areas after fire or clear cutting, either by seeding or root suckering. *P. tremula* is the only endemic *Populus* sp native to Estonia. The share of forest land area with *P. tremula* as the dominant tree species is 5.3%. As a typical tree in mixed stands on fertile site types, it constitutes 7.4% of the growing stock of Estonian forests (Yearbook Forest, 2009).

An artificial cross between *P. tremula* L. and *P. tremuloides* Michx., known as hybrid aspen (*Populus* × *wettsteinii* Hämet-Ahti), was first described at the beginning of the 1920s in Germany (Wettstein, 1933). Hybrid aspen is capable of growing faster in dimensions and shows higher biomass productivity than its parent species during the first 20–30 years, as confirmed in several experimental and commercial plantations in Scandinavia (Langhammer, 1976; Yu, 2001; Rytter and Stener, 2005; Heräjärvi and Junkkonen, 2006; Rytter, 2006), Central Europe (Janson, 1977; Melchior, 1985; Tiefenbacher, 1991; Liesebach *et al.*, 1999) and North-America (Zsuffa, 1976; Li *et al.*, 1993). Presumably hybrid aspen exceeds its parental species in growth rate due to the phenomenon of heterosis. There are two leading hypotheses to explain the genetic basis of heterosis: dominance and overdominance. Li and Wu (1996) have found that in the case of aspen hybrids heterosis might be due to an overdominance interaction between two alleles, one from the

P. tremuloides parent and the other from the *P. tremula* parent, at the same loci. At the same time the fast growth of hybrid aspen in northerly regions (e.g. in Finland) is partly related to its longer growing season compared to local aspen, which is adapted to shorter growing seasons (Yu *et al.*, 2001c). Such an effect is stronger when parent(s) of the hybrid originate from southerly parts of the distribution range compared to the location where the hybrid is cultivated. However, too southerly origin of the parent(s) may lead to frost damage when the growing season starts too early in spring and lasts too long in autumn (Christersson, 1996; Yu *et al.*, 2001c). Regarding physiological traits that could help to explain the hybrid vigour, it has been observed that hybrid aspen has stomata with larger guard cells, but a lower stomatal density than *P. tremula* (Yu, 2001), and higher leaf-level photosynthesis intensity (Šilina, 2006). In general, significant variability in growth, phenology, physiology and phytochemistry has been observed among hybrid aspen clones (Yu, 2001; Yu *et al.*, 2001b, 2001c; Rytter and Stener, 2003; Yu and Pulkkinen, 2003; Häikiö *et al.*, 2007; Häikiö *et al.*, 2009; Tullus *et al.*, 2010).

2.2. Management and purposes of hybrid aspen plantations

Hybrid aspen plantation is established with plants belonging to previously selected clones that have been commercially propagated using micropropagation or from root cuttings (Stenvall *et al.*, 2004, 2005, 2006). In Scandinavia the planting density has usually been 1100–1600 plants ha^{-1} (Rytter and Stener, 2005), usually site preparation is done and chemical or mechanical weed control during the first year(s) is advisable.

Hybrid aspen can be managed in short rotations of 20–30 years for the production of pulpwood (Figure 1; Hynynen and Karlsson, 2002; Hynynen *et al.*, 2004). Even shorter rotations are suggested for the successive vegetatively regenerating hybrid aspen stands for the production of biofuels (Liesebach *et al.*, 1999; Rytter, 2006). Due to larger stand density and already existing root system from previous generation, the yield of the root sucker generation is presumably higher compared to the first planted generation (Figure 1). The mean annual biomass increment of regenerating hybrid aspen stands may reach 7.9–9.5 t DM ha^{-1} yr^{-1} (Liesebach *et al.*, 1999; Karacic *et al.*, 2003; Rytter, 2006). A silvicultural concept that combines early harvests of root suckers with conventional forestry is proposed for hybrid aspen in later generations (thinnings in Figure 1). The large early biomass quantities could be exploited by corridor cleaning and used as biofuels, while the remaining stand could be managed with ordinary forestry practices to produce pulpwood and logs (Rytter, 2006).

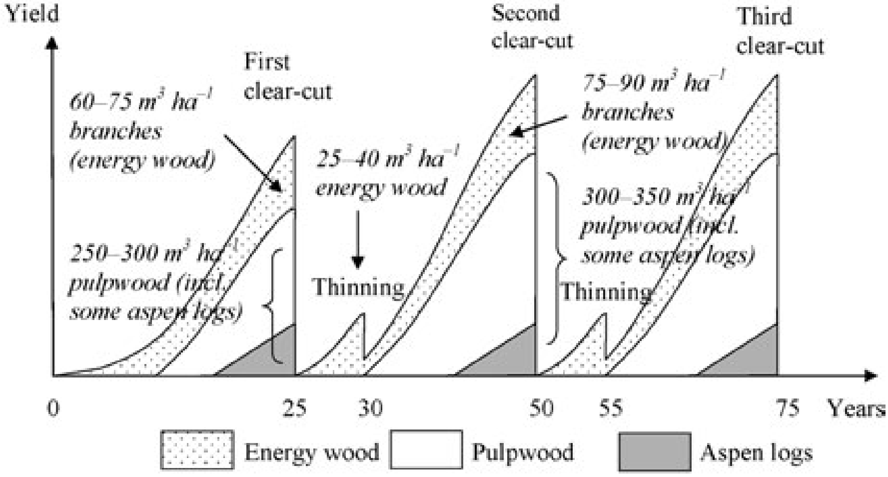

Figure 1. Theoretical management scheme for a hybrid aspen plantation

The aim of short-rotation aspen plantations has changed during the past 50–60 years from producing raw material for the match industry to supplying pulp and paper mills, with the most recent emphasis on biofuel production (Christersson, 1996; Beuker, 2000; Rytter, 2006). Since the end of the 1980ies aspen wood has been an important raw material for the pulp and paper industry. The wood of hybrid aspen is low in lignin and high in carbohydrates (Tullus *et al.*, 2010) and its wood is amenable to many kinds of chemical or mechanical pulping (Macleod, 1987; Karl, 1988; Yu *et al.*, 2001a; Yu *et al.*, 2001b). Aspen has thin-walled fibres of narrow diameter which are ideal for producing a high-density paper sheet with a smooth surface (Karl, 1988; Dhak *et al.*, 1997). The white-coloured aspen wood bleaches easily, reducing the use of chemicals and making the production of aspen pulp less harmful to the environment.

The results from a Lusatian lignite mining region in Germany have indicated 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 post-mining landscapes (Bungart and Hüttl, 2001). Hybrid poplars have been found to have good potential for reforestation of reclaimed surface mined lands also in the Appalachian coal producing region in the USA (Casselman *et al.*, 2006).

2.3. Site requirements of SRF plantations with *Populus* species

A few studies have previously addressed site–growth relations of hybrid aspen in small experimental plantations (e.g. Yu and Pulkkinen, 2003; Table 1). Almost no studies have been conducted in large-scale commercial plantations covering several tens of hectares. Thus hereinafter the overview of site–growth relations relies mainly on the studies with parental species of hybrid aspen and poplars in general.

Aspens are known as fast-growing light-demanding trees preferring fertile sites, well-drained and aerated nutrient-rich soils with a medium texture (sandy loam or loamy sand) derived from base-rich parent material, whereas soils that are saturated and water-logged during the growing season and soils with heavy texture are considered less favourable (Laas, 1987; Perala, 1977; Stanturf *et al.*, 2001; Chen *et al.*, 2002). Aspen has been found to have a certain thermophilic preference in boreal climate. Canadian studies have established that the most productive growth occurred at lower elevations and warm-aspect slopes in the boreal white and black spruce zone (Chen *et al.*, 2002), and that a low mean growing season temperature resulted in overall poor growth of *P. tremuloides* (Landhäusser and Lieffers, 1998).

Soil N is the most important nutrient in the boreal and hemiboreal forests. In addition, aspen communities appear to be more dependent upon N and other organically bound nutrients than coniferous stands (Strong and La Roi, 1985). Results from North-America and Canada have shown that the annual N demand of fast-growing poplars and their hybrids is much greater compared to other endemic deciduous and coniferous trees (Stanturf *et al.*, 2001). At the same time many poplar species do not respond to N additions unless accompanied by additions of P, K, or other nutrients (Blackmon, 1976). The positive effect of P-fertilization on the growth performance of hybrid aspen seedlings has been noted in Canada (Liang and Chang, 2004). In addition, Zn and lime can be beneficial for the fast growth of poplar (Heilman and Xie, 1993). According to Stanturf *et al.* (2001) poplars prefer pH levels of 6.0–6.5, but they grow well between 5.5 and 7.5.

2.4. Research needs

The main objective of the current study was to develop a better understanding of some of the ecological and silvicultural aspects of hybrid aspen – a new deciduous tree for Estonian forestry and a relatively new deciduous tree in the forestry practice of the countries within the distribution ranges of *P. tremula* and *P. tremuloides*. A selection of recent publications (published after 1995) in peer-reviewed scientific journals dealing with hybrid aspen is given in Table 1. Hybrid aspen has provided versatile study material for the researchers. In Table 1 studies related to forestry and silviculture are listed, but hybrid aspen has been used also as a model species to study more fundamental issues of tree genetics (e.g. Fladung *et al.*, 2010) and physiology (e.g. Häikiö *et al.*, 2009; Rasulov *et al.*, 2009). Recent forestry-related studies have frequently focused on clonal differences, propagation methods and some silvicultural aspects of hybrid aspen. Usually the studies are based on small-scale experimental plantations, which have provided adequate data for answering the questions raised.

However, in order for hybrid aspen to become an economically important tree for the production of pulpwood or energy wood, commercial hybrid aspen plantations covering large areas need to be established. Thus more studies about the site preferences of hybrid aspen would be useful for providing recommendations for successful establishment of large-scale plantations in the region. For SRF plantations it has commonly been found that growth and production data from small-scale experimental plots tends to overestimate the respective productivity figures (Dickmann, 2006).

While planning the current study, the existing commercial plantations were deliberately selected for establishing the network of experimental plots instead of creating a series of small study plots on various soil types. This caused some reservations in the design of the experiment but was aimed at providing more realistic results for silvicultural interpretations.

As mentioned in the Introduction, the relations between the properties of abandoned agricultural soils and the growth of the trees in SRF plantations in boreal and hemiboreal conditions have been little studied. The current study was planned also to provide new knowledge about these issues.

Table 1. Main topics of a selection of recent (published after 1995) publications related to hybrid aspen in peer-reviewed journals

Main topic of the study (source)
Hybrid aspen and hybrid poplars in Sweden (Christersson, 1996)
Heterosis and genotype–environment effect (Li and Wu, 1997)
Genetic and physiological basis of heterosis (Li *et al.*, 1998)
Comparison with other deciduous stands on agricultural land (Telenius, 1999)
Effects of spacing and rotation period (Liesebach *et al.*, 1999)
Aspen breeding in Finland (Beuker, 2000)
Afforestation of mining landscapes (Bungart and Hüttl, 2001)
Physiological and anatomical characters for selecting clones (Yu, 2001)
Rooting of stem cuttings (Yu *et al.*, 2001a)
Genetic control of wood physichochemical properties, growth and phenology of clones (Yu *et al.*, 2001b)
Growth and phenology of clones (Yu *et al.*, 2001c)
Occurrence of *Neofabraea populi* (Kasanen *et al.*, 2002)
Nutrient content in stems, nutrient removal with harvest (Rytter, 2002)
Genotype–environment effect on growth of clones (Yu and Pulkkinen, 2003)
Clonal variation in nutrient content in biomass (Rytter and Stener, 2003)
Effect of P and S fertilization on growth and nutrient uptake (Liang and Chang, 2004)
Propagation of hybrid aspen using root cuttings (Stenvall *et al.*, 2004)
Productivity and thinning effects (Rytter and Stener, 2005)
Propagation of hybrid aspen using root cuttings (Stenvall *et al.*, 2005)
Combined management regime (Rytter, 2006)
Propagation of hybrid aspen using root cuttings (Stenvall *et al.*, 2006)
Impacts of elevated ozone and N on growth and photosynthesis (Häikiö *et al.*, 2007)
Influence of pruning on wood characters (Rytter and Jansson, 2009)
Effect of site preparation method and previous land use on understorey vegetation diversity (Soo *et al.*, 2009a)
Comparison of floristic diversity with silver birch plantations (Soo *et al.*, 2009b)
Cellulose and lignin content in stemwood (Tullus *et al.*, 2010)

3. AIMS OF THE STUDY

The main hypotheses of the study were:

1) hybrid aspen is a suitable deciduous tree for establishing SRF plantations on abandoned agricultural lands in Estonian climate and soil conditions (**I–IV**);
2) hydrophysical soil properties are significant growth factors for young hybrid aspens on abandoned agricultural lands where soil nutrient stocks are generally high (**I**; **II**).

The specific aims of the study were:

1) to estimate the growth and productivity of young hybrid aspen plantations (**I–IV**);
2) to study the effect of physical and chemical properties of former agricultural soils on the growth and foliar nutrient concentrations of hybrid aspen (**I**; **II**);
3) to determine the production, allocation, concentration of major mineral nutrients and calorific value of above-ground leafless biomass in 7-yr-old hybrid aspen plantations (**III**);
4) to study the suitability of hybrid aspen for afforestation of exhausted opencast oil shale quarries (**IV**);
5) to improve knowledge about site–growth relations in SRF plantations with hybrid aspen and provide practical recommendations for site selection (**I–IV**).

4. MATERIALS AND METHODS

4.1. Study area

4.1.1. Climate and soil conditions

The study area lies in the hemiboreal (boreo-nemoral) forest zone. The mean annual temperature during the studied period (1999–2006) was 6.1 ± 0.86 °C; mean annual precipitation was 630 ± 30.5 mm (**II**). The mean precipitation during the growing season (April–October) was 409 ± 31.1 mm. The study period includes two dry years: 2002 (precipitation during the growing season: 274 mm) and 2006 (310 mm, Figure 2 in **II**).

Most of the studied hybrid aspen plantations (n = 16) are situated in the south and south-eastern part of Estonia (Figure 2), where soils have developed on reddish till on Devonian sands and clays. The dominating soils in this region are *Albeluvisols*, *Luvisols* and *Planosols*, one plantation lies within the region of eroded soils of Haanja upland. Five plantations are situated in the central part of Estonia, where soils have developed on calcareous till on Silurian limestone. In this region the typical soils are *Cambisols* and *Luvisols*. Three plantations on abandoned agricultural lands are situated in North Estonia, where soils have developed on stony calcareous till on Ordovician limestone. In this region typical soils are *Leptosols* and *Calcaric Cambisols*. The study also includes two hybrid aspen plantations established for the reclamation of Aidu opencast oil shale quarry in North Estonia (**IV**). The first plantation had been established directly on levelled quarry spoil (*Calcaric Regosol*). The other plantation lies on a part of the quarry that had been reclaimed as agricultural land i.e. after levelling of the quarry spoil it was covered with the previously removed *Calcaric Cambisol* topsoil.

The regional distribution of the studied plantations was affected by the overall distribution of hybrid aspen plantations in Estonia. More plantations have been established in the south and south-eastern parts of the country, since there is a higher than average share of abandoned agricultural lands (Astover *et al.*, 2006) comprising soil types that were considered to be suitable for high hybrid aspen productivity (Reisner, 2001). All the studied plantations on abandoned agricultural lands were established by one private forest enterprise (AS Metsind) as a pilot project to introduce hybrid aspen in Estonian conditions. Thus a variety of soil types were selected for afforestation in order to acquire knowledge about site preferences of hybrid aspen in Estonia (Reisner, 2001).

4.1.2. Studied plantations and experimental plots

The study comprises 24 commercial hybrid aspen (*Populus* x *wettsteinii* Hämet-Ahti = *P. tremula* L. x *P. tremuloides* Michx.) plantations on previous agricultural lands and two plantations on the reclaimed Aidu oil shale quarry (Figure 2; Table 2). These plantations were established in springs 1999 and 2000. One-year-old micropropagated hybrid aspens belonging to 27 clones were used as planting material, on average 15 different clones per plantation. Plants of different clones were planted randomly. Planting material originated from Finland. According to the Finnish Plant Production Inspection Centre, these clones are marked from C05-99-8 to C05-99-34 (Tullus, 2005b). The origin of the material can be traced back to the 1950s, when a large number of aspen hybrid families were produced from crosses between female *P. tremula* in Finland and male *P. tremuloides* in Canada and the northern part of the USA (Yu and Pulkkinen, 2003).

The average spacing has been 2–2.5 x 3–3.5 m and planting density has varied in the range of 1200–1600 trees ha^{-1}. In the observed plantations the average planting density was 1300 trees ha^{-1}. In all plantations, 0.3–0.6 m photodegradable plastic protectors or 1.1 m net-like shelters have been used to prevent damage by rodents, hares (*Lepus* sp) and roe-deer (*Capreolus capreolus* L.). None of the studied plantations have been fenced.

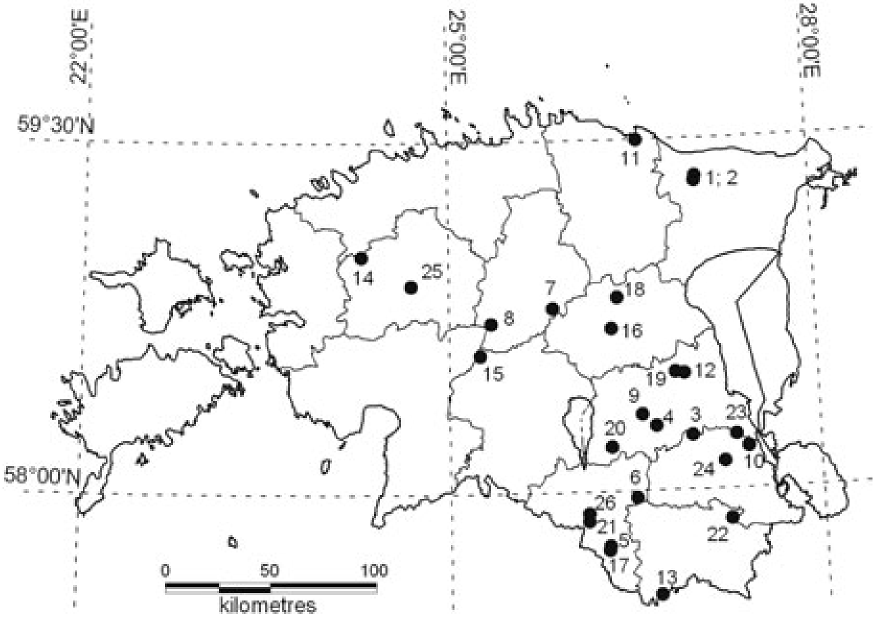

Figure 2. Locations of the studied hybrid aspen plantations (n = 26), the numbers are consistent with Table 2.

From 2003 to 2004 a network of 58 permanent experimental plots was created for studying and monitoring the growth performance of hybrid aspen in Estonia at various site conditions (Figure 2, Table 2). In each plantation one to five experimental plots were established. The number of experimental plots depended on the size of the plantations and the expected variability in soil conditions. The plots were located in typical parts of the microrelief of the respective plantation or part of the plantation. Most of the plots are circular plots with an area of 0.1 ha. In the oil shale quarry the size of the plots is 0.05 ha.

Table 2. Locations of the studied plantations and number of experimental plots

No	Plantation ID (real estate name)	Year of establishment	Location	Plots
1	Aidu quarry I	2000	59°20´N; 27°03´E	3
2	Aidu quarry II	2000	59°19´N; 27°03´E	4
3	Ahjametsa	1999	58°13´N; 26°57´E	1
4	Hannu	2000	58°16´N; 26°40´E	2
5	Jaaska	1999	57°46´N; 26°15´E	2
6	Kauru	1999	57°58´N; 26°29´E	1
7	Koogi	1999	58°47´N; 25°51´E	1
8	Laada/Muruoja	2000	58°43´N; 25°20´E	5
9	Laaska	2000	58°19´N; 26°33´E	3
10	Maltsi	2000	58°10´N; 27°24´E	3
11	Mikkeri	1999	59°29´N; 26°34´E	1
12	Mägra	2000	58°30´N; 26°54´E	2
13	Nakri	2000	57°33´N; 26°39´E	1
14	Niidu	1999	59°00´N; 24°16´E	1
15	Nässu	1999	58°35´N; 25°14´E	1
16	Oja	2000	58°41´N; 26°19´E	1
17	Orandu	1999	57°45´N; 26°15´E	2
18	Otsa	2000	58°49´N; 26°22´E	1
19	Pikste	2000	58°30´N; 26°50´E	2
20	Põhja	2000	58°11´N; 26°18´E	3
21	Reku	2000	57°52´N; 26°06´E	3
22	Rusima	2000	57°52´N; 27°14´E	2
23	Sikka	1999	58°13´N; 27°18´E	5
24	Sikuti	1999/2000	58°07´N; 27°12´E	4
25	Sõeru	2000	58°53´N; 24°41´E	2
26	Uniküla	1999	57°54´N; 26°06´E	2
	Total			58

4.2. Studied characteristics

4.2.1. Tree growth

In all experimental plots the following dimensions of the above-ground part of the trees were measured at the ages of five (**I; IV**) and seven years (**II; III**): tree height (*H*, ±0.1 m), diameter of the stem at breast height (DBH, ±0.1 cm), height increment of the current year (*Z*, ±0.1m), height of the beginning of the live crown (HLC, ±0.1m), diameter of the tree crown (DC, ±0.1 m). Basal area (BA, m^2 ha^{-1}) was estimated as the cross-sectional area (over the bark) at breast height. For characterizing the growth of the trees in each plot, arithmetic mean values of the respective characteristics were used. Eleven plots were re-measured at the age of nine years (Jänes, 2009; Tullus *et al.*, 2009). Within six plots the trees were numbered in order to study their individual development depending on the clone and site properties; in these plots trees have been measured annually. The growth data from plantations older than seven years is briefly used in the overview part of the current thesis for characterizing the growth development of hybrid aspen plantations. Site–growth relations are based on measurements in five- and seven-year-old plantations (**I–IV**).

4.2.2. Productivity

In order to estimate the above-ground leafless biomass (ALB) production of the studied hybrid aspen plantations, model trees were analysed at the ages of seven (**III**) and nine years (Jänes, 2009). The model trees were fractionated (current-year top of the stem, current-year shoots, older branches, stemwood, stembark) and subsamples were taken for the analysis of dry matter content, biomass allocation, nutrient content and calorific value. The respective methodology is described in detail in paper **III**. To estimate the above-ground biomass of the growing trees in relation to DBH, the power function was used, while it has proved to give the best fit for the mentioned allometric relation (Johansson, 1999a, 1999b).

$$\mathrm{ALB} = b_0 \times \mathrm{DBH}^{b_1}$$

where ALB = above-ground leafless biomass of the tree or tree component,

b_0 and b_1 are parameter estimates, and DBH is diameter of the stem at breast height. A measure of the fit of the nonlinear regression was based on the coefficient of determination: $R^2 = 1 - (\mathrm{SSE}/\mathrm{SStotal\ (corrected)})$. Parameter estimates for seven- and nine-years-old hybrid aspens are provided in Table 3; these estimates were used in order to calculate ALB development from the age of five to seven and eight to ten years respectively.

Table 3. Parameters of the biomass equation, based on model trees taken from seven- and nine-years old hybrid aspen plantations

Age	Parameter	Parameter estimate	R^2	p
7 (**III**)[a]	b_0	107.7192	0.989	<0.001
	b_1	2.2371		
9 (Jänes, 2009)[b]	b_0	0.0525	0.998	<0.001
	b_1	2.5548		

[a] output in g; [b] output in kg

In order to estimate the stem volume of the studied plantations, the allometric equation suggested for hybrid aspens (Rytter and Stener, 2005) was used.

4.2.3. Leaf properties

In order to evaluate the nutritional status of the trees, foliar concentrations of major mineral nutrients (NPK) were analysed in the middle of the fifth (**I; IV**) and the seventh (**II**) growing seasons. The leaves were taken from the middle part of the canopy (fifth growing season) or from the lower border of the upper third of the canopy (seventh growing season) from 6 to 10 sample trees from each plot according to the distribution of the breast height diameters of all the trees. Leaves were dried with a desiccator (Memmert 100-800) at 70 °C to constant weight before measurement. Single leaf blade area was measured with WinFOLIA ver. 5.0a (Regent Instruments Inc.) software and leaves were weighed with equipment KERN EW 150-3M to the nearest 0.001 g. On the basis of single leaf area (cm^2) and weight (g), leaf weight per area (LWA, $\mathrm{g\ m}^{-2}$) was derived.

4.2.4. Soil properties

Soil pits were dug in the centre of each experimental plot. Soil type was estimated according to the World reference base for soil resources (WRB, 2006). As commercial plantation sites were not randomly, rather to some extent pre-selectively established, soil types were not evenly presented. For statistical analyses a certain soil-based generalization had to be made in order to make the variability of soil properties within a group smaller than that within the whole soil range. The soils were grouped according to drainage (depending on their position on the relief and the depth of occurrence and intensity of gley features in the soil profile) as follows: well-drained mineral soils, as automorphic; soils with redoximorphic (*stagnic*) properties in subsoil, as semi-hydromorphic, and mineral soils developed under the influence of a high ground-water table, as hydromorphic (reductomorphic) soils. Such grouping was based on the catena concept, according to which up-slope soils are usually well-drained and oxidized while soils at the base of the slope, at least seasonally, are poorly drained and reduced. The degree of gleyzation governs several inherent soil properties and conditions (aeration, temperature, redox potential, biological activity). Hydromorphic soils had been drained for agriculture and therefore could have a better aeration status than indicated by their drainage class, but generally they still preserved their impeded drainage.

Volumetric proportion of fine earth and rock fragments was estimated for each soil horizon on the field. Soil texture of each pit was determined per horizon by the combined sieve and pipette method (USDA, 1996).

In order to determine pH_{KCl}, total N, available P and available K in the soil humus horizon, samples were taken from four random locations in each experimental plot. Chemical analyses were conducted on air-dried samples from which crop residues, root fragments and gravel larger than 2 mm had been removed. The total N in soil samples was determined by the Kjeldahl procedure. To analyse available P and K in the soil, Mehlich 3 extracant was used. The soil pH in 1M KCl suspensions was measured in the ratio 10 g : 25 ml. For each experimental plot, the mean of the four subsamples was calculated. Organic carbon was determined by wet oxidation in H_2SO_4 solution, where $K_2Cr_2O_7$ is used as an oxidant according to Tyurin (1935). Analyses were performed by the Laboratory of Agrochemistry of the Agricultural Research Centre in Saku [/http://pmk.agri.ee]. Soil nutrient concentrations were converted to nutrient stocks (contents by soil volume and bulk density, **II; III**).

For bulk density (BD, g cm^{-3}), triplicate undisturbed core samples with a 50 cm^3 steel cylinder were taken from the middle of demarcated horizon boundaries. Field sampling was done at neither too dry nor wet conditions; very clayey or organic soils capable of expansive volume change were not included in the selection. Samples were dried at 105 °C for 24 hours. Net wet and dry weights were recorded to the nearest 0.01 g and bulk density was measured as dry mass per 50 cm^3 volume. Specific surface area (SSA, m^2 g^{-1}) 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, mm, **III**) in master soil horizons was estimated according to Kitse (1978) as a function of soil specific surface area and bulk density and corrected with the concentration of gravel and stones. AWC was defined as volumetric difference between field capacity and wilting point i.e. between those water potentials. The lower limit was a constant –1500 kPa for all soils, but the upper limit varied according to soil texture: –10 kPa for sandy soils and –33 kPa for loams and clay loams.

The quality of the studied soils, based on soil crop productivity, was assessed according to the methodology by the Estonian Land Board (Maade tootlikkuse…, 1992).

4.3. Chemical analysis of the plant samples

The concentrations of major mineral nutrients (NPK) in the tree leaves (**I; II; IV**) and ALB fractions (**III**) were determined. The concentration of total N in plant samples was determined by standard Kjeldahl procedure using a Kjeltec Auto 1030 Analyzer (FOSS Tecator AB, Höganäs, Sweden); P was determined spectrophotometrically from Kjeldahl digest using a FIAstar 5000 Analyzer (FOSS Tecator AB, Höganäs, Sweden). Concentration of K was determined flamephotometrically. For determination of calorific values (kJ g^{-1}) of ALB fractions (**III**), the sub-samples were analysed using adiabatic measurement mode with the IKA calorimeter system C 5003 control. In order to evaluate the energetic values of hybrid aspen plantations the dry masses of tree compartments were multiplied with the respective calorific values.

The analyses of NPK and calorific values were performed in the Laboratory of Biochemistry and the Laboratory of Wood Properties of the Estonian University of Life Sciences.

4.4. Statistical analysis

Descriptive statistics, simple regression coefficients and the respective p values were calculated with STATISTICA 7 (StatSoft, Inc., 2004). Normality of the studied variables was checked with the Shapiro-Wilk test; if necessary, log-transformation of the variables was used. Coefficient of variation (Cv, **I**) was derived as follows: Cv (%) = standard deviation / arithmetic mean * 100 %. One-way ANOVA was used to test the significance of differences between group means of growth traits, and foliar and soil properties. Tukey HSD (**I; III; IV**) and Fisher LSD (**II**) multiple comparison tests were applied to determine the significant differences between group means after one-way ANOVA. Distance weighted least squares fitting procedure was used for smoothing the distribution curves of tree height (**I; IV**). Parameter estimates for the biomass equations (**III**) were obtained with proc NLIN using SAS for Windows 9.1.3 (SAS Institute, 2002/2004). The mean values are followed by ± 1 standard error of the estimate in the text. Level of significance $\alpha = 0.05$ was applied in all cases.

5. RESULTS

5.1. Growth and productivity

The growth of hybrid aspens showed high variability during the first decade (**I–IV**, Table 4, Figure 3). The coefficient of variation of plot mean tree heights was 35% at the age of five years (Table 1 in **I**) and 31% at the age of seven years. The maximum and minimum plot mean height differed more than five times at the age of seven years (Table 4). The considerable increase in growth development in most of the plantations occurred after the first five to seven years (Figure 3). The average survivability after the fifth growing season was 81% (**I**) and 80% after the seventh growing season. However, severe damage by browsing (mostly by small rodents, roe-deer and hares) had occurred on 10% of the plots on abandoned agricultural lands by the age of seven years. Considerable moose browsing started to occur on stands surrounded by large natural forests after the age of nine years.

Table 4. Average growth characteristics ± standard error (range) of hybrid aspen plantations in Estonia

Growth characteristic	Plantation age			
	5	7	9	10
Plots	51	45	11	5
H (m)	2.7 ± 0.13 (1.1–4.7)	4.5 ± 0.22 (1.5–8.0)	9.5 ± 0.37 (7.6–11.6)	11.4 ± 0.75 (9.0–13.0)
Z (m)	0.7 ± 0.04 (0.2–1.4)	1.0 ± 0.05 (0.2–1.9)	1.8 ± 0.12 (1.4–2.2)	1.7 ± 0.11 (1.4–1.9)
DBH (cm)	1.6 ± 0.14 (0.1–3.9)	3.8 ± 0.22 (1.0–7.0)	8.6 ± 0.35 (7.1–10.5)	10.0 ± 0.49 (8.7–11.1)
HLC (m)	0.6 ± 0.02 (0.3–0.9)	0.7 ± 0.03 (0.4–1.2)	n.m.[a]	2.0 ± 0.27 (1.2–2.6)
DC (m)	1.2 ± 0.06 (0.3–2.1)	1.7 ± 0.07 (0.5–2.6)	n.m.	n.m.
BA (m^2 ha^{-1})	0.3 ± 0.05 (max = 1.5)	1.6 ± 0.19 (max = 5.3)	7.2 ± 0.71 (4.5–11.2)	10.6 ± 1.21 (6.7–13.7)
Stem volume (m^3 ha^{-1})	1.4 ± 0.14 (0.4–4.9)	5.5 ± 0.75 (0.5–22.8)	36.7 ± 4.66 (19.0–64.8)	62.6 ± 9.95 (31.6–87.1)
ALB (t DM ha^{-1})	0.6 ± 0.10 (max = 3.0)	3.2 ± 0.41 (max = 11.8)	17.3 ± 2.04 (9.7–28.4)	27.7 ± 3.76 (15.9–37.5)

[a] n.m. – not measured

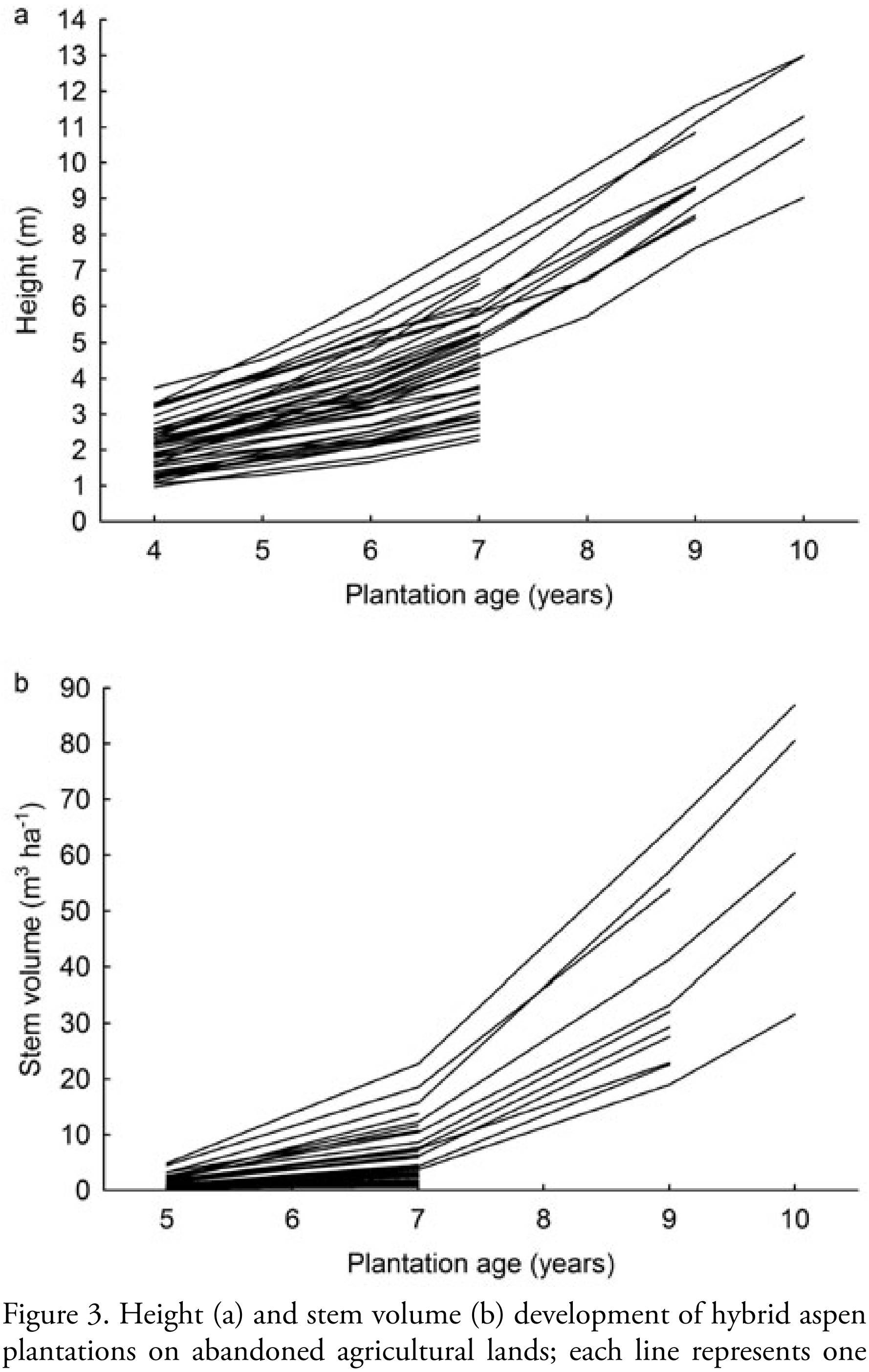

Figure 3. Height (a) and stem volume (b) development of hybrid aspen plantations on abandoned agricultural lands; each line represents one experimental plot

The height increment of the fifth growing season depended more on the size the tree had achieved during the previous growth period than on the plantation growth class (Figure 4a; **I**). Thus it was concluded that the preliminary ranking of plantations and sites by growth speed could change during the development of the plantation, when other growth factors that had been less influential during the first years after planting may become more decisive (**I**). At the age of seven years a similar approach showed that the highest trees in the shortest plantations (3rd growth class in Figure 4b) no longer grew as fast as the trees of the same height but growing in plantations belonging to better growth classes.

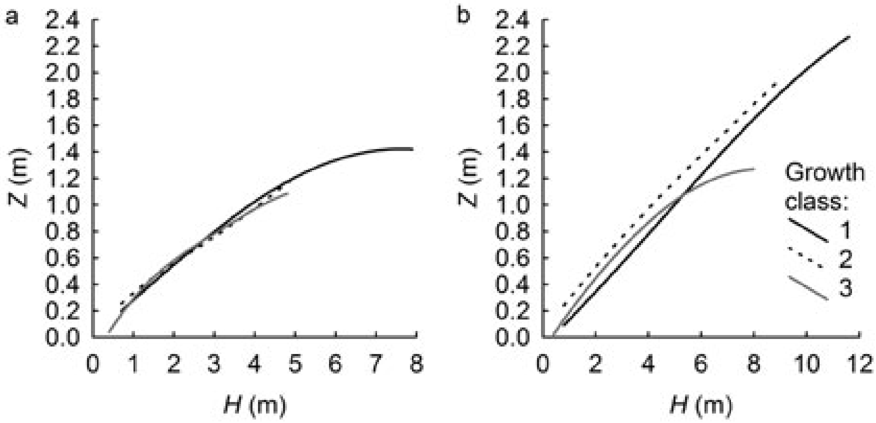

Figure 4. Relation curves between height increment (*Z*) and height (*H*) of individual trees in three plantation growth classes (class 1: the highest, class 3: the shortest plantations) at the ages of a) five (**I**) and b) seven years

The ranking of 45 plots by mean tree height was compared between the ages of five and seven years. The change in plot ranks varied from –8 to +11. The ranking showed the greatest improvement in plantations established on *Luvisols* and *Cambisols* and decreased most considerably in plantations on *Gleysols* (see Figure 11b in the Discussion). The change in ranking was significantly related to available water content in 75 cm soil layer ($r = 0.30$; $p = 0.05$), especially on automorphic soils ($r = 0.49$; $p = 0.03$).

5.2. Biomass characteristics (III)

The mean dry matter content in the above-ground part of the winter-cut hybrid aspen model trees was 46 ± 0.3%, varying significantly between tree compartments following the sequence stembark ≥ current-year shoots ≥ old branches > stemwood (Table 4 in **III**). The highest share of above-ground biomass (73 ± 0.9%) was contained in stems, followed by branches (18 ± 0.8%) and current-year shoots (9 ± 0.5%). The share of stembark from the total stem biomass, excluding the top shoot, was significantly related to the DBH of the model tree (Figure 5).

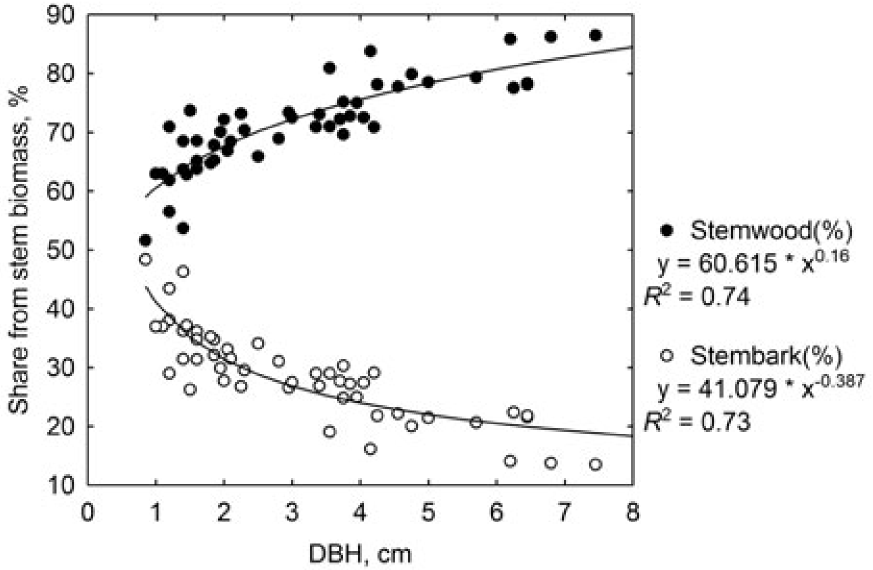

Figure 5. Regression lines between wood and bark content in the stem and diameter of the stem at breast height (DBH) of the biomass model trees (**III**)

The amount of N accumulated in the ALB of 7-yr-old plantations varied between 14.4 and 48.5 kg ha^{-1} (5.62–6.62 kg t^{-1} DM) the amount of P, between 1.7 and 5.9 kg ha^{-1} (0.70–0.77 kg t^{-1} DM), and the amount of K, between 6.5 and 21.9 kg ha^{-1} (2.58–3.00 kg t^{-1} DM). The average N:P:K ratio in the ALB was 100:12:45. The removal of major mineral nutrients from the site with the removal of woody biomass in 7-yr-old plantations would be relatively small, constituting 0.5–3.4% of the nutrient stock in the soil humus horizon (**III**).

More than half of the energetic value of ALB in 7-yr-old hybrid aspen plantations was accumulated in the stemwood, followed by branches and stembark (Table 5 in **III**). The calorific values differed significantly between tree compartments, following the sequence: current-year shoots ≥ stembark ≥ old branches > stemwood (Table 8 in **III**).

5.3. Foliar properties (I; II)

The foliar nutrient concentrations and single leaf area increased with age (Table 5). Foliar N concentration was significantly correlated with tree height (**I; II**). At the age of five years the regression between foliar N and *H* was linear (**I**) and it became curvilinear at the age of seven years (**II**), allowing the sufficient and insufficient level of foliar N for fast growth of hybrid aspen in Estonia to be estimated (Figure 6).

Table 5. Foliar characteristics of 5- and 7-yr-old hybrid aspens

Foliar characteristic	Plantation age	
	5	7
N concentration (%)	2.2 ± 0.04 a[a]	2.5 ± 0.04 b
P concentration (%)	0.20 ± 0.010 a	0.24 ± 0.007 b
K concentration (%)	0.76 ± 0.046 a	0.79 ± 0.020 a
Area (cm^2)	19.3 ± 0.95 a	24.8 ± 0.86 b
Weight (g)	0.19 ± 0.010 a	0.21 ± 0.007 a
LWA ($g\ m^{-2}$)	98.2 ± 1.08 b	85.9 ± 0.92 a

[a] letters denote statistically significant differences in foliar characteristics between the ages of five and seven years

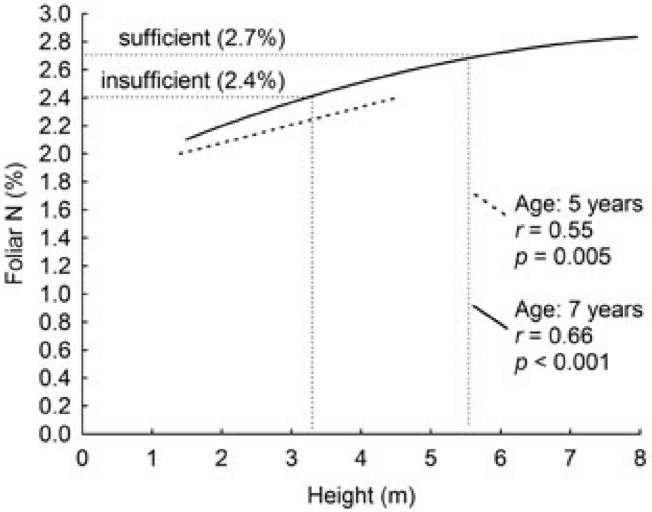

Figure 6. The relationships between foliar N and mean tree height in hybrid aspen plantations at the ages of five (**I**) and seven years (**II**)

The average foliar N:P:K ratio was 100N:9P:30K. The results concerning sufficiency ranges of foliar N and P were comparable to other studies with hybrid aspen (Table 5 in **II**). However, foliar K was close to or below the lower limit of the sufficiency range suggested by other authors. Foliar K was related to extractable K in the soil, although neither tree growth nor foliar N:K ratio were related to K content in the soil (Table 2 in **II**).

5.4. Relations between tree growth and soil properties (I; II)

The growth traits of the trees were significantly related to soil physical and chemical properties (Table 6). The growth had been faster on loamy sand or sandy loam textured soils and slower on clay loams (Table 3 in **I**).

The growth rate of young hybrid aspens was significantly related to available water content (AWC) in the topsoil, and the relations were stronger on well-drained automorphic soils and in the case of a dry growing season with insufficient precipitation (**II**). AWC in the topmost 25 cm soil layer did not vary considerably in former field soils; the distinction of sites by AWC and tree growth was more pronounced in deeper soil layers (Figure 7). The relationships between tree growth and $AWC_{0–75\ cm}$ suggested that the sufficient $AWC_{0–75\ cm}$ level would be 154 mm (20.5 vol. %) for all studied soil groups and 157 mm (20.9 vol. %)

for automorphic soils; the insufficient $AWC_{0–75\ cm}$ levels would be 138 mm (18.4 vol. %) and 121 mm (16.1 vol. %) respectively (Figure 8).

Table 6. Correlations between mean tree height and soil variables in hybrid aspen plantations at the ages of five (**I**) and seven (**II**) years, significant relations are marked as follows: $0.1 > p > 0.05^{(*)}$, $0.05 > p > 0.01^{*}$, $0.01 > p > 0.001^{**}$, $p < 0.001^{***}$

Soil variable	Age	Soil classification			
		All soils	Automorphic	Semi-hydromorphic	Hydromorphic
Depth	5	**0.41****	**0.57****	0.26	**0.84****
	7	**0.34***	**0.54***	0.18	**0.72**$^{(*)}$
pH	5	**–0.40****	**–0.57****	**–0.51***	0.45
	7	**–0.50*****	**–0.65****	**–0.45**$^{(*)}$	0.31
C stock	5	0.15	0.30	0.10	–0.48
	7	0.12	0.23	0.09	–0.46
N stock	5	0.09	0.18	0.13	–0.51
	7	0.07	0.12	0.06	–0.37
P stock	5	**0.39****	**0.50***	0.15	**0.88****
	7	**0.33***	**0.46***	0.14	**0.90****
K stock	5	0.12	**0.34**$^{(*)}$	0.04	–0.22
	7	0.13	0.31	0.09	–0.19
Bulk density	5	0.08	–0.18	0.30	0.29
	7	0.00	–0.13	0.20	–0.23
SSA	5	**–0.29***	–0.31	–0.34	–0.43
	7	**–0.33***	**–0.43**$^{(*)}$	–0.09	–0.43
Clay	5	**–0.39****	**–0.44***	–0.37	**–0.66**$^{(*)}$
	7	**–0.43****	**–0.53***	–0.29	–0.47
Sand	5	**0.25**$^{(*)}$	0.11	0.18	**0.64**$^{(*)}$
	7	0.14	0.12	–0.04	0.60
Gravel	5	**–0.28**$^{(*)}$	–0.32	**–0.45**$^{(*)}$	–0.36
	7	**–0.31***	**–0.39**$^{(*)}$	–0.17	–0.28
$AWC_{0–75\ cm}$	5	**0.34***	**0.49***	0.05	**0.78***
	7	**0.44****	**0.62****	0.00	**0.75**$^{(*)}$
$AWC_{0–25\ cm}$	5	0.19	0.31	–0.06	0.65
	7	0.24	**0.36**$^{(*)}$	–0.07	0.59
$AWC_{25–50\ cm}$	5	**0.29***	**0.38**$^{(*)}$	0.08	**0.82***
	7	**0.36***	**0.49***	0.08	**0.81***
$AWC_{50–75\ cm}$	5	**0.41****	**0.56****	0.15	0.50
	7	**0.53*****	**0.71*****	0.17	0.49

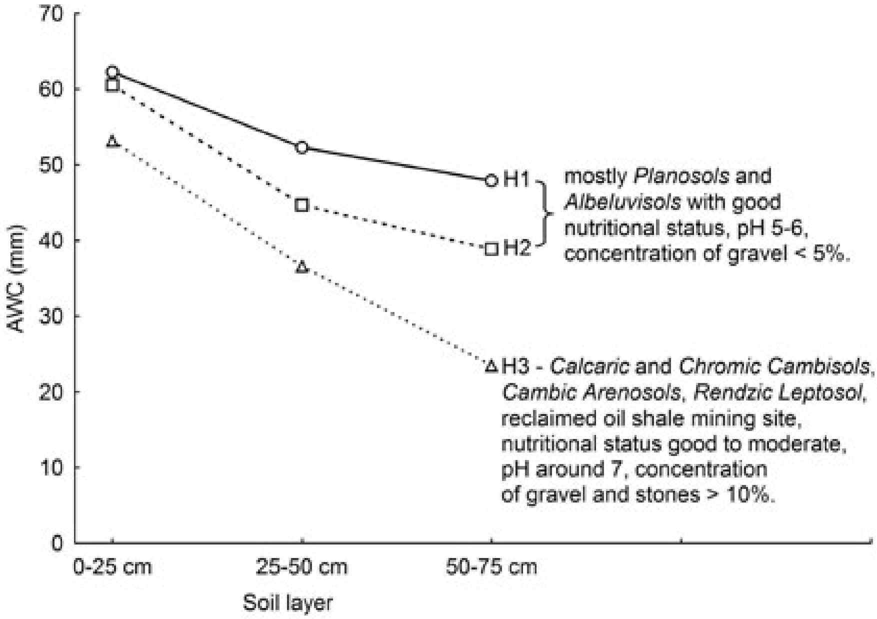

Figure 7. The mean AWC by soil depths in plots grouped according to mean tree height (H1–good growth, H > 5 m; H2–moderate growth, H= 3–5 m; H3–poor growth, H < 3 m; 7 plots in each group) on automorphic soils (**II**)

Throughout the study the sites were grouped into three drainage classes following the hydrocatena concept. Based on the results (**I; II**), mainly due to the high variability of soil types within the automorphic soils group, a more detailed classification involving at least four drainage classes would be beneficial for general site assessment (Figure 9). The final decision on site quality should be based, however, on exact soil type (please see Figure 11 in the Discussion).

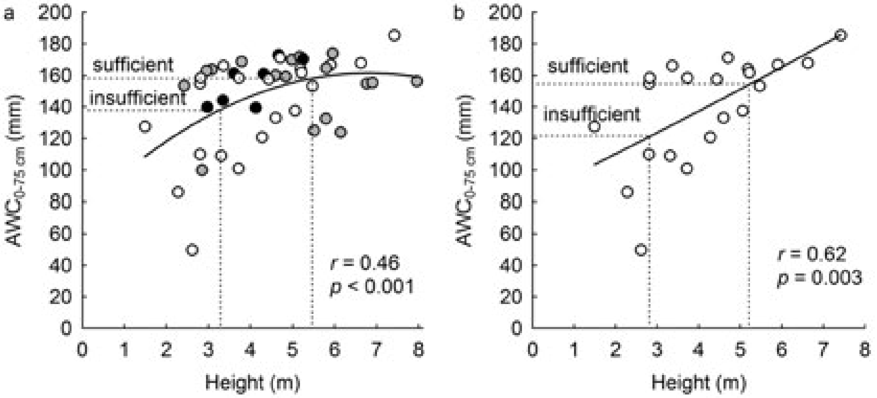

Figure 8. The relationships between AWC$_{0–75\ \text{cm}}$ and mean height of hybrid aspens including a) all studied soil moisture groups: automorphic (empty circles), semi-hydromorphic (grey circles) and hydromorphic (black circles) soils, and b) including only automorphic soils (**II**)

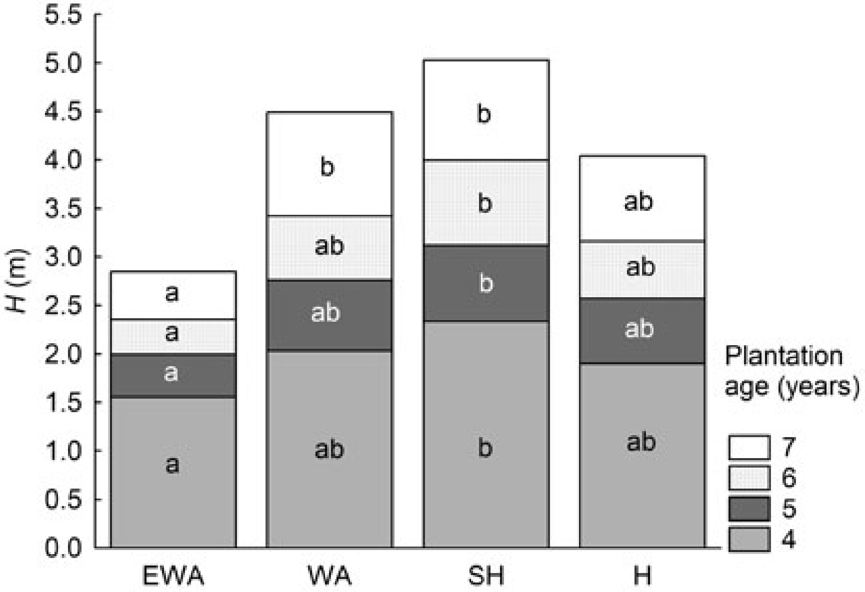

Figure 9. The height development of hybrid aspen plantations at various soil drainage classes (EWA: excessively well-drained automorphic, WA: well-drained automorphic, SH: semi-hydromorphic, H: hydromorphic soils), letters denote significant differences in group means at the same age

The comparison of the mean growth rate of the trees in plantations established on different soil types suggested that early growth has been faster on moderately drained *Albeluvisols*, *Luvisols* and *Planosols* (Table 2 in **I**; Table 1 in **II**). In traditional forestry these soils correspond to *Oxalis* and *Oxalis-Myrtillus* site types (please see Figure 11 in the Discussion). The early growth of hybrid aspens was slow on part of *Cambisols*, *Leptosols* and *Gleysols*, which correspond to excessively well-drained or temporarily water-logged sites. (Figure 11).

The average soil quality, based on soil crop productivity, was 53 ± 1.7 points (21–67 points); it was similar in all moisture groups. Soil quality was significantly correlated with the mean height of hybrid aspen plantations at the age of 7 years ($r = 0.44$; $p = 0.005$); the relationship was stronger in the automorphic soils group ($r = 0.70$; $p < 0.001$). Soil quality was significantly related to AWC in 75 cm soil layer ($r = 0.54$; $p < 0.001$, automorphic soils: $r = 0.69$; $p = 0.001$), A-horizon texture: gravel ($r = -0.49$; $p = 0.002$), sand ($r = -0.47$; $p = 0.003$) and silt ($r = 0.57$; $p < 0.001$) and chemical properties: pH ($r = -0.36$; $p = 0.002$), N stock ($r = 0.36$; $p = 0.02$) and C stock ($r = 0.42$; $p = 0.008$).

5.5. Hybrid aspen on an exhausted oil shale quarry (IV)

Trees had grown significantly faster during the first five years in the former quarry site where levelled spoil had been covered with removed topsoil compared to the plantation that had been established directly on levelled quarry spoil (Table 2 in **IV**). The growth rate of hybrid aspens in the quarry site covered with previously removed soil has been comparable with the results from former arable land on similar soil in the same region.

Regarding topsoil properties, bare quarry spoil was low in N and P and had a high pH level (Figure 2 in **IV**). The quarry site with restored topsoil had higher nutrient concentrations but was still low in plant-available water (**II; IV**). The unfavourable soil properties were reflected also in significantly lower foliar concentrations of nutrients in quarry sites compared to plantations on abandoned agricultural lands (Figure 3 in **IV**).

6. DISCUSSION

6.1. Early growth of hybrid aspen

The current study analysed the growth of hybrid aspens during the first five to seven years (**I–IV**); the growth development of the trees has been measured up to the age of 10 years (Figure 3). This constitutes less than half of the predicted rotation period of 25 years. Thus final conclusions about the growth and suitability of hybrid aspen for Estonian conditions cannot be drawn here. However, the early growth speed of hybrid aspen in Estonia can be compared to a) growth data from countries with longer experience with hybrid aspen, b) growth data about local fast-growing deciduous stands and plantations of the same age (Figure 10).

Due to the relatively low density of the studied hybrid aspen plantations (on average 1042 ha^{-1}), their superiority in growth rate over domestic fast-growing deciduous tree species was not revealed yet in total yield per hectare. At the age of 10 years, the average stem volume of hybrid aspen plantations was estimated at 63 m^3 ha^{-1}, reaching 87 m^3 ha^{-1} (Figure 3; Table 4). This is comparable to silver birch plantations of the same age but with 2129 trees ha^{-1}, where 49 m^3 ha^{-1} up to 77 m^3 ha^{-1} has been recorded (Jänes, 2009; Tullus *et al.*, 2009), although the average dimensions of the birches were considerably smaller (Figure 10). In a grey alder plantation with 7400 trees ha^{-1}, the stem volume at the age of 10 years was approximately 99 m^3 ha^{-1} (Uri *et al.*, 2009) and in natural *P. tremula* stands on the best sites, approximately 63 m^3 ha^{-1} with 4750 live trees ha^{-1} has been estimated (Krigul, 1971).

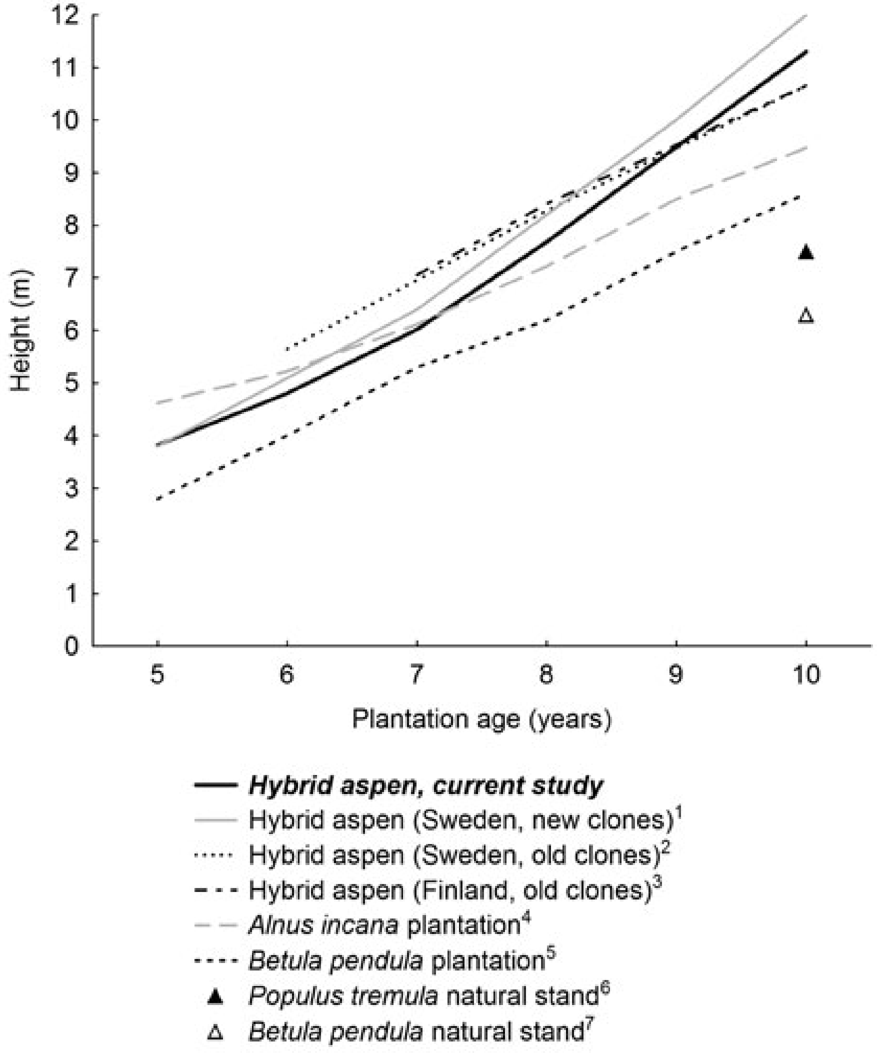

Figure 10. Height development of young fast-growing deciduous stands with hybrid aspen ([1]Rytter and Stener, 2005; [2]Johnsson, 1976; [3]Hynynen and Karlsson, 2002), *Alnus incana* ([4]Uri *et al.*, 2009), *Betula pendula* ([5]Jänes, 2009; [6]Krigul, 1971) and *Populus tremula* ([6]Krigul, 1971)

In Sweden in a 10-yr-old hybrid aspen plantation the mean annual increment of stem volume has been estimated to be around 7 m^3 ha^{-1} yr^{-1} (total yield 70 m^3 ha^{-1} yr^{-1}) reaching 10 m^3 ha^{-1} yr^{-1} (total 100 m^3 ha^{-1} yr^{-1}) (Rytter and Stener, 2005). In general the growth development of hybrid aspen in Estonian plantations during the first decade has been roughly comparable to other regions where hybrid aspen is cultivated (Figure 10), although the mean production figures could be slightly lower. A possible reason for this is that the planting material that has been used in Estonian plantations originates from Finland, i.e. hybrid aspen clones that have been selected for Finnish conditions have been planted in Estonia. At the same time, in Finland and Sweden planting material that has been selected for these particular regions has been mainly used. The clones that were used in the studied plantations were selected from crossings made in 1950s (Yu and Pulkkinen, 2003). New clones with increased productivity rates have been selected meanwhile in Scandinavia (Rytter and Stener, 2005). It must also be considered that the annual mean temperature has increased during the second half of the 20th century by 1.0–1.7 °C and climatic spring has begun almost one day earlier every year (Jaagus, 2006). New clones that are better adapted to these changes could have even faster growth in our latitudes.

The mean dry matter (DM) content in ALB was 46% (**III**), which is in accordance with other studies with winter-cut model trees (Liesebach *et al.*, 1999; Christersson, 2008). The average share of current-year shoots and branches in the total ALB was 26.8±0.89%, being slightly higher than the 23–24% reported in other studies (Johansson, 1999a; Telenius, 1999). Calorific values of hybrid aspen stemwood (19.33±0.05 kJ g^{-1}) and stembark (19.98±0.10 kJ g^{-1}) are comparable with the results in a 35-yr-old natural *P. tremula* stand, where a calorific value of 19.38±0.05 kJ g^{-1} has been estimated for stemwood and 20.22±0.13 kJ g^{-1} for stembark (Lõhmus *et al.*, 2000). The concentration and content of three major mineral nutrients (N, P, K) were studied in different above-ground parts of 7-yr-old hybrid aspens. They are all known as seasonally mobile elements in biomass, which are retranslocated during the summer from the foliage to other parts of the tree, where they are stored during winter (Pregitzer *et al.*, 1990; Dickmann *et al.*, 2001; Kauter *et al.*, 2003). In 7-yr-old plantations 36–41% of nutrients accumulated in ALB were located in the current-year shoots and old branches (Figure 5 in **III**), which agrees with a previous study in young hybrid aspen stands, where nutrient removal in branches was 50% or more of the removal in stems, although this share will decrease in older stands (Rytter, 2002). The lowest concentrations and contents of NPK were estimated for stemwood (Table 6 and Figure 5 in **III**). The nutrient contents in dry biomass (Table 5 in **III**) were in a comparable range with the respective values in a young silver birch stand (Uri *et al.*, 2007). Thus there is no difference in the potential nutrient removal with harvested biomass between these two fast-growing deciduous trees that are both recommended for afforestation of abandoned agricultural land.

Due to extreme substrate conditions, the growth of the trees had been expectedly slow on levelled quarry spoil (**IV**). However, trees in the quarry site with restored topsoil had shown similar growth speed with plantations on abandoned agricultural lands in the same region. In general these soils were not the most promising for hybrid aspen (**II**).

6.2. Relations between tree growth and soil properties

The relations between hybrid aspen growth and soil properties were studied in five- (**I**) and seven-yr-old (**II**) plantations. In general the relations, especially regarding hydro-physical soil properties, became stronger with increasing age (Table 6). Probably during the first years after establishment the growth of the trees is still strongly dependent on several other factors, e.g. quality of planting material and planting, competition with weeds and weather during the first growing seasons, rather than directly on soil properties. The analysis of height increment of trees belonging to different plantation growth classes also suggested that the differentiation of the plantations by growth speed was not directly related to soil properties at the age of 5 years (Figure 4). By the age of 7 years the growth class with the shortest plantations had more clearly separated from the other growth classes. The changes in ranking of the plots by growth speed during a short time interval (from 5 to 7 years) confirmed that the results about soil preferences based on young plantations should be handled cautiously while making final conclusions about the most suitable soils for hybrid aspen.

Based on the results (**I; II**), automorphic and semi-hydromorphic soils that have a more clayey subsoil overlain by porous and somewhat lighter texture humus horizons (e.g. *Albeluvisols*, *Luvisols* and *Planosols*) could be more suitable for fast aspen growth. Such a two-layered texture profile could be caused by the process of till ablation and also illuvation during soil development. It means that nutrient acquisition conditions for the tree roots within the same soil type or soil group could be strongly influenced by changes in sand and clay concentrations along the soil profile. Lower-lying soil horizons of *Luvisols, Albeluvisols* and *Planosols* are more clayey, less leached and therefore consist of more bases. Base rich parent material favoured trembling aspen growth in Canada (Chen *et al.*, 2002). A sharp decrease in the hydraulic conductivity of the B-horizons caused the temporary appearance of perched water, its rise toward the surface, and the presence of the capillary fringe above the free gravitational water table. Thus a short-term surplus of water might rather be an advantage than a disadvantage for hybrid aspen.

Soil texture had a significant influence on growth rate of trees. In general, fast growth was observed on loamy sands and sandy loams; clay loams were less favourable (**I**), which agrees with other studies with aspens and poplars (Stanturf *et al.*, 2001). The concentrations of gravel and clay negatively affected the growth rate; the concentration of sand showed positive correlation with growth (Table 6). Good growth on sandy soils and warm-aspect slopes confirms the thermophilic preference of aspen (Chen *et al.*, 2002). Sandy soils warm up earlier in spring, which should favour the adaptation of hybrid aspen to longer growing seasons (Yu *et al.*, 2001c). However, this could become a serious disadvantage in dry growing seasons. It partly explains the slower early growth of hybrid aspen on hydromorphic soils, which warm up later in spring delaying the start of the growing season. The fastest growth on hydromorphic soils was observed when the concentration of sand increased in lower soil layers, offering a natural drainage system (**I**).

Soil available water content (AWC) was significantly related to tree growth (**II**), which is in accordance with other studies (Dietz and Weigelt, 1987; Sampson and Allen, 1999; Wall and Heiskanen 2003, 2009). Although indirectly estimated AWC could involve some multicollinearity with soil organic matter and nutrient content, it could be a significant indicator for assessing the suitability of abandoned agricultural lands for afforestation. AWC in deeper soil layers (25–50 and 50–75 cm) showed stronger and more significant relations with tree growth, confirming the importance of deeper soil layers for water and nutrient uptake of the trees (Göransson *et al.*, 2006). The importance of AWC in lower soil layers indicates also the potential for water storage in the soil during dry growing seasons when AWC in topsoil could be depleted. In addition, AWC was corrected according to the volume of stones, which generally increases with depth. Soils with stony subsoil contain less plant-available water and restrict root development.

Most of the studied soils had a pH level of the A-horizon within the favourable range suggested for poplars and aspens: 5.0–6.5 (Lu and Sucoff, 2001; Stanturf *et al.*, 2001). In this range the relation between pH and tree growth was insignificant. Within the whole range of studied soils the relation between pH and tree growth was negative (Table 6; **I; II**). This was probably due to fact that within the studied selection of soils, stony soils with unfavourable water conditions for fast growth of aspen were mainly represented in northern Estonia, where soils have developed on Silurian and Ordovician carbonate rocks and thus have a higher pH level (**II**). The more vigorous aspen growth was observed in the southern part of Estonia, where sandy soils have developed from Devonian sandstone rocks and thus usually have lower pH levels (**II**).

The nutritional status of the studied former field soils can be considered good; the average concentrations of major mineral nutrients were comparable to the optimal levels in Estonian field soils (**II**). Our data showed that element inputs from previous agricultural management still supported native nutrient-poor soils, equally with pedogenetically nutrient-rich soils. Most of the studied previous field soils had relatively light loamy sand and sandy loam textures (**I**). On forest lands, such soils have low P concentrations, but the P content was higher in the studied sites; there also existed a positive correlation between soil P and growth of hybrid aspen (**I; II**). Generally, soil pH was in favourable range for P uptake (**II**). Less drainable semi-hydromorphic and hydromorphic soils having *stagnic* and *gleyic* properties favor reductive conditions in soils and could improve P uptake as the soluble fraction in the soil increases (Scalenghe *et al.*, 2002). The studied hydromorphic soils were low in available P and there was a significant correlation between tree height and soil P (Table 6). However, the mean growth speed as well as foliar P of trees was not considerably lower on hydromorphic soils compared to semi-hydro- and automorphic soils (**II**); thus higher water availability could have compensated the below optimal content of nutrients in the soil. The negative correlation between soil P and foliar N/P ratio in hydromorphic soils (Table 2 in **II**) reflected retarded N uptake despite improved P uptake.

Soil N, which is considered the main growth limiting nutrient in boreal areas, was shown here to be insignificantly related with the growth of the trees (Table 6; **I; II**). However, foliar N was in strong and significant correlation with growth (Figure 6), indicating the importance of N acquisition for the trees. Since foliar N concentrations on semi-hydromorphic soils were above the sufficiency level – 2.4%, we can conclude that N–acquisition was a more limiting factor for hybrid aspen growth on automorphic and hydromorphic soils (**II**). Although the total and mineralisable N pool in the topsoil of cultivated land is usually lower than in forest soils, N might not be limiting for the planted trees, especially when the soils are high in other nutrients e.g. P (Falkengren-Grerup *et al.*, 2006). The differences in N content between continuously forested and cultivated soils could be higher regarding the organic layer, which is more decisive for plants on forest lands, while on afforested agricultural lands the nutrients are distributed more evenly within the plough layer (Wall and Hytönen, 2005). The formation of a litter layer and a forest floor during further stand development could additionally improve N supply in the studied young plantations, as aspen are known to be more dependent on organic N (Strong and La Roi, 1985).

Foliar K was related to extractable K in the soil, although neither tree growth nor foliar N:K ratio were related to K content in the soil (Table 2 in **II**), thus it cannot be concluded that K is limiting hybrid aspen growth. K is antagonistic to the uptake of Ca and Mg (Diem and Godbold, 1993). Ca is unlikely to be limited since the former agricultural fields received frequent inputs of lime or other fertilizer containing Ca (e.g. superphosphate). Foliar K:N ratio was close to 0.30, which is somewhat lower than the optimal 0.35, what has been determined for *Picea abies* foliage (Linder, 1995), but higher than in other Swedish studies, where it ranged from 0.24 for *Fagus sylvatica* up to 0.28 for *Quercus robur* (Göransson *et al.*, 2006). Differences in observed foliar K levels could also be affected by differences in sampling and analysis methods. There could be differences between pot (*ex-situ*) and field (*in-situ*) experiments. In addition, genetic (clonal) background affects the phytochemistry of trees (Lindroth and Hwang, 1996; Prasolova *et al.*, 2005) and thus critical levels for foliar nutrients could vary among hybrid aspen clones selected in different regions.

6.3. Silvicultural implications

6.3.1. Site selection

In general, abandoned agricultural soils with higher quality for crop productivity were also more promising for hybrid aspen. The average soil quality within the study area was estimated as 53 points and the most vigorous growth was observed on soils with a quality over 50 points. In general, these soils are considered very good also for agriculture and the share of such land among the abandoned agricultural land resources is relatively low (Astover *et al.*, 2006). The average quality of arable soils in Estonia is 43 points, the soils with quality under 35 points are considered less valuable for crop production (Eesti maaelu arengukava, 2009). From this perspective the current study confirmed the common contradiction that although less fertile abandoned agricultural sites are recommended for afforestation, this is not true for the economically profitable establishment of SRF plantations with aspens and poplars.

Soil water regime, texture and calcareousness of parent material have been used as predictors of forest site productivity in Estonia (Figure 11; Lõhmus, 2004). In Estonia the most productive forest soils are *Luvisols*, *Planosols* and some *Albeluvisols* and *Gleysols*. On automorphic soils tree productivity depends primarily on the subsoil texture (Kõlli 2002). Our results confirmed that similar soil-based site quality predictors can be used also for selecting suitable abandoned agricultural sites for afforestation. The most suitable soils for hybrid aspen would be *Albeluvisols*, *Luvisols* and *Planosols* (**I**; **II**). This is in accordance with the site preferences of *P. tremula* in Estonia (Laas, 1987). Although the properties of abandoned field soils are to a certain extent different from native forest soils, the growth speed of the trees in the studied plantations could be linked to the soil type based ordination of forest site types where areas with contrasting growth intensities were revealed (Figure 11).

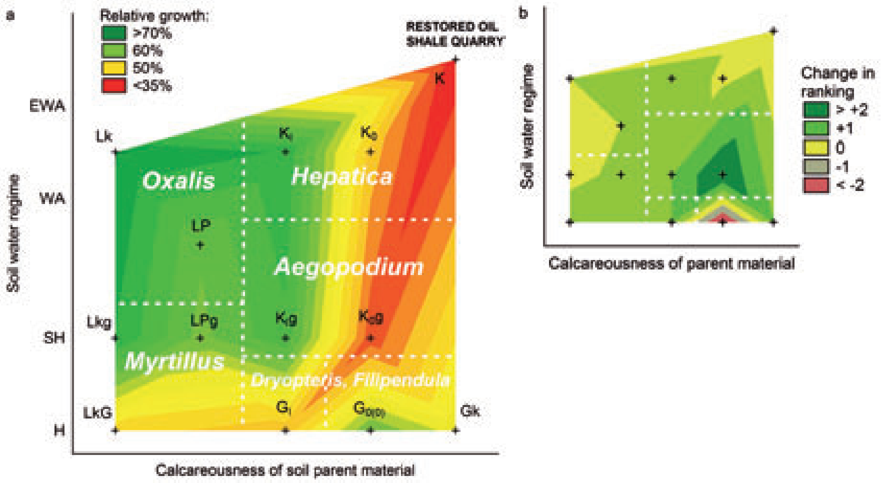

Figure 11. a) Relative growth (the heighest 7-yr-old plantation = 100%) of hybrid aspen on abandoned agricultural soils ordinated according to the matrix of post-lithogenic mineral soils (Kõlli, 2000) and the respective forest site types (Lõhmus, 2004) and b) the change in ranking of the

plots by growth speed from the age of five to seven years. Abbreviations and soil codes are explained in Table 6

Table 6. Explanation of abbreviations and soil codes in Figure 11

Soil water regime	Soil code	Corresponding soil types (WRB, 2006) present in the study area	Plots
EWA	Excessively well-drained automorphic soils		
	K	*Rendzic Leptosol, Calcaric Cambisol*	3
WA	Well-drained automorphic soils		
	K_0	*Calcaric Cambisol, Chromic Cambisol, Eutric Cambisol, Cambic Arenosol*	7
	K_I	*Calcaric Luvisol, Haplic Phaeozem*	2
	Lk	*Glossic Albeluvisol, Leptic Podzol*	3
	LP	*Mollic Planosol*	9
SH	Semi-hydromorphic soils		
	K_0g	*Eutric Cambisol, Gleyic Cambisol*	2
	K_Ig	*Gleyic Luvisol, Cambic Arenosol*	3
	Lkg	*Gleyic Albeluvisol*	2
	LPg	*Gleyi-Mollic Planosol, Gleyic Planosol*	9
H	Hydromorphic mineral soils		
	LkG	*Dystric Gleysol*	1
	G_I	*Haplic Gleysol*	1
	$G_{0(0)}$	*Mollic Gleysol*	4
	Gk	*Calcaric Gleysol*	1

Such a pattern was evident already at the age of 5 years, except for *Luvisols* (**I**), where height growth has improved from age 5 to 7 years. Also plantations on *Cambisols*, which are generally considered as fertile soils, have shown improvement in the growth speed (Figure 11b).

The impact of AWC on tree growth was stronger in a growing season with insufficient precipitation (Table 3 in **II**). This indicates a possible risk, especially when the establishment of hybrid aspen plantations coincides with a dry growing season, which could result in considerable mortality of planted trees. From this aspect semi-hydromorphic soils should be preferred. High stoniness reduces AWC in the soil and thus dry automorphic field soils, as well as the stony substrate of exhausted oil shale quarries are not favourable for the fast growth of hybrid aspen. However, for ecological restoration of exhausted mining sites, deciduous tree species that are able to dwell in such extreme conditions should be considered from a biological diversity point of view in order to reduce the present predominance of coniferous stands in previously restored Estonian opencast oil shale mining sites (**IV**). On abandoned agricultural lands the proper site selection for establishing a hybrid aspen plantation should be based on maximizing the profitability of the investment, i.e. only sites that have proved suitable for fast growth and high biomass productivity of trees should be preferred. Due to high establishment cost, SRF plantations with hybrid aspen would probably not be justified merely for their potential soil restoring effect in agriculturally degraded landscapes.

6.3.2. Establishment and management

A higher planting density than the currently used 1100–1600 plants ha^{-1} in Estonia and Scandinavia (**I**; Rytter and Stener, 2005), is not economically justified due to the high cost of micropropagated hybrid aspen plants (€0.7plant^{-1}). However, 4200–5555 plants ha^{-1} has been recommended in Germany for establishing aspen short-rotation coppicing plantations (Liesebach *et al.*, 1999). Establishment grants and/or cheaper hybrid aspen propagation methods, e.g. using root cuttings, would allow the initial spacing to be increased for bioenergy production in short rotations.

An important aspect in the management of hybrid aspen plantations is the proper prediction of the maturity of the stand. One way is to establish a general felling age, e.g. 25 years for the production of pulpwood. But due to different spacing and variable growth intensity on different soils, the target stem diameter at breast height can be recommended as a more precise measure for deciding the proper felling time (Tullus, 2005a, 2005b). Target diameter is the maximum average diameter of the stems that the stand can achieve before the process of intensive self-thinning begins. If the target diameter is achieved for the first time the manager can decide whether to clear-cut the stand or make a thinning and let the remaining trees grow until the next target-diameter is achieved and then make the clear-cut.

The analysis of bark content in the stems of young hybrid aspens revealed that it dropped significantly (to 24%) when the DBH of model trees reached 4 cm; the subsequent decrease in bark content with growing DBH was slower (Figure 5). Similarly, it has been found that bark content in young poplar stems stabilized at 17.5% when DBH reached 4 cm (Guidi *et al.*, 2008). In a willow plantation the respective diameter at 55 cm has been found to be 2 cm, when bark content stabilized at 20% (Adler *et al.*, 2005). Trees exceeding a certain size limit at harvest ensure higher stemwood content in biomass, resulting in lower ash content and lower emission of pollutants during combustion. We conclude that for the hybrid aspen energy wood coppicing system, 4 cm DBH could be a reasonable target diameter. In addition less major nutrients per dry weight of biomass are removed from the plantation when larger trees are harvested (Figure 6 in **III**).

In general, SRF plantations with poplars and willows in the boreal region require fertilization (Weih, 2004). However, hybrid aspen has demonstrated high biomass productivity also in unfertilized sites (Rytter, 2006). Within the studied selection, stony soils with low AWC level were mainly found to be unfavourable for the fast growth of hybrid aspen (**II**). Even fertilization would probably not compensate the unfavourable hydrophysical properties of such soils. The 25-yr rotation period would be sufficient for the formation of a forest floor and normal nutrient cycling processes. In general the forest floor under deciduous trees has shown high nutrient mineralization rates (Kanerva and Smolander, 2007; Uri *et al.*, 2008). Thus it is hard to predict how much the harvest would reduce the nutrient stock available for the subsequent rotation. Probably the fertilization need will be higher in short-rotation coppice systems (with rotations less than 10 years), where nutrient removal with successive harvests exceeds the share of nutrients returned to the soil through litter and weathering.

6.4. Future prospects

The current study was planned as part of a long-term research programme. The collected data and results can be used as a basis for several studies related to ecology and management of SRF plantations. Growth development and plant-soil relations in hybrid aspen plantations need to be studied and monitored during the whole rotation period in order to draw final conclusions about the feasibility of hybrid aspen cultivation in Estonian climate and soil conditions. The long-term impact of hybrid aspen plantations on soil properties, nutrient removal with harvest and the consequent need for fertilization should be further clarified. Further soil monitoring within the network of permanent experimental plots should focus on the possible changes in the significance of soil-related growth factors in older plantations. Both above-ground (light) and below-ground (root) competition will intensify in older plantations. Thus the need for and degree of thinnings, optimal spacing and DBH of the trees at harvest need to be studied. In order to achieve optimal growth and productivity, breeding and selection of hybrid aspen clones for Estonian climate and soil conditions would be beneficial. The genotype x environment effect on the growth and biomass characteristics of hybrid aspen, depending on the purpose of the plantation (production of energywood, pulpwood or aspen logs) should be clarified. Environmental and economic aspects of hybrid aspen plantations in comparison with other fast-growing tree species should also be analysed.

CONCLUSIONS

1. Hybrid aspen showed fast growth during the first ten years in well-suited sites in Estonian plantations, confirming its suitability for SRF in the hemiboreal region. The growth characteristics had high variability during the first five to seven years (**I–IV**); generally the growth rate increased from this age onwards. The conclusions about the productivity potential of hybrid aspen as well as its site preferences, drawn on the basis of less than half of the predicted rotation period, should be treated with caution. The changes in the ranking of plantations according to growth rate, as well as the importance of site factors is likely to change to a certain extent in older plantations. New clones with improved growth rates and selected particularly for local soil and climate conditions should be considered for further cultivation in Estonia.

2. In general the site preferences of hybrid aspen have been similar with the site preferences of its parent species (*Populus tremula* and *P. tremuloides*). Fast growth occurred on fertile previous agricultural soils with a high quality score for crop production. An ideal previous agricultural soil for hybrid aspen would be a nutrient-rich, well-aerated, moderately drained soil with relatively light loamy sand or sandy loam texture above more clayic subsoil (e.g. *Albeluvisols*, *Luvisols* and *Planosols*) and with high water holding capacity. Such soils correspond to *Oxalis*, *Oxalis-Myrtillus* and partly *Aegopodium* and *Hepatica* forest site types. Excessively well-drained automorphic soils (e.g. stony and shallow *Leptosols* and *Cambisols*) and some water-logged hydromorphic soils (*Gleysols*) were not favourable for the fast growth of hybrid aspen (**I**; **II**). Site selection should be based on soil type; more general site assessment (e.g. according to soil water regime) is less accurate.

3. Hydrophysical properties, rather than nutrient stocks from past fertilization of abandoned agricultural soils have been decisive for the growth rate of the trees in young hybrid aspen plantations (**I**; **II**). Available water content in soil (especially in subsoil), estimated indirectly as a function of bulk density and soil specific surface area, was found to be a decisive site quality indicator (**II**). In general, the need for fertilization did not emerge in young plantations. In sites where the growth of the trees had been slow due to poor nutrient acquisition properties, the trees would hardly have benefited from fertilization.

4. Above-ground leafless biomass characteristics of hybrids aspens (dry matter content, allocation, nutrient concentrations and calorific values) were comparable to other fast-growing deciduous trees (e.g. *P. tremula* and *B. pendula*). In order to ensure better quality of biomass for energy (higher wood content) the target DBH of hybrid aspens at energy wood harvest should be at least 4 cm (**III**).

5. Hybrid aspen was able to grow on exhausted oil shale quarry substrate, despite its poor water and nutritional properties. The growth of the trees was faster on a quarry site with restored topsoil, compared to bare levelled quarry spoil. However, the vigorous growth of hybrid aspen was not realised in the restored quarry sites, where the plantations have more of an ecological than commercial value (**IV**).

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SUMMARY IN ESTONIAN

PUUDE KASV JA SEDA MÕJUTAVAD TEGURID NOORTES HÜBRIIDHAAVAISTANDIKES

Sissejuhatus

Lühikese raieringiga metsandus (SRF) on uudne metsakasvatuslik meetod hemiboreaalsesse metsavööndisse kuuluvas Eestis. Viimase paarikümne aasta jooksul on huvi SRF vastu tõusnud seoses: 1) üha kasvava puittoorme vajadusega kogu maailmas; 2) endistele põllumajandusmaadele alternatiivsete kasutusvõimaluste otsimisega; 3) Eesti kohustusega Euroopa Liidu liikmena suurendada taastuvenergia osakaal 20%-ni aastaks 2020. Eesti kliimas SRF jaoks sobilik puuliik peab olema noores eas kiirekasvuline ning samas külmakindel. Teiste maade kogemuse põhjal on meie regioonis üheks kõige kiiremakasvuliseks lehtpuuks hübriidhaab – hariliku haava (*Populus tremula* L.) ja Ameerika haava (*P. tremuloides* Michx.) kunstlikul teel saadud ristand, mis ületab heteroosi tõttu kasvukiiruse ning biomassiproduktsiooni poolest tunduvalt oma lähteliike. Hübriidhaavaistandike kasvatamise peamiseks eesmärgiks on toota 25-aastase raieringiga paberipuitu (jämedamatest tüvedest haavapalki), pärast istutatud põlvkonna raiumist kasvab uus hübriidhaavaistandiku põlvkond vegetatiivselt juurevõsudest (joonis 1). Juurevõsupõlvkonda võib majandada väga lühikese raieringiga energiapuidu tootmiseks või rakendada kombineeritud varianti, kus peale intensiivset harvendust esimese 5 aasta jooksul jäetakse osa puid kasvama pikema raieringiga paberipuidu saamiseks (joonis 1). Eestis on alates 1999. aastast rajatud endistele põllumajandusmaadele üle 700 ha hübriidhaavaistandikke, hübriidhaaba on katseliselt istutatud ka ammendatud põlevkivikarjääri metsastamiseks. Hübriidhaavaga seotud varasemad metsanduslikud uurimused tuginevad enamasti väikesepindalalistel katsekultuuridel, hübriidhaabade kasvu mõjutavaid tegureid suurepindalalistes tootmiskultuurides on suhteliselt vähe uuritud. Samuti on meie regioonis vähe uuritud endiste põllumuldade sobivust SRF istandike kasvatamiseks. Maaharimise tõttu on taolistele muldadele iseloomulik kontrastsus künnihorisondi ja alumise mullakihi omaduste vahel, ning degradeeritud mullastruktuur (võib esineda tihenemist). Võrreldes looduslike (metsa)muldadega on endiste põllumuldade orgaanilise aine sisaldus väiksem ning selle jaotus ühtlasem A-horisondis. A-horisont võib olla osaliselt segunenud selle all oleva E- või B-horisondiga. Toitainete (P, K) sisaldus on põllumuldades väetamise tõttu suurem ja võib püsida suurena ka aastakümneid peale põlluharimist.

Looduslikult (geneetiliselt) happelised mullad on lupjamise teel muudetud vähemhappelisteks. Turvastunud ja gleimullad (madalamad alad) on kuivenduse tõttu vähem liigniisked kui vastavad metsamullad.

Arvestades eeltoodut, püstitati käesoleva doktoritöö peamised hüpoteesid: 1) hübriidhaab on sobilik lehtpuu endistele põllumajandusmaadele SRF istandike rajamiseks Eesti kliima- ja mullatingimustes (**I–IV**); 2) mulla hüdrofüüsikalised omadused on olulised noorte hübriidhaabade kasvu mõjutavad tegurid toitainetega hästi varustatud endistel põllumuldadel (**I**; **II**). Doktoritöö detailsed eesmärgid olid: 1) hinnata puude kasvu ja produktsiooni noortes hübriidhaavaistandikes (**I–IV**); 2) uurida endiste põllumuldade keemiliste ja füüsikaliste omaduste mõju hübriidhaabade kasvukiirusele ja toitainete omastamisele (**I**; **II**); 3) määrata maapealse lehtedeta biomassi produktsioon, allokatsioon, peamiste toitainete sisaldus ja kalorsus noortes hübriidhaavakultuurides (**III**); 4) uurida hübriidhaava sobivust ammendatud põlevkivikarjääride metsastamiseks (**IV**); 5) täiendada olemasolevaid teadmisi taim-muld suhetest SRF istandikes ja anda praktilisi soovitusi kasvukoha valikuks hübriidhaavaistandike rajamiseks (**I–IV**).

Metoodika

Püstitatud küsimustele vastuste leidmiseks rajati 58 püsikatsealast (á 0,1 ha) koosnev katsealade võrgustik 26 hübriidhaavakultuuris (joonis 2). Kultuurid on rajatud 1999. ja 2000. aastal. Istutusmaterjalina kasutati 27 Soome päritolu hübriidhaavaklooni taimi seaduga 1200–1600 taime ha^{-1}. Igal katsealal mõõdeti kõigi puude takseertunnused (kõrgus, kõrguse jooksev juurdekasv, tüve rinnasdiameeter, elusvõra alguse kõrgus, võra läbimõõt). Istandike maapealse lehtedeta biomassi produktsiooni ning biomassi omaduste (allokatsioon, kütteväärtus, toitainete sisaldus) hindamiseks analüüsiti 51 mudelpuud (**III**). Istandike tüvepuidu tagavara hinnati kirjanduses esitatud valemi kaudu. Artiklid **I–IV** tuginevad 5- ja 7-aastastes istandikes tehtud mõõtmistel, doktoritöö ülevaateosas on esitatud istandike kasvukäik vanuses 5 kuni 10 a. Hübriidhaabade toitainete omastamise iseloomustamiseks analüüsiti puulehtede mõõtmeid ja peamiste toitainete sisaldust. Mullaomaduste määramiseks tehti igal katsealal sügavkaeve, koostati mullakirjeldus ja määrati mullaliik. Igast mullahorisondist võeti alamproovid lõimise, lasuvustiheduse ja eripinna määramiseks. A-horisondi toitainesisalduse ja pH analüüsimiseks võeti igal katsealal proovid neljast kohast. Mulla omastatava vee varud (**II**) määrati Eesti muldade jaoks välja töötatud meetodi abil mulla eripinna ja lasuvustiheduse kaudu.

Tulemused ja arutelu

Esimese 10 aasta jooksul olid hübriidhaabade kasvutunnused suure varieeruvusega (**I–IV**; joonis 3; tabel 4). Puude säilivus oli 7ndaks aastaks 80%, märgatav metskitsekahjustus esines 10% katsealadest, alates 9ndast kasvuaastast ilmnes kohati ka ulatuslikum põdrakahjustus, eelkõige suurte metsamassiividega piirnevates istandikes. Puude kõrguse juurdekasv sõltus 5ndal kasvuaastal eelkõige puu suurusest, mitte aga istandiku kasvuklassist (**I**; joonis 4a). Pärast 7ndat kasvuaastat olid eristunud kõige aeglasema kasvuga istandikud, kus suurimad puud ei kasvanud enam sama kiiresti kui sama kõrged puud paremates istandikes (joonis 4b). Puude keskmisel kasvukiirusel põhinev katsealade järjestus muutus osaliselt 5ndast kuni 7nda kasvuaastani. Kasv oli kiirenenud gleistunud leostunud ja leetjatel muldadel (joonis 11b). Uuritud 5 kuni 10-aastaste hübriidhaavaistandike kasvukäigu võrdlus kirjanduses esitatud andmetega hübriidhaavaistandike ning kohalike kiirekasvuliste lehtpuupuistute kasvukäiguga kinnitas hübriidhaava suurt kasvukiirust ja produktsioonivõimet Eesti kliima- ja mullatingimustes. Hübriidhaab ületas kodumaiseid kiirekasvulisi lehtpuid (arukask, hall lepp, harilik haab) eelkõige üksikpuude mõõtmete poolest (joonis 10), kultuuride tüvepuidu tagavarad 10 a vanuses olid vaadeldud puuliikide puistutes sarnased, kuna hübriidhaavakultuurid olid teiste lehtpuude kultuuridest ja looduslikest puistutest tunduvalt hõredamad. Uuritud kultuurid olid rajatud Soome tingimustes enam kui poole sajandi eest aretatud hübriidhaavakloonidesse kuuluvate taimedega. Seetõttu jäi nende kasvukiirus mõnevõrra väiksemaks võrreldes uuemate Skandinaavias ja Soomes aretatud kloonidega.

Seitsmeaastaste hübriidhaabade maapealse (lehtedeta) biomassi keskmine kuivainesisaldus oli 46 ± 0,3% (**III**), varieerudes usaldatavalt puu osade vahel (tüvekoor ≥ 1a võrsed ≥ vanad oksad > tüvepuit). Tüve kooreprotsent tüve kogumassist kahanes puu rinnasdiameetri kasvades kiiresti kuni 4 cm rinnasdiameetrini, diameetri edasise suurenemisega kaasnes aeglasem kooreprotsendi vähenemine (joonis 5). Maapealsesse biomassi seotud toitainete osakaal seitsmeaastastes istandikes oli väike võrreldes nende elementide varuga mulla A-horisondis (**III**). Hübriidhaabade maapealse biomassi kütteväärtused erinesid puu osade vahel järgmiselt: 1a võrsed ≥ tüvekoor ≥ vanad oksad > tüvepuit (tabel 8 artiklis **III**). Analüüsitud biomassi omaduste (allokatsioon, toitainesisaldus ja kütteväärtus) poolest oli hübriidhaab sarnane teiste kiirekasvuliste lehtpuudega (nt arukask, harilik haab).

Hübriidhaava lehtede keskmised toitainete sisaldused oli suurenenud viiendast seitsmenda kasvuaastani (tabel 5). Lehtede N sisaldus oli usaldatavas seoses puu kõrgusega (**I**; **II**). Kiireks kasvuks piisav lehtede N sisaldus oli 2,7% ja ebapiisav 2,4% (joonis 6). Lehtede P ja K sisaldus (seitsmeaastastel puudel vastavalt 0,24 ja 0,79%) ei olnud usaldatavas seoses puude kasvuga (**I**; **II**). Lehtede N ja P sisaldus sarnanes kirjanduses esitatud tulemustega hübriidhaava ja teiste papli perekonna liikide kohta (tabel 5 artiklis **II**), K sisaldus oli käesolevas töös mõnevõrra väiksem, mis võib olla tingitud erinevustest leheproovide kogumise ja analüüsimise metoodikas.

Hübriidhaabade kasvukiirus sõltus usaldatavalt endiste põllumuldade füüsikalistest ja keemilistest omadustest (tabel 6; **I**; **II**). Üldiselt oli noorte puude kasv kiirem saviliiv ja liivsavi ning aeglasem savilõimisega ja suure koresesisaldusega muldadel (tabel 3 artiklis **I**). Endiste põllumuldade grupeerimine niiskusrežiimi alusel andis üldistava hinnangu muldade sobivusest hübriidhaava kasvatamiseks. Kasv oli kiirem parasniisketel ja gleistunud muldadel, mõnevõrra aeglasem gleimuldadel ja oluliselt aeglasem põuakartlikel muldadel (joonis 9). Mullaliikidest sobisid hübriidhaavale enam parasniisked või gleistunud leetunud, näivleetunud ja leetjad mullad, millele tavametsanduses vastab jänesekapsa, jänesekapsa-mustika ja osaliselt naadi ning sinilille kasvukohatüüp (joonis 11a). Väga soodsaks osutusid ülaosas kahekihilise lõimisega mullad, kus pealmise kergema lõimisega mullakihi all asub tihedam, vettpidavam mullakiht. Ühelt poolt soodustab see puude juurestiku kiiremat arengut ning tagab mulla ülaosas hea drenaaži ning samas piisava veega varustatuse kasvuperioodi jooksul. Teisalt takistab alumine savikam mullakiht toitainete väljaleostumist, on alustega küllastunud ja ühtlasi põhjustab ajutist ülavett, mis kiirekasvulistele haabadele on pigem soodne. Kolmandaks soojenevad ülaosas liivasema lõimisega mullad kevadel kiiremini ning puude kasvuperiood saab alata varem kui näiteks hüdromorfsetel gleimuldadel. Samas tuleb silmas pidada, et käesolev töö kirjeldab hübriidhaabade kasvu seoseid mullatingimustega kultuurides, mille vanus on vähem kui pool planeeritud 25-aastasest raieringist. Seega on võimalik kultuuride ümberreastumine kasvukiiruse poolest ning kasvu mõjutavate tegurite tähtsuse teatav muutumine vanemates istandikes.

Käesoleva töö tulemused näitasid mulla hüdrofüüsikaliste omaduste olulisust hübriidhaabade kasvule noores eas (**I**; **II**). Oluliseks kasvukoha sobivuse indikaatoriks võib pidada kaudselt määratavat mulla omastatava vee varu (AWC) 75 cm mullakihis (**II**). Seosed AWC ja puude kasvukiiruse vahel olid tugevamad põuakartlikel ja parasniisketel (automorfsetel) muldadel ning põuase kasvuperioodiga aastal (**II**). Piisavaks AWC-ks 75 cm mullakihis võib automorfsetel muldadel lugeda 150–160 mm ja ebapiisavaks alla 120–130 mm (joonis 8). Eelkõige on oluline AWC mulla sügavamates kihtides (25–50 ja 50–75 cm), mis mõjutas kultuuride diferentseerumist kasvukiiruse poolest enam kui pealmise 25 cm mullakihi AWC (joonis 7). Pealmise 25 cm mullakihi AWC varieerus suhteliselt vähe ning tõenäoliselt oli enamasti piisav puude kasvuks vajalike toitainete omastamiseks. Kuigi enamus puujuurtest paikneb mulla pealmises kihis, omastavad puud vett ja toitaineid ka sügavamatest mullakihtidest, mille vastavad omadused mõjutavad seega oluliselt puude kasvukiirust. Mulla alumiste kihtide hüdrofüüsikalised omadused on eriti olulised põuastel kasvuperioodidel, mil omastatav vesi võib mulla ülakihist peaaegu täiesti kaduda.

Uuritud muldade peamiste toitainete sisaldus ja varud olid üldiselt sarnased või veidi kõrgemad Eesti põllumuldade keskmistest näitajatest (**II**). Enamasti oli hübriidhaavakultuure rajatud põllumajanduse seisukohast viljakatele muldadele, keskmiseks hindepunktiks oli 53 punkti. Puude kasv oli usaldatavas positiivses korrelatsioonis mulla hindepunktiga, olles tunduvalt kiirem muldadel, mille hindepunkt oli vähemalt 50 punkti. Seega kinnitas uurimus juba varasemast teadaolevat vastuolu: kuigi metsastamiseks soovitatakse eelkõige väheviljakaid endisi põllumajandusmaid, kujuneb SRF kultuuride rajamine paplite ja haabadega edukaks just viljakatel muldadel.

Ühe allteemana uuriti hübriidhaabade kasvu ammendatud põlevkivikarjääris rajatud istandikes (**IV**). Antud kasvukoha substraati iseloomustab suur kivisus, kõrge pH, madal toitainesisaldus ja väike omastatava vee varu. Puud olid kasvanud kiiremini karjäärialal, mis oli taastatud põllumaana, s.t. peale puistangu tasandamist kaeti ala enne kaevandamist eemaldatud huumuskattega. Sellistes tingimustes oli hübriidhaabade kasv sarnane karjääriga samas regioonis asuvatele endistele põllumajandusmaadele rajatud istandikega. Kuid kasv oli tunduvalt aeglasem hübriidhaavale sobilikuks osutunud endistel põllumuldadel kasvavate istandike omast (tabel 2, joonis 1 artiklis **IV**).

Järeldused ja vajadus edasiseks uurimiseks

Uurimistöö tulemusena tehtud peamised järeldused:

1. Hübriidhaavaistandike kasvukäik esimese 10 aasta jooksul näitab, et hübriidhaab on Eesti kliima- ja mullatingimustes noores eas kiirekasvuline ja suure produktsioonivõimega lehtpuu.
2. Endistel põllumajandusmaadel on puude kasv noores eas seotud eelkõige mulla hüdrofüüsikaliste omadustega, eelnevalt väetatud muldade toitainevarud on olnud enamasti piisavad. Hübriidhaavale sobilikud mullad on ülaosas kergema lõimisega parasniisked või gleistunud leetunud, näivleetunud ja leetjad mullad (**I**; **II**).
3. Kaudselt määratavat taimede poolt omastatava vee varu mullas võib pidada heaks indikaatoriks kasvukoha valikul, seejuures on olulised ka alumiste mullakihtide omadused (**II**).
4. Hübriidhaabade biomassi allokatsioon, kuivaineühiku toitainesisaldus ja kütteväärtus on sarnased teiste kiirekasvuliste lehtpuude vastavate näitajatega. Energiapuidu tootmisel peaks tüve sihtdiameeter olema vähemalt 4 cm, mis tagab suurema puidu osakaalu biomassis (**III**).
5. Hübriidhaab suudab kasvada karjääripuistangu ekstreemsetes tingimustes, kuid seal ei avaldu noores eas tema suur kasvupotentsiaal, puud kasvavad kiiremini taastatud huumuskattega karjäärialal (**IV**).

Käesoleva töö raames tehtud uuringud kavandati pikaajalise uurimisprogrammi osana. Kogutud andmeid ja analüüsitulemusi saab kasutada lähte- ja taustamaterjalina mitmesuguseid SRF istandike ökoloogilisi ja majanduslikke aspekte käsitlevates uuringutes. Nii puude kasvukäigu kui ka taim-muld seoste osas on vajalik tervet raieringi hõlmav kasvukäigu ja biomassiproduktsiooni uuring, mille põhjal saaks teha lõplikud järeldused hübriidhaava kasvatamise sobivuse kohta Eesti tingimustes. Selgitamist vajab SRF istandike pikaajaline mõju mulla omadustele, raietega ökosüsteemist äraviidavate toitainete kogus ja võimalik vajadus väetamiseks. Edasine püsikatsealadel planeeritud mulla monitooring keskendub puude toitainete omastamist mõjutavate tegurite olulisuse võimalikule muutusele vanemates istandikes ning täiendavate endistel põllumuldadel puude kasvu mõjutavate tegurite selgitamisele. Vanemates istandikes hakkab puude kasvu mõjutama nii maapealne valgus- kui ka maaalune juurkonkurents, selgitada tuleb harvendusraiete vajadus ja intensiivsus, optimaalne istutustihedus ning puude arv lõppraiel ja istandike raieküpsuse määramiseks sobilikud kriteeriumid. Edaspidiseks hübriidhaava kultiveerimiseks võib soovitada Eesti kliima- ja mullatingimustes selekteeritud hübriidhaavakloone, mis tagaks istandike veelgi suurema produktiivsuse. Selgitamist vajab nii kasvukoha kui klooni mõju hübriidhaabade kasvukiirusele ja biomassi omadustele sõltuvalt istandike eesmärgist (energiapuit, paberipuit või haavapalk). Lisaks kasvukiirusele tuleks hübriidhaaba võrrelda teiste kiirekasvuliste puuliikidega ka ökonoomilisest aspektist.

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Early growth of hybrid aspen (*Populus* × *wettsteinii* Hämet-Ahti) plantations on former agricultural lands in Estonia

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Abstract

Since 1999 hybrid aspen plantations have been established on former agricultural lands for production of pulpwood as a practice of short rotation plantation forestry in boreal Estonia. During the early growth period the dimensions of the trees have been highly variable. The main objective of the study was to explain the high variability in early growth speed of hybrid aspens by differences in physicochemical soil properties. A network of 51 experimental plots was created to study growth–soil interactions in 5-year-old plantations at various sites. The mean height of the trees was 2.7 ± 0.02 m, mean diameter at breast height was 1.9 ± 0.02 cm and mean current year height increment was 0.7 ± 0.01 m. Mean foliar concentrations of main mineral nutrients were estimated as follows: N 2.15%, P 0.20%, K 0.76%. Trees have grown faster on Arenosols, Albeluvisols and Planosols. Growth intensity has been poor on Luvisols, Cambisols and Gleysols. While evaluating site quality based on soil texture and drainage condition, we found, that in general, hydromorphic soils have been less favourable. At a young age, hybrid aspen grew faster on automorphic soils with loamy sand and on semihydromorphic soils with loam, silt loam and sandy loam texture. The study of height increment in 5-year-old hybrid aspen plantations allows us to predict that the modest growth rate during the first years after planting could improve at an older age. Preliminary impact hierarchy of site properties, especially soil moisture condition, may change during later growth stages, when light competition in the canopy layer of the stand and nutrient competition between the tree roots in the soil will become more decisive for the growth performance of the trees.

Keywords: Hybrid aspen; Early growth; Plantation forestry; Afforestation

1. Introduction

Fast-growing poplars and their hybrids are used in short-rotation forestry in many countries. Production plantations of poplars established with highly selected interspecific hybrid varieties and intensive agronomic-style tending practices are among the highest yielding crop trees in the temperate zone (Stanton, 2004). The only endemic *Populus* sp. in Estonia is European aspen (*P. tremula* L.). The share of forest land area with *P. tremula* as the dominant tree species is 5.4%. As a typical tree in mixed stands on fertile site types, it constitutes 8.1% of the growing stock of Estonian forests (Yearbook forest, 2004).

A cross between *P. tremula* L. and *P. tremuloides* Michx., known as hybrid aspen (*Populus* × *wettsteinii* Hämet-Ahti), was first described at the beginning of the 1920s in Germany (Wettstein, 1933). Presumably hybrid aspen exceeds its parental species in growth rate due to the phenomenon of heterosis. There are two leading hypotheses to explain the genetic basis of heterosis: dominance and overdominance. Li and Wu (1996) have found that in case of aspen hybrids heterosis might be due to overdominance interaction between two alleles, one from the *P. tremuloides* parent and the other from the *P. tremula* parent, at the same loci. The predicted rotation period for hybrid aspen in boreal conditions is 20–30 years for the production of pulpwood. Hybrid aspen has been grown and studied most intensively in Sweden, Finland and the Great Lakes Region in the USA (Benson and Einspahr, 1967; Li et al., 1998; Dickmann, 2001; Yu et al., 2001a; Karacic et al., 2003; Rytter and Stener, 2003, 2005).

In Estonia the first known experiment with a small number of hybrid aspens dates back to the 1980s. Larger scale cultivation for production of pulpwood started in 1999.

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Seven hundred hectares of hybrid aspen plantations had been established on former agricultural lands in Estonia by autumn 2005. Two experimental plantations have been established for afforestation of reclaimed oil-shale mining areas.

Seven hundred hectares is minute compared to the total area of forestland in Estonia (2.3 Mha) or compared to the approximate area of agricultural land that has been abandoned since the beginning of the 1990s (440 thousand ha). Nevertheless, it is the nation's largest project in short-rotation plantation forestry.

In the light of this, in 2002 a long-term research and monitoring programme was initiated in hybrid aspen plantations. The main research objective is to assess the general potential and feasibility of growing hybrid aspen in Estonian conditions. Investigation of relations between the growth of the trees and soil properties is the most important, but not the only part of the research programme. The scope of the programme includes the biodiversity of hybrid aspen plantations, determination of the best hybrid aspen clones, hybrid aspen wood properties, economic profitability and environmental impacts of short-rotation plantations (Tullus et al., 2005).

Most of the recent studies have focused on the clonal differences of physicochemical and phenotypical properties of hybrid aspen (e.g. Yu et al., 2001b; Rytter and Stener, 2003). Significant genotype × environment interaction on the growth of hybrid aspens has been observed (e.g. Li and Wu, 1997; Yu and Pulkkinen, 2003). The results have indicated that the selection of fast growing clones is essential for increasing the biomass production from short rotation aspen plantations. However, the expression of the hybrid vigour (heterosis) is highly dependent on the environment (Li and Wu, 1997; Yu et al., 2001a). In order to benefit from the genotype × environenvironment effect we must also determine the optimal site conditions for the particular species in general.

In clonal forestry it is recommended to establish stands with a mixture of clones from a biodiversity and pest-control point of view (Roberds and Bishir, 1997; Weih, 2004). In the current study we focus on production plantations where the same principle has been followed in Estonia. Therefore, we have not included the clonal component while describing the growth-site relations.

The main hypothesis of our study was that the high variability in early growth speed of hybrid aspens can be explained by differences in physicochemical soil properties. We tried to investigate why the hybrid vigour had revealed itself in only a few cases, and to determine the combination of physicochemical soil properties in which hybrid aspen has displayed superior growth rate. The objectives of the present paper are (i) to describe the basic dendrometric characteristics in 5-year-old hybrid aspen plantations in Estonia; (ii) to describe interactions between tree growth and properties of the leaves and soil; (iii) to predict whether the modest growth rate will persist during the whole rotation, or whether the influence of factors that have suppressed growth will change.

2. Materials and methods

2.1. Plant material

For establishing the plantations, 1-year-old micropropagated hybrid aspens belonging to 27 clones had been used, on average 15 different clones per plantation. Plants of different clones were planted randomly. Planting material originated from Finland. According to the Finnish Plant Production Inspection Centre, these clones are marked as C05-99-8 until C05-99-34. The origin of the material can be traced back to the 1950s, when a large number of aspen hybrid families were produced from crosses between female *P. tremula* in Finland and male *P. tremuloides* in Canada and the northern part of the USA (Yu and Pulkkinen, 2003).

2.2. Plantations

The hybrid aspen plantations under investigation were established in 1999 and 2000. All the studied plantations have been established on previous agricultural lands.

The average spacing has been 2–2.5 × 3–3.5 m and planting density has varied in the range of 1200–1600 trees per ha. In the observed plantations the average planting density was 1300 trees per ha. In all plantations, 0.3–0.6 m biodegradable plastic tubes or 1.1 m net-like shelters have been used to prevent damage by rodents, hares (*Lepus* sp.) and roe-deer (*Capreolus capreolus* L.). None of the studied plantations have been fenced.

2.3. Experimental plots

From 2003 to 2004 a long-term network of 51 experimental plots was created for studying and monitoring the growth performance of hybrid aspen in Estonia at various site conditions. The experimental plots are located in 24 hybrid aspen plantations across the country (between 57°30′–59°30′N and 24°30′–27°30′E). Each plot is a circle with an area of 0.1 ha, on average 106 trees per plot. Dendrometric characteristics were measured in 5-year-old plantations after the end of the intensive vegetation period. Twenty plots were measured in the autumn of 2003 in 11 plantations that had been established in 1999, and 31 plots in the autumn of 2004 in 13 plantations that had been established in 2000.

Height (HT), diameter at breast height (DBH), height increment (*Z*), height of the beginning of the living crown (BLC), and maximum diameter of the crown (DC) were measured at the end of the fifth growing season. If the height of the tree was less than 1.3 m, DBH was not measured. Because of tree shelters, it was not possible to measure basal diameter or diameter at 55 cm. On the basis of HT and *Z* the relative height increment (Zr) was derived (Zr = 100 × Z/HT).

2.4. Soil properties

Soil pits were hand dug in the centre of each experimental plot. Plots were located on microrelief that was typical for the particular plantation. Soil type was estimated according to the FAO-UNESCO (1994) classification. Four subsamples were taken from each soil horizon and mixed to form a composite sample for chemical and textural analysis. For bulk density, triplicate core samples were taken from the middle of demarcated horizon boundaries. Coarse sand (2.0–0.5 mm) and medium sand (0.5–0.2 mm) were separated by sieving. Clay (<0.002 mm) and silt (0.02–0.002 mm) were determined by the pipette method, and fine sand (0.2–0.02 mm) was calculated as the difference (Soil Survey Manual, 1996).

The total nitrogen in soil samples was determined by the Kjeldahl procedure. To analyse available phosphorus and potassium in the soil, Mehlich 3 extracant was used. The soil pH in 1 M KCl suspensions was measured in the ratio 10 g:25 ml. The growth of hybrid aspens in each experimental plot is characterized by the arithmetic mean values of the growth traits of the measured trees within the 0.1 ha plot. Soil properties of each experimental plot are based on physicochemical analysis of samples taken from one soil pit in the center of each plot. The reliability of such an approach could be disputed. Therefore, in 15 experimental plots an 18 m transect of four soil pits (distance between the pits was 6 m; center of the transect overlaps the center of the experimental area) was established to test the homogeneity of humus horizon properties (pH_{KCl}, concentrations of NPK) within one experimental plot. According to one-way ANOVA, soil properties were significantly different among the studied 15 experimental plots (pH_{KCl}: $F = 26.38$, $P < 0.001$; N: $F = 60.21$, $P < 0.001$; P: $F = 18.27$, $P < 0.001$; K: $F = 9.83$, $P < 0.001$). Plot means based on the transect were strongly and significantly correlated with values based on one soil pit (pH_{KCl}: $r = 0.91$, $P < 0.001$; N: $r = 0.98$, $P < 0.001$; P: $r = 0.92$, $P < 0.001$; K: $r = 0.88$, $P < 0.001$). We concluded that soil properties determined on the basis of one soil pit per experimental plot are sufficiently reliable for describing the soil conditions of each plot.

2.5. Leaf properties

Leaf samples were gathered from 24 experimental plots in August 2003 and 2004. Ten model trees, based on the distribution of DBH, were selected from each plot and 15 leaves were collected from each tree from the middle part of the canopy. Leaves were dried with a desiccator (Memmert 100–800) at +70 °C for 24 h before measurement. Single leaf blade area was measured with WINFOLIA ver. 5.0a (Regent Instruments Inc.) software and leaves were weighed with equipment KERN EW 150–3 M (accuracy 0.001 g). On the basis of single leaf area (cm^2) and weight (g), leaf weight per area (LWA, $g\ m^{-2}$) was derived. For chemical analysis, leaves from 6 trees out of 10 model trees were selected (altogether 144 trees from 24 experimental plots). These trees were selected on the basis of their dimensions (HT and DBH): 2 smallest, 2 medium and 2 largest model trees. Nitrogen determination was performed by standard Kjeldahl procedure using "Kjeltec Auto 1030", and Phosphorus was determined spectrophotometrically from Kjeldahl digest using "FiaStar 5000". Concentration of Potassium was determined flame-photometrically.

2.6. Data analysis

Descriptive statistics (arithmetic mean, standard error of the mean, standard deviation, lower and upper quartile, minimum and maximum value), simple regression coefficients and the respective *P*-values were calculated with STATISTICA 7 (StatSoft Inc, 2004). Coefficient of variation (Cv) was derived as follows: Cv (%) = standard deviation/arithmetic mean × 100%. SAS for Windows 8.2 (SAS Institute, 1999/2001) was used for the advanced analysis of the data. One-way ANOVA (in SAS proc GLM) was used to test the significance of differences between group means according to different grouping scenarios described below:

1. Significance of differences in chemical soil properties (based on four samples per each plot) between 15 experimental plots, and in the dendrometric characteristics of all the measured trees ($n = 4996$) among 51 plots was tested, as a precondition for the further analysis of the factors that have affected early growth of hybrid aspens.
2. In order to compare height increment and relative height increment in plantations with different growth rates, experimental plots were divided into three growth classes (17 experimental plots in each class) according to the mean HT of the trees (class 1 comprised plots with the highest mean HT and class 3 with the lowest).
3. Experimental plots were divided into four groups according to the dominant profile texture and into three groups according to the moisture condition of the A-horizon (Table 3), in order to study the influence of soil physical properties on the growth of hybrid aspens.
4. In order to compare leaf properties between plantations that had shown different growth speed, experimental plots ($n = 24$) were divided into three classes according to plot means of HT. Class 1 comprised eight plots with highest values of mean HT and class 3 comprised 8 plots with the smallest mean HT.
5. For within-plot comparison of physicochemical leaf properties, six model trees from each studied plot were divided into three classes according to their HT; class 1 comprised two tallest, class 2 two medium-sized and class 3 two shortest trees from each plot.

Tukey HSD multiple comparison test was applied to determine the significant differences between group means after one-way ANOVA. Distance weighted least squares fitting procedure (STATISTICA 7) was used for smoothing the distribution curves of HT and *Z* in different soil groups (stiffness = 0.1) and the relation curves between *Z* and HT in three growth classes (stiffness = 0.6).

The mean values are followed by ±1S.E. in the text. Level of significance $\alpha = 0.05$ was applied in all cases.

3. Results

3.1. Growth characteristics

The density of the studied 5-year-old plantations varied from 650 to 1440 trees per ha; the average density was 1059 ± 23 trees per ha. As the average initial density had been 1300 trees per ha, the average survivability of hybrid aspen after the 5th growing season was 81%.

The most conspicuous feature of the studied dendrometric characteristics (Table 1) is their high variability. The highest and the lowest recorded mean HT of trees in the studied 5-year-old plantations (4.7 ± 0.08 and 1.1 ± 0.06 m, respectively) differed more than four times. HT of the biggest trees reached over 7 m and DBH over 6 cm.

In seven experimental plots the mean HT was more than 4.0 m, and the mean Z was over 1 m in six plots. The distribution of 5-year-old hybrid aspens by HT is shown in Fig. 1.

In Fig. 1 data on all the measured trees (altogether 4996 trees from 51 experimental plots) is presented and we can observe that, although most trees have shown quite modest growth rate there are some that have grown 2–3 times faster. The distribution of the trees by DBH is similar.

In order to study the relations between the growth characteristics, Pearson's correlation coefficients were computed. All the measured dendrometric characteristics are significantly ($P < 0.01$) correlated to each other. The weakest correlation coefficients were between BLC and other characteristics. BLC also had the lowest coefficient of variation (Table 1). In quite sparsely spaced young plantations the light conditions are similar in all canopy layers and intensive natural pruning has not yet begun. Analysis of variance was applied to test the significance of the differences in 51 plot means of the studied dendrometric characteristics. The differences in all traits (HT, DBH, Z, BLC and DC) were significant at $P < 0.001$. According to one-way ANOVA the current year height increment was significantly different between experimental plots belonging to different growth classes ($F = 35.52$, $P < 0.001$) but the differences in relative height increment were not significant ($F = 0.61$, $P = 0.55$). Fig. 2 represents relations between HT and Z in the three plantation growth classes. The aim is to compare the height increment of trees with the same height, but belonging to different height class plantations.

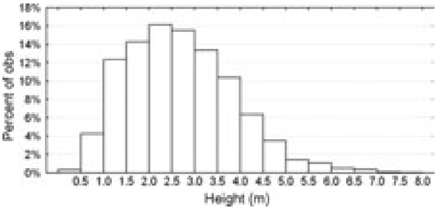

Fig. 1. Distribution of the measured trees by height. Upper boundaries of height classes are displayed on the horizontal axes.

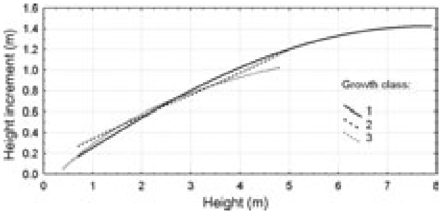

Fig. 2. Relation curves between height increment and height in three growth classes (class 1 = the highest, class 3 = the shortest plantations).

3.2. Soil properties

The relations between the physicochemical properties of the A-horizon and plot means of HT and Z were studied among all experimental plots together at first. Thickness of the A-horizon significantly affected mean HT ($r = 0.41$, $P = 0.003$) and Z ($r = 0.38$, $P = 0.006$); $\mathrm{pH_{KCl}}$ of the A-horizon was in negative

Table 1
Basic statistics of the measured characteristics: tree height (HT), diameter of the stem at breast height (DBH), height increment of the fifth year (Z), diameter of the crown (DC) and height of the beginning of the living crown (BLC)

Growth characteristic	Number of trees and plots		Mean ± 1S.E.	S.D.	Lower quartile	Upper quartile	Min value	Max value	Coef. of variation (%)
HT (m)	A	4996	2.7 ± 0.02	1.18	1.8	3.5	0.4	7.9	43
	B	51	2.7 ± 0.13	0.93	1.9	3.5	1.1	4.7	35
DBH (cm)	A	4428	1.9 ± 0.02	1.20	0.9	2.6	0.1	7.0	65
	B	51	1.6 ± 0.14	0.99	0.7	2.2	0.1	3.9	63
Z (m)	A	4996	0.7 ± 0.01	0.39	0.4	1.0	0.0	2.9	54
	B	51	0.7 ± 0.04	0.26	0.5	0.9	0.2	1.4	37
DC (m)	A	4996	1.2 ± 0.01	0.59	0.8	1.6	0.1	4.0	49
	B	51	1.2 ± 0.06	0.43	0.9	1.4	0.4	2.1	37
BLC (m)	A	4714	0.6 ± 0.01	0.22	0.4	0.7	0.1	1.4	39
	B	46	0.6 ± 0.02	0.13	0.5	0.6	0.3	0.9	23

A: basic statistics calculated on the basis of all measured trees. B: basic statistics calculated on the basis of plot means.

Table 2
Soil classification, concentrations of main mineral nutrients and pH of the humus horizon and respective mean tree height (HT) and height increment of the fifth year (*Z*) of the studied experimental plots

Soil classification (FAO-UNESCO)	N1[a]	N2[b]	HT ± 1S.E. (m)	*Z* ± 1S.E. (m)	Humus horizon			
					pH_{KCl}	Extractable		Total N (%)
						P (mg kg^{-1})	K (mg kg^{-1})	
Automorphic soils (upland well-drained soils)								
Calcaric Cambisol	2	168	1.2 ± 0.04	0.2 ± 0.02	7.2	82	276	0.17
Calcaric Luvisol	1	75	2.2 ± 0.07	0.6 ± 0.04	6.3	18	88	0.14
Cambic Arenosol	3	262	2.8 ± 0.09	0.6 ± 0.02	6.0	151	90	0.08
Chromic Cambisol	3	292	2.5 ± 0.05	0.8 ± 0.02	6.8	50	139	0.13
Pachi-Cambic Arenosol	1	124	4.7 ± 0.08	1.4 ± 0.03	4.5	153	42	0.08
Eutric Cambisol	2	146	2.2 ± 0.06	0.5 ± 0.02	6.5	149	125	0.08
Glossic Albeluvisol	2	191	3.1 ± 0.06	0.8 ± 0.02	4.8	40	44	0.07
Haplic Phaeozem	1	117	3.5 ± 0.06	0.9 ± 0.04	6.4	32	82	0.08
Leptic Podzol	1	107	4.5 ± 0.12	0.8 ± 0.03	5.0	300	133	0.16
Mollic Planosol	9	862	2.6 ± 0.03	0.7 ± 0.01	6.0	111	113	0.09
Rendzic Leptosol	1	115	1.8 ± 0.06	0.5 ± 0.02	7.5	43	147	0.24
Total	26	2459	2.7 ± 0.03	0.7 ± 0.01	6.1	103	119	0.11
Semihydromorphic soils								
Buried-gleyic soil	1	81	4.0 ± 0.11	1.0 ± 0.04	5.4	83	66	0.13
Gleyic Albeluvisol	2	199	3.5 ± 0.07	0.8 ± 0.02	4.4	76	94	0.14
Gleyic Cambisol	1	94	1.6 ± 0.04	0.6 ± 0.02	6.7	98	48	0.21
Gleyic Luvisol	2	185	2.8 ± 0.05	0.5 ± 0.02	6.0	84	97	0.09
Gleyic Planosol	1	113	4.2 ± 0.12	1.0 ± 0.05	6.1	112	118	0.10
Pachi-Gleyic Cambisol	1	99	2.8 ± 0.07	0.9 ± 0.02	5.9	28	65	0.17
Molli-Gleyic Planosol	8	825	2.6 ± 0.04	0.7 ± 0.01	5.6	50	75	0.13
Total	16	1596	2.9 ± 0.03	0.7 ± 0.01	5.6	65	80	0.13
Hydromorphic soils (lowland water-logged soils)								
Calcaric Gleysol	1	118	2.6 ± 0.06	0.7 ± 0.02	7.5	41	63	0.27
Eutric Fluvisol	1	132	1.9 ± 0.04	0.4 ± 0.02	4.7	30	238	0.18
Eutric Gleysol	1	95	2.3 ± 0.05	0.7 ± 0.03	5.3	38	60	0.11
Mollic Gleysol	5	470	2.7 ± 0.04	0.7 ± 0.02	6.0	42	91	0.24
Total	8	815	2.5 ± 0.03	0.6 ± 0.01	5.9	40	102	0.22

[a] Number of experimental plots.
[b] Number of observed trees.

correlation with HT ($r = -0.32$, $P = 0.02$). The concentration of P was weakly related to HT ($r = 0.28$, $P = 0.045$); no significant correlation was found for N and K. Concerning the physical properties of the A-horizon, growth performance of hybrid aspens during the first 5 years was negatively correlated with the concentration of clay (HT: $r = -0.39$, $P = 0.005$; *Z*: $r = -0.40$, $P = 0.003$) and gravel (HT: $r = -0.43$, $P = 0.002$). No significant correlation was found between HT, *Z* and the concentration of sand in the A-horizon. During the following analysis, experimental plots were grouped according to both soil properties and growth characteristics for more detailed results. Table 2 represents the studied experimental plots by soil types, main properties of the humus horizon, and growth performance of hybrid aspens. One experimental plot lies on Sapric Histosol and due to extreme soil conditions was excluded from further analysis.

According to the moisture regime, most of the study areas are situated on automorphic soils ($n = 26$), followed by soils indicating temporary waterlogging in autumn or in early spring, i.e. semihydromorphic soils ($n = 16$) and hydromorphic soils ($n = 8$). During the first 5 years, hybrid aspens have grown faster on automorphic and semihydromorphic field soils; growth has been slower on hydromorphic soils.

The most common soil type in the studied plantations was Planosols ($n = 18$), followed by Cambisols ($n = 9$) and Gleysols ($n = 7$). Such a division is affected by the share of soil types on agricultural lands in south-eastern and central parts of Estonia (Kokk, 1995), where most of the experimental plots are situated. Table 2 shows the high variability in the concentrations of NPK in the humus horizon of the studied field soils. This could be explained by different fertilizing practices during the previous use.

Correlation coefficients describing the relations between growth of the trees in 5-year-old hybrid aspen plantations and chemical and physical soil properties were computed in three moisture classes (automorphic, semihydromorphic and hydromorphic soils). Thickness of the humus horizon was positively correlated with HT and DBH; on automorphic soils, $r = 0.47$ ($P = 0.016$) and $r = 0.51$ ($P = 0.008$), respectively; on hydromorphic soils $r = 0.84$ ($P = 0.008$) and $r = 0.90$ ($P = 0.002$), respectively. No significant correlation at $P < 0.05$ was observed on semihydromorphic soils.

Table 3
The influence of soil texture and moisture condition on mean tree height (HT), height increment of the fifth year (*Z*) and relative height increment (Zr) of 5-year-old hybrid aspens

Dominant profile texture	Soil classification			
	Automorphic	Semi-hydromorphic	Hydromorphic	Total
HT means ± 1S.E. (m)				
Clay loam	N/A[a]	N/A	1.5 ± 0.03 3	1.5 ± 0.03 4
Loam and silt loam	1.3 ± 0.04 c3[b]	3.5 ± 0.05 a1	2.5 ± 0.05 b2	2.9 ± 0.04 2
Sandy loam	2.5 ± 0.02 b2	2.9 ± 0.05 a2	2.5 ± 0.04 b2	2.6 ± 0.02 3
Loamy sand	3.5 ± 0.06 a1	2.1 ± 0.04 b3	3.6 ± 0.07 a1	3.1 ± 0.02 1
HT total	2.7 ± 0.03 b	2.9 ± 0.03 a	2.5 ± 0.03 c	2.7 ± 0.02
Z means ± 1S.E. (m)				
Clay loam	N/A	N/A	0.3 ± 0.02 4	0.3 ± 0.02 4
Loam and silt loam	0.2 ± 0.02 c3	0.9 ± 0.02 a1	0.5 ± 0.01 b3	0.7 ± 0.01 3
Sandy loam	0.7 ± 0.01 b2	0.8 ± 0.01 a2	0.7 ± 0.02 b2	0.7 ± 0.01 2
Loamy sand	0.8 ± 0.02 b1	0.6 ± 0.02 c3	1.1 ± 0.04 a1	0.8 ± 0.01 1
Z total	0.7 ± 0.01 a	0.7 ± 0.01 a	0.6 ± 0.01 b	0.7 ± 0.02
Zr means ± 1S.E. (%)				
Clay loam	N/A	N/A	19.9 ± 0.17 3	19.9 ± 1.31 3
Loam and silt loam	18.3 ± 1.36 b3	24.9 ± 0.52 a2	20.9 ± 0.63 b3	22.7 ± 0.40 3
Sandy loam	28.0 ± 0.29 a1	28.9 ± 0.46 a1	26.6 ± 0.50 a2	28.2 ± 0.22 1
Loamy sand	24.3 ± 0.42 c2	27.6 ± 0.70 b1	31.5 ± 0.93 a1	26.1 ± 0.35 2
Zr total	26.8 ± 0.24 a	27.7 ± 0.32 a	24.6 ± 0.39 b	26.8 ± 0.17

[a] Data not available.

[b] Letters within each row and numbers within each column denote significant differences between means determined by Tukey HSD test ($P < 0.05$) after one-way ANOVA.

In our study, hybrid aspen has preferred slightly acid automorphic soils during the first five growing seasons. We found that pH_{KCl} of the humus horizon was in negative correlation with mean HT ($r = -0.51$, $P = 0.008$), DBH ($r = -0.50$, $P = 0.01$) and Z ($r = -0.42$, $P = 0.03$). No significant correlations were observed on semihydromorphic and hydromorphic soils.

The concentration of extractable P in the humus horizon was correlated with *Z* and Zr in plantations on hydromorphic soils ($r = 0.92$, $P = 0.001$ and $r = 0.83$, $P = 0.01$, respectively). No significant correlations were observed on automorphic and hydromorphic soils. No significant relations were found between concentrations of N and K in the humus horizon and the growth traits within soil moisture groups.

Soils were divided into four groups according to the dominant profile texture and moisture condition of the A-horizon, in order to study the influence of soil physical properties on the growth of hybrid aspens. The results (Table 3) show that plot means of HT, *Z* and Zr are significantly related to soil texture and moisture conditions.

The differences in growth characteristics are significant between soils with different textures within the same moisture class as well as between moisture classes.

The mean HT is significantly different between three moisture classes, but there is no significant difference in mean values for *Z* and Zr between automorphic and semihydromorphic soils. The growth rates have equalised in the mentioned soil classes after five growing seasons.

We studied the effect of soil texture change (differences in the share of soil fractions between centre of the A-horizon and the soil layer at a depth of 0.5 m) on mean HT of the plantations in three groups distinguished by soil moisture condition (auto-, semi-hydro- and hydromorphic soils). Most of the relations were weak and non-significant. The only exception was the influence of the change in sand concentration on the growth of the trees on hydromorphic soils (Fig. 3).

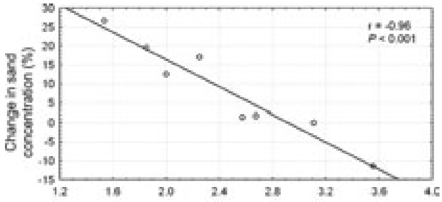

Fig. 3. Relations between height and change in sand concentration from the center of the A-horizon to 0.5 m depth in hydromorphic field soils.

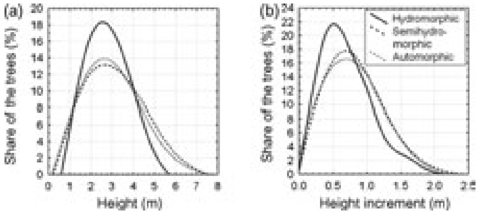

Fig. 4. Distribution curves of height (a) and height increment (b) in three soil moisture classes in 5-year-old hybrid aspen plantations.

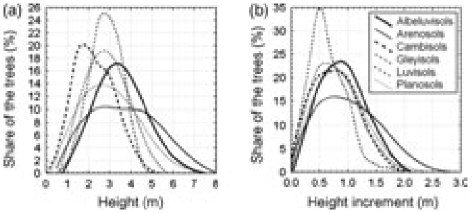

Fig. 5. Distribution curves of height (a) and height increment (b) in different soil classes in 5-year-old hybrid aspen plantations. Soils represented by less than three experimental plots are excluded.

As the next step, a more detailed study was contrived to find out in which soil groups hybrid aspen has achieved the largest dimensions and if *Z* in 5-year-old plantations is still higher in these groups compared to other soil groups. Although we could observe a clear difference in the share of tall trees (HT > 6 m) between hydromorphic and other soils, this tendency is not so clear in the case of *Z* (Fig. 4).

Large trees (HT > 6 m) and also very small trees are missing on hydromorphic soils.

Distribution curves of HT and *Z* in different soil types were derived in order to find out if the same tendency could be observed (Fig. 5).

From the graphs (Fig. 5) we can see that, according to maximum attained HT of the trees in 5-year-old plantations, soils can be divided into two groups. Initial growth acceleration has been better on Arenosols, Albeluvisols and Planosols, while the distribution curves of *Z* are more overlapping, except for Luvisols and Arenosols. Seemingly Arenosols have been the best soil type for hybrid aspens in our study. Altogether 4 experimental plots had been established on Arenosols. Inside this soil group, we found that concentration of N had a strong and significant impact on the mean HT ($r = 0.99$, $P = 0.012$) and *Z* ($r = 0.97$, $P = 0.03$). In two out of the four plots, trees had grown more slowly and the concentration of N in the soil was also lower.

3.3. Leaf properties

The mean foliar concentrations of mineral nutrients and average size of the leaves of 144 analysed trees are presented in Table 4. We observed that in 5-year-old hybrid aspen stands the average foliar NPK ratio was 100N:9P:36K and the average LWA was 98 g m^{-2}. The concentration of P in the leaves was significantly related to the concentration of extractable P in the A-horizon of the soil ($r = 0.62$, $P = 0.001$). No significant correlations between the leaves and soil were found for the concentrations of N and K. Also no significant relations were observed between NPK in the leaves and the share of soil fractions (humus, gravel, clay, sand, dust) in the A-horizon.

Plot means of HT and *Z* were in weak significant correlation with mean concentration of N in the leaves ($r = 0.55$, $P = 0.005$ and $r = 0.50$, $P = 0.01$, respectively). Foliar concentrations of P and K were not significantly correlated with the dimensions of the trees.

The physicochemical properties of the leaves were compared between experimental plots belonging to different growth classes. According to one-way ANOVA the mean HT in the three growth classes was significantly different ($F = 71.6$, $P < 0.001$). The results (Table 4) showed that the model trees from experimental plots with higher mean HT (classes 1 and 2) had significantly higher concentrations of N and P in the leaves. Concentration of K in the leaves was higher in plots from class 3 (Table 4). The size of the leaves was not significantly different among the three classes.

The physicochemical properties of the leaves were compared also within the experimental plots. Within a plot the model tree HT class was not significantly correlated with leaf properties, although slightly larger mean values of concentration of N, single leaf area, weight, and LWA were found for larger-sized trees.

4. Discussion

According to the study, most of the trees have shown quite a modest growth rate during the first 5 years. However, there were also plantations where trees showed 2–3 times faster growth, which confirms that in well suited site conditions hybrid aspen has high production potential in Estonia. One reason for unequal growth rates could be the different genetic background of the trees. Twenty seven hybrid aspen clones had been randomly planted, on average 15 clones per one plantation. According to literature, hybrid aspen clones have shown a high level of variability in phenological, physiological, growth, and wood properties (Yu et al., 2001b; Yu and Pulkkinen, 2003). In our study the variation of dendrometric characteristics within

Table 4
Physicochemical properties of the leaves (±1S.E.)

	Concentration of mineral nutrients in the leaves			Single leaf		
	N (%)	P (%)	K (%)	Area (cm^2)	Weight (g)	LWA[a] (g m^{-2})
Total	2.15 ± 0.02	0.20 ± 0.00	0.76 ± 0.02	19.35 ± 0.54	0.19 ± 0.01	98.2 ± 0.7
Plantation height class						
1	2.32 ± 0.03a[b]	0.23 ± 0.01a	0.67 ± 0.03b	18.62 ± 0.77a	0.19 ± 0.01ab	100.1 ± 0.9a
2	2.07 ± 0.03b	0.19 ± 0.01b	0.78 ± 0.03ab	20.91 ± 0.97a	0.21 ± 0.01a	99.9 ± 1.1a
3	2.07 ± 0.04b	0.20 ± 0.01b	0.83 ± 0.04a	18.50 ± 1.02a	0.17 ± 0.01b	94.6 ± 1.3b

[a] LWA—leaf weight per area.

[b] Letters within each column denote significant differences between means determined by Tukey's test ($P < 0.05$) after one-way ANOVA.

an experimental area was relatively lower than that of all the studied trees (Table 1). For example the average coefficient of variation of HT within experimental plots was 35% compared to 43% for all measurements. Therefore, it is unlikely that differences in the plot mean growth characteristics are influenced more strongly by the choice of clones than by differences in site properties. Based on ANOVA we are able to state that the great variability in growth rate does not have an occasional nature. Dimensions of the trees are significantly different among the studied experimental plots. Therefore, the aim of the following analysis was to determine the factors that have had significant impact on the early growth of hybrid aspen.

The influence of genotype on the growth of the trees cannot be denied. One feature that is presumably controlled by genotype is the shape of the tree crown; in the current study, DBH and DC showed higher coefficients of variation compared to HT (Table 1). Visual observations allow us to predict that different clones should be partly detected in nature according to their phenotypic features, particularly the habitus of the crown. Subsequent research should concentrate on selection of the best performing hybrid aspen clones in Estonian soil and climate conditions. In addition to superior growth characteristics, susceptibility to diseases, pests and browsing must be considered. The most frequent reasons that have caused the death of hybrid aspens during the first growing seasons in Estonia have been droughty weather after planting, and intensive weed competition (Reisner, 2001; Vares, 2005). During the first 5 years browsing by big game has not been considerable, with some exceptions, especially by roe deer bucks, but the situation is likely to change in older stands when more intensive browsing by elk (*Alces alces* L.) will presumably occur (Tullus et al., 2004).

The growth characteristics in 5-year-old hybrid aspen plantations that have shown faster growth rate in Estonia are comparable to the results from Sweden and Finland. According to Yu et al. (2001a) the mean HT of four different hybrid aspen clones, based on five top height trees, varied from 4.4 to 5.5 m and mean DBH from 3.6 to 4.3 cm in 5-year-old stands in South-Finland. Plot means of HT based on five top height trees for the five highest experimental plots in our study were between 5.2 and 6.8 m and the respective values for DBH were between 4.4 and 6.3 cm. In Sweden the mean HT of a 5-year-old experimental hybrid aspen plantation has been recorded as 4.7 m (Johnsson, 1967). The greatest plot mean of HT (4.7 ± 0.1 m) in Estonia was measured on an experimental plot that is situated in the middle of a slope. Above average growth characteristics (mean HT 3.3 ± 0.1 m) were also recorded for another experimental area on a slope. The positive correlation between growth of hybrid aspens and slope of the site has been observed also in Finland (Yu and Pulkkinen, 2003).

The distribution of the trees by dendrometric characteristics at an early growth stage raises the question: will the differentiation of plantations at a young age intensify or diminish at an older age? There are some signs that indicate that the growth speed of hybrid aspen at a young age is not related to the growth speed in the following years. The factors that cause growth stress at a young age could lose their influence at an older age. A similar trend has been noticed in Sweden (Rytter and Stener, 2005). An indication of this is the fact that according to ANOVA the relative height increment of the fifth growing season is similar in plantations with different growth rates.

From Fig. 2 we can observe that relation curves between HT and *Z* in different growth classes are overlapping. We can conclude, for example: the tallest trees from the third plantation class (shortest plantations) have demonstrated equal height increment with the shortest trees from the first class (highest plantations), the height of the mentioned trees is the same.

The height increment of the fifth growing season depends more on the size the tree has achieved during the previous growth period than on the plantation (site properties) where it grows. Such a conclusion is probably valid only in young stands. By the fifth growing season the differentiation of the plantations by growth parameters has been most strongly affected by physical soil properties (soil texture, moisture condition) as well as by intensity of browsing. The influence of the soil mineral nutrient pool has been of smaller importance on abandoned agricultural lands that have been fertilised during the previous land use. Fig. 2 shows that the rise in height increment of taller trees is stabilizing at about 1.4 m. We can forecast that the following growth period (5–10 years) will not substantially increase the differences in mean absolute values of growth parameters. But the transposition in growth speed might happen, influenced by clonal heritage. The comparison of different hybrid aspen clones in Finland (Yu et al., 2001a) has shown that the ranking of clones for stem volume and other growth characters changed considerably during the first 5 years.

Plant–soil–nutrient interactions are determined by a wide range of environmental and plant characteristics. Nutrient availability to the plant depends not just on the quantity of the element in the soil, but also on whether it is in a form the plant can use, and whether the nutrient is mobile or immobile in the soil. Mineral nutrient acquisition depends on root activity, adequate soil water levels, presence of root pests in the soil, mycorrhizal fungi, etc. (Dickmann et al., 2001).

In boreal forests the concentration of available N is considered the most limiting factor for the growth of the trees. We did not observe any relations between foliar N and N in the A-horizon of the soil in young hybrid aspen plantations. Due to fertilization practice during the former land use it is possible that previous field soils contain a sufficient supply of N and other mineral nutrient for the early growth period of hybrid aspen plantations. On the other hand we can predict that these supplies are not likely to meet the annual nutrient consumption of fast-growing hybrid aspen during the whole rotation period. Among the studied soil groups, N concentration had significantly influenced the growth of the trees in plantations established on Arenosols. Both very well and quite poorly growing stands were present on Arenosols. Consequently the concentration of mineral nutrients in the soil, particularly N, has started to affect the growth speed. Therefore, the need to fertilise the plantations is probably going to arise. The impact of soil N supply on the growth speed of hybrid aspen could strengthen after the canopy closure, which means intensifying competition for light and root competition for mineral nutrients between the trees. Results from North-America and Canada have shown that the annual N demand of fast-growing poplars and their hybrids is much greater compared to other endemic deciduous and coniferous trees (Stanturf et al., 2001). At the same time many poplar species do not respond to N additions unless accompanied by additions of P, K, or other nutrients (Blackmon, 1976). Nitrogen is said to be the major nutrient limiting poplar productivity, although P, Zn and lime can be beneficial (Heilman and Xie, 1993). In our study, faster-growing hybrid aspen plantations had a larger concentration of N in the leaves, which means better N acquisition.

According to literature the optimal foliar NPK ratio for poplars is 100N:11P:48K (Stanturf et al., 2001). In Finland the mean foliar N concentration of 5-year-old hybrid aspens has been measured as 2.61%, the mean single leaf area as 18.44 cm^2 and the mean LWA as 72.3 g m^{-2} (Yu, 2001). In Estonia the average foliar NPK concentrations in a 35-year-old *P. tremula* stand have been measured as follows: N 1.9%, P 0.15% and K 1.5% (Mandre et al., 1998). According to the current study the average foliar N and P concentrations in 5-year-old hybrid aspen stands were slightly greater and the concentration of K was two times smaller. LWA is supposed to be the highest in dominating trees and in the top part of the canopy. In a 35-year-old *P. tremula* stand the mean LWA has been measured as 76 g m^{-2} in Estonia, whereas the respective value for suppressed trees and lower canopy layers was 65 g m^{-2}, and for dominant trees and upper canopy layers 100 g m^{-2} (Tullus and Tamm, 1997). According to Niinemets and Kull (1994) the mean LWA based on leaves gathered from the upper and lower third of the canopy has been measured as 86.7 ± 2.4 g m^{-2} for *P. tremula* in Estonia. The average LWA of hybrid aspen in our study (98 g m^{-2}) is comparable to the results from the upper canopy layers of *P. tremula*. The canopies of the studied 5-year-old hybrid aspens have not closed yet, light conditions are similar in all canopy layers, and LWA has maximum values inherent to the species. The leaves are slightly thicker in plantations with higher mean HT.

Critical value for P in poplar leaf was found to be 1.4 g kg^{-1} (van den Burg, 1985) and for N 23–25 g kg^{-1} (van den Burg, 1985; van den Driessche, 1999). According to Table 4, and the above presented literature values—the aspens in our plantations were well supplied with these nutrients.

At the same time no significant correlation was found between foliar N concentration and concentration of N in the humus horizon. Consequently, foliar N concentration related to growth speed of the trees has been affected by other factors that have ensured better N acquisition from the soil in young plantations. One reason for that could be microbiological activity, which is better on automorphic well aerated soils with smaller bulk density. For example, the low N concentrations in flooded woody plants reflects reduced absorption of nitrate due to the effect of low oxygen supply on root metabolism; also the uptake of potassium and phosphorus is reduced in waterlogged soils (Kozlowski et al., 1991).

The study of relations between physicochemical soil properties and growth characteristics allows us to make some general conclusions about site preferences in 5-year-old hybrid aspen plantations during the early growth period. Most of the field soils in the current study had relatively light loamy sand and sandy loam textures. In forest lands, such soils have low P concentrations. On previous agricultural lands the P content of soils is higher due to fertilizing during previous use and this has probably enhanced the early growth of hybrid aspen. Positive effect of P-fertilization on the growth performance of hybrid aspen seedlings has been noted in Canada (Liang and Chang, 2004).

Among the studied soil properties, soil texture and moisture condition had the strongest and most reliable influence on mean growth characteristics in 5-year-old hybrid aspen plantations. Our study confirmed the suitability of automorphic and semihydromorphic soils with sandy loam and loamy sand texture for hybrid aspen. The same tendency has been observed also in North-America for poplars in general (Stanturf et al., 2001). The absence of very large and very small dimensional trees on hydromorphic soils shows that apparently hybrid aspens have not suffered from drought on these soils, but they are nevertheless growing in sub-optimal site conditions. Trees with a long height increment in the fifth growing season are present in all soil moisture groups. This could mean that the impact of soil moisture condition on the growth of the trees may change during the following growth period in some cases.

Soils with high clay content and growing-season water tables <60 cm deep are less productive for aspen growth (Perala, 1977; Stanturf et al., 2001). The higher concentration of sand in the upper layers of automorphic soils means better aeration and good conditions for root development and nutrient acquisition. The temperature of sandy soils rises faster in spring, which means that trees can start growth earlier. According to Yu et al. (2001a), hybrid aspen flushes earlier in spring and has a longer growth period compared to *P. tremula*. Aspen has been found to have a certain thermophilic preference in boreal climate. Canadian studies have established that the most productive growth occurred at lower elevations and warm-aspect slopes in the boreal white and black spruce zone (Chen et al., 2002), and that a low vegetation temperature of 6 °C resulted in overall poor growth of *P. tremuloides* (Landhäusser and Lieffers, 1998). From another point of view sandy soils, beside their faster warming, could also have a disadvantage if drought occurred during the vegetation period.

According to Stanturf et al. (2001) poplars prefer pH levels of 6.0–6.5, but they grow well between 5.5 and 7.5. We established a weak negative correlation between pH of the humus horizon and the tree growth on automorphic soils. It might be not a direct influence while sandy soils have usually lower pH levels. Coarse texture in combination with high pH (e.g. Calcareous Luvisols) resulted in a significantly slower growth rate (Table 2). Aspen appears to be a Ca-demanding species and it accumulates relatively large quantities of Ca in its stems, although the maximum accumulation rate does not occur until trees are at least 20–30 years old (Alban, 1982).

The most productive aspen growth occurs on well drained and aerated, loamy, nutrient-rich soils derived from base-rich parent materials (Chen et al., 2002). The common feature of till-developed soils that are typical for South-East Estonia is their duplex profile. This two layered texture profile could be caused by the process of till ablation or also illuvation during soil development. It means that nutrient acquisition conditions for the tree roots within the same soil type or soil group could be strongly influenced by the change of sand and clay concentrations along the soil profile. Lower-lying soil horizons of Luvisols, Albeluvisols, Planosols are more clayey, less leached and therefore consist of more bases. Base rich parent material favoured trembling aspen growth in Canada (Chen et al., 2002).

We established that hybrid aspens have grown better when the concentration of sand in deeper layers of hydromorphic soils has been higher (Fig. 3). The concentration of sand in the lower layers of hydromorphic soils acts as a natural drainage system. Apparently the high within-group variability of hybrid aspen growth characteristics on hydromorphic soils (Table 2) could be at least partly explained by changes in the sand concentration along the soil profile. Temporary anaerobic conditions in clay soils have suppressed the growth of hybrid aspen during the first 5 years. In addition to worse nutrient acquisition conditions and aeration of clay soils, they also warm up later in spring, which has probably delayed the start of the growth period. Root densities for the aspen in the clay loam soil texture series were negatively correlated with clay content and bulk density (Strong and La Roi, 1985).

In many landscapes, pedogenesis occurs in response to the way water moves through the landscape; therefore, the spatial distribution of topographic attributes that characterize these flow paths inherently capture the soil variability as well (Moore and Hutchinson, 1991). Within their natural habitat many poplar species grow on the lower inclined parts of the relief, where mineral-rich water flows from the surroundig slopes (Dickmann, 2001). A greater forest productivity on lower slopes was expected, as lower slopes usually have a greater variability of soil moisture and nutrients (Fralish, 1994). According to hydrophysical properties, the mobility of water in coarse textured soils is higher than in heavy textured soils. On clay soils the rise in sand concentration in deeper soil layers assures a better infiltration rate and better aeration conditions for the deeper tree roots.

The study of distribution curves of HT and *Z* in different soil classes (Figs. 4 and 5) showed that although tall trees were not present in all soil classes, the differences in distribution of the height increment of the fifth growing season were not so notable. This is another distinctive feature of the studied hybrid aspen plantations, which shows that site-growth interactions during the early growth period are about to change during the next years. The ranking of the plantations by mean HT after the fifth growing season should not be considered as a basis for making predictions for the whole rotation period.

5. Conclusions

Based on our results we found evidence supporting the main hypothesis of the study that the high variability in early growth speed of hybrid aspens can be explained by differences in physicochemical soil properties.

The first objective of the study was to describe the basic dendrometric characteristics in 5-year-old hybrid aspen plantations in Estonia. We established that the growth traits were highly variable, the plot means differed over three times. The within plot variability was lower than that of all observations, the growth of the trees was significantly different between the plots.

The second objective was to describe interactions between tree growth and properties of the leaves and soil. The growth rate of the studied trees was significantly correlated with dominant soil profile texture and drainage condition. Weak correlation was found between mean growth characteristics (HT, *Z*), pH level, concentration of extractable P in the humus horizon and thickness of the humus horizon. The initial soil-growth study showed that during the early growth period hybrid aspens preferred aerobic conditions and benefit from faster soil warming in the spring, which was ensured by the coarse texture of soils. We doubt that the better growth on sandy automorphic soils could be maintained for the whole tree growth period, rather it is a reflection of the easier development of the root system. However, biologically vigorous early growth could also be advantageous for the following years. Growth of the trees has been better on automorphic and semi-hydromorphic soils; hydromorphic clay soils have been less favorable. The change in the share of texture fractions along the soil profile has a significant impact for aspen growth. Higher sand content in deeper layers has been an advantage for the early growth of hybrid aspen on hydromorphic soils. During the first 5 years the impact of the concentration of the main mineral nutrients on the growth of the trees has been lower than the influence of soil texture and moisture conditions. The concentrations of P and K in the leaves were not significantly correlated and the concentration of N was in weak significant correlation with the size of hybrid aspens. No significant relations were found between foliar concentrations of NPK and the concentrations of the respective nutrients in the humus layer. Since the most important factors that have affected the early growth of hybrid aspen have been moisture and aeration conditions of the soil, and the supply of main mineral nutrients in previous field soils has been good, there is no direct need for fertilization.

The third objective was to make predictions about the changes in the ranking of plantations by growth speed and about the importance of growth factors during the remaining rotation period. We can conclude that the early growth of the trees is influenced by several occasional factors within one plantation as well as between different plantations. Based on the study of current year height increment and relative height increment it can be predicted that the modest growth rate of hybrid aspens during the first years after planting could recover after some years in some stands. In the fifth season the height increment depends on the size that the trees have already achieved, and some factors that have been important during the previous years are less important. The ranking of 5-year-old plantations by growth speed is therefore likely to change during the following years.

Although fast growth speed was observed only in a few plantations and a relatively small proportion of trees, it still confirms that in proper site conditions hybrid aspen could be a promising deciduous for pulpwood production on abandoned agricultural lands in Estonia. While the high variability in growth characteristics must be at least partly influenced by the clonal origin of the planting material, the selection of high-yielding hybrid aspen clones should be considered for better and more homogeneous growth results in Estonian conditions.

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REGULAR ARTICLE

The impact of available water content in previous agricultural soils on tree growth and nutritional status in young hybrid aspen plantations in Estonia

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Abstract The impact of soil available water content (AWC) on the growth and foliar nutrient concentrations of trees in 7-yr-old hybrid aspen (*Populus tremula* L. x *P. tremuloides* Michx.) plantations established on abandoned agricultural lands was studied. AWC in the topmost 75 cm soil layer was significantly related to height growth and foliar N concentration of hybrid aspens. The correlations were stronger on well-drained automorphic soils and in the case of a dry growing season with insufficient precipitation. AWC over 150–160 mm can be considered sufficient, and below 120 mm insufficient for fast growth of hybrid aspen. The differences in AWC were less pronounced in the top 25 cm soil layer but were more noticeable in the 25–50 and 50–75 cm soil layers. AWC estimated as a function of soil specific surface area and bulk density was shown here to be a significant indicator for site selection for establishing hybrid aspen plantations. Foliar N concentration over 2.7% can be considered optimal and below 2.4%, insufficient for hybrid aspen on the studied soils. Foliar concentrations of P (on average 0.24%) and K (on average 0.79%) varied little and, thus, did not correlate with tree growth. The most suitable previous agricultural soils for afforestation with hybrid aspen would be moderately drained *Albeluvisols*, *Luvisols* and *Planosols*.

Keywords Abandoned agricultural land · Available water content · Foliar nutrients · Hybrid aspen · Short-rotation forestry · Soil properties

Introduction

Climatic conditions and nutrient availability are important regulators for tree growth especially in boreal areas, as nutrient mineralization is slow (Weih 2004). Soil water properties influence both nutrient uptake by the plants as well as biotic and abiotic processes in the soil, which in their turn affect the content of available nutrients for the plants. Soil available water content (AWC) can be used as an indirect measure of site quality in forestry or agriculture. AWC is the amount of water actually available to the plants; it is the amount of water

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stored in the soil at field capacity minus the water that will remain in the soil at permanent wilting point (FAO 1985). It can be estimated as a function of mean weight diameter of soil particles, soil specific surface area and bulk density (Kitse 1978; Walczak et al. 2002).

The application of short-rotation plantation forestry (SRF) and agroforestry practices has steadily expanded northward reaching hemi-boreal and boreal regions with long traditions of natural long-rotation forest management systems. In particular, abandoned agricultural lands are recommended for the establishment of SRF plantations (Karacic et al. 2003; Weih 2004). At the same time little information is available about site selection for SRF plantations in the mentioned region. Although the impact of soil water and nutrients on biomass production of trees, both in natural and plantation forestry systems has been well documented on forest lands (Chen et al. 1998; Sampson and Allen 1999) and in agricultural systems (Wassenaar et al. 1999; Morgan et al. 2003), less attention has been paid to the relation of tree growth regarding these soil properties on afforested agricultural sites (Wall and Heiskanen 2003, 2009). Soil nutrient supplying ability is a function of a complex of biotic and abiotic processes associated with the characteristics of the soil, past management practices, and current nutrient additions (Kelly and Ericsson 2003). Due to long-term tillage and fertilization the physico-chemical properties of field soils are somewhat different from the equivalent forest soils. Cultivation creates a sharp plough layer boundary between top- and subsoil, decreases organic matter content and degrades soil structure and even some compaction problems can occur on fields. After more than 30 years of tree growth, the soil humus horizon properties can still be more similar to arable than to pristine forest soil with respect to organic carbon and phosphorus content (De Keersmaeker et al. 2004; Smal and Olszewska 2008). In general, previous agricultural land use increases soil fertility and the impact from previous use is long lasting (Wall and Heiskanen 2003; Wall and Hytönen 2005).

Young hybrid aspen plantations on abandoned agricultural lands were selected for the current growth-site study since hybrid aspen is recommended for SRF in boreal climate, industrial plantations have been established at various site conditions and few studies have previously focused on hybrid aspen site requirements in the region. Hybrid aspen is capable of growing faster than its parent species during the first 20–30 years, as confirmed in several experimental and commercial plantations in Scandinavia (Yu 2001; Rytter and Stener 2005; Heräjärvi and Junkkonen 2006; Rytter 2006), Germany (Liesebach et al. 1999) and North-America (Li et al. 1993). The aim of short-rotation aspen plantations has changed during the past 50–60 years from producing raw material for the match industry to supplying pulp and paper mills, with most recent emphasis on biofuel production (Beuker 2000; Rytter 2006). The length of the rotation period varies from less than 10 years, suggested for biofuel coppice systems, up to 20–30 years, for production of pulpwood and aspen logs (Liesebach et al. 1999; Beuker 2000; Tullus et al. 2009). Aspens are known as fast-growing trees preferring fertile sites, well-drained and aerated nutrient-rich soils with a medium texture (sandy loam or loamy sand) derived from base-rich parent material, whereas soils that are saturated and water-logged during the growing season and soils with heavy texture are considered less favourable (Stanturf et al. 2001; Chen et al. 2002; Tullus et al. 2007). At the same time, in Canada mature aspen trees growing on clay-rich soils had greater height growth compared to coarser till or sandy soils (Paré et al. 2001; Martin and Gower 2006).

Maximum demand of nutrients in poplar plantations is thought to occur by 5 or 6 years of age (Nelson et al. 1987), but this could be several years later in hemi-boreal sparse aspen plantations, where mean annual biomass increment at an age of 7 years could be still rather low, reaching 2 t DM ha^{-1} yr^{-1}; however at this age a rapid increase in annual biomass production occurs and already 6 t DM ha^{-1} yr^{-1} has been estimated at an age of 9 years (Tullus et al. 2009).

Soil N is the most important nutrient in the boreal and hemi-boreal forests. In addition, aspen communities appear to be more dependent upon N and other organically bound nutrients than coniferous stands (Strong and La Roi 1985). In recently abandoned agricultural soils organic matter containing N is more evenly distributed vertically in topsoil due to previous cultivation activities. Thus N uptake conditions are different from native forest soils where organic matter has gradual distribution in topsoil (Vesterdal and Raulund-Rasmussen 1998;

Wall and Hytönen 2005). The nutritional status of the trees is commonly characterized by analyzing foliar nutrient concentrations and their ratios. In the case of hybrid aspen, critical foliar levels have been reported in the temperate zone (van den Burg 1985, 1990; Jug et al. 1999).

In the current study we will analyse the importance of AWC, nutrient content and pH level of former agricultural soils for the growth and foliar nutrient concentrations of hybrid aspen at an early age. The study area comprises soil types varying from excessively drained xeromorphic *Rendzinas* to temporarily water-logged hydromorphic *Gleysols*. The hypotheses were: (1) AWC in former field soils is an important growth factor for young hybrid aspens especially on well-drained automorphic soils and in growing seasons with insufficient precipitation; (2) sufficient water supply and aeration improves tree nutrition. The practical goal of the study is to improve the methods of site selection based on soil properties for the establishment of hybrid aspen plantations and to evaluate which soils are more promising for afforestation with hybrid aspen.

Materials and methods

Study area

The study comprises 45 permanent experimental plots (each 0.1 ha) within 22 commercial hybrid aspen (*Populus tremula* L. x *P. tremuloides* Michx.) plantations on abandoned agricultural lands and one plantation in a reclaimed oil shale quarry in Estonia. The plantations were established in 1999 and 2000 with 1-yr-old micropropagated plants belonging to 27 different clones (Tullus et al. 2007, 2008). The average density of the plantations at the age of 7 years was 1,042±29 trees ha^{-1}. Most of the sites are located in South-Estonia (Fig. 1), because of the relatively high share of abandoned agricultural lands in this part of the country (Astover et al. 2006), including soils considered suitable for afforestation with hybrid aspen. In each plantation, one to five experimental plots were established. The number of experimental plots depended on the size of the plantation and the expected variability in soil properties. The plots were located in typical parts of the micro-relief of the respective plantation or part of the plantation.

Tree growth data (height and height increment of the current year) from experimental plots in 7-yr-old plantations was used in the study. The trees were measured after the end of the growing season in 2005 (in plantations that had been established in 1999) and in 2006 (in plantations that had been established in 2000). In order to characterize climatic conditions of the study area within the study period, temperature and precipitation data from eight weather stations of the Estonian Meteorological and Hydrological Institute (EMHI) was used. The mean annual temperature during the studied period was 6.1±0.86°C; mean annual precipitation was 630±30.5 mm. The mean

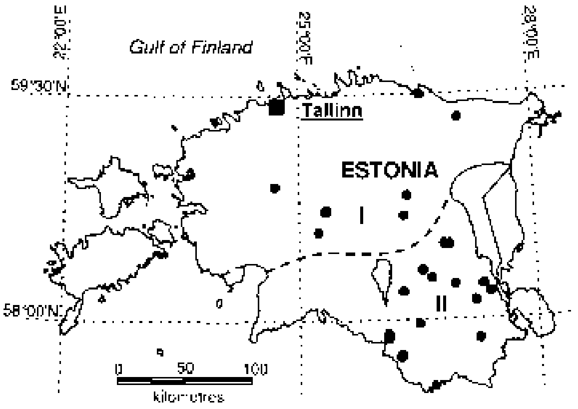

Fig. 1 Locations of the experimental areas. Dashed line indicates the boundary in soil bedrock between Silurian and Ordovician limestone (I) and Devonian sands and clays (II)

precipitation during the growing season (April–October) was 409±31.1 mm. The period from 1999 to 2006 includes two dry years: 2002 (precipitation during the growing season: 274 mm) and 2006 (310 mm) (Fig. 2). As in 2006 some of the studied plantations reached the age of 7 years, we compared the impact of AWC on the current year height increment in those plantations in a dry (2006) and a normal (2005) year. From this aspect we analysed only plantations established in 2000, since plantations established in 1999 did not cover the same range of site properties (AWC range) and thus it would not have been correct to analyse them together.

According to Walter (1955) sufficient moisture for plant growth is secured if precipitation bars rise above the temperature trend line on the climate diagram and the opposite situation indicates drought conditions within the growing season, which happened in July 2006 (Fig. 2).

Soil characterization and analyses

Soil pits were dug in the centre of each experimental plot. Soil type was estimated according to the World reference base for soil resources (WRB 2006). As commercial plantation sites were not randomly, rather to some extent pre-selectively established, soil types were not evenly presented. For statistical analyses a certain soil-based generalization had to be made, in order to make the variability of soil properties within a group smaller than that within the whole soil range (Supplementary Table 1). The soils were grouped according to drainage (depending on their position on the relief and the depth of occurrence and intensity of gley features in the soil profile) as follows: well-drained mineral soils, as automorphic (21 experimental plots); soils with redoximorphic (*stagnic*) properties in subsoil, as semi-hydromorphic (17 plots) and mineral soils developed under the influence of a high ground-water table, as hydromorphic (reductomorphic) soils (7 plots). Such grouping was based on the catena concept, according to which up-slope soils are usually well-drained and oxidized while soils at base of the slope, at least seasonally, are poorly drained and reduced. The degree of gleyzation governs several inherent soil properties and conditions (aeration, temperature, redox potential, biological activity). Hydromorphic soils had been drained for agriculture and therefore could have a better aeration status than indicated by their drainage class, but generally they still preserved their impeded drainage.

In order to determine pH_{KCl}, total N, available P and available K in the soil humus horizon, samples were taken from four random locations in each experimental plot. Chemical analyses were conducted on air-dried samples from which crop residues, root fragments and gravel larger than 2 mm had been removed. The total N in soil samples was determined by the Kjeldahl procedure. To analyse available P and K in the soil, Mehlich 3 extracant was used. The soil pH in 1M KCl suspensions was measured in the ratio 10 g : 25 ml. For each experimental plot, the mean of the four subsamples was calculated. Organic carbon was determined by wet oxidation in H_2SO_4 solution, where $K_2Cr_2O_7$ is used as an oxidant according to Tyurin (1935). Analyses were performed by the Laboratory of Agrochemistry of the Agricultural Research Centre in Saku [/http://pmk.agri.ee]. Soil nutrient concentrations were converted to contents by soil volume and bulk density in humus horizons (Supplementary Table 1). The nutrient contents in the soil humus horizon were calculated as follows:

$$\mathrm{Ncont} = \mathrm{BD} \times L \times \mathrm{Nconc} \times (1 - \mathrm{Gr}),$$

where Ncont = content of the nutrient in the humus horizon, BD = bulk density of the humus horizon, L = depth of the humus horizon, Nconc = concentration of

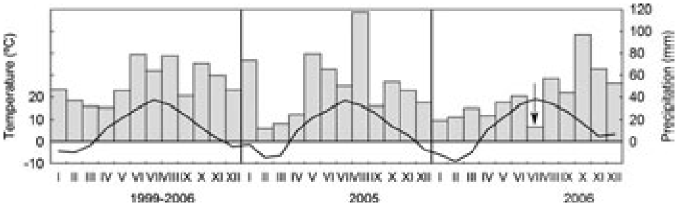

Fig. 2 Climate diagram of the study area. The arrow indicates drought conditions in 2006

the nutrient and Gr = concentration of gravel (soil particles with diameter >2 mm).

We assumed that humus horizons, which in some cases coincided with the plough layers of the studied previously cultivated soils, were generally vertically homogenized in the uppermost part. This was the result of previous tillage, especially in respect to organic matter. Therefore we presented soil nutrients as contents in humus horizon (Supplementary Table 1). In general, semi-hydromorphic soils showed lower pH and hydromorphic *Gleysols* had higher organic C reserves. The higher phosphorus content in semi-hydromorphic and automorphic soils was probably anthropogenic i.e. these soils had been subjected to more intensive field cropping and more P fertilization, compared to *Gleysols*.

Volumetric proportion of fine earth and rock fragments was estimated for each soil horizon on the field. Soil texture of each pit was determined per horizon by the combined sieve and pipette method (USDA 1996).

For bulk density, triplicate undisturbed core samples with 50 cm^3 steel cylinder were taken from the middle of demarcated horizon boundaries. Field sampling was done at neither too dry nor wet conditions, very clayey or organic soils capable of expansive volume change were not presented in the selection. Samples were dried at 105°C for 24 h. Net wet and dry weights were recorded to the nearest 0.01 g and bulk density was measured as dry mass per 50 cm^3 volume. Specific surface area 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). Specific surface area is closely related to particle size and gives a good indication of the water content of a soil, since the more colloidal particles (humus, clay) in a soil, the larger its specific area.

Available water content (AWC, mm) in master soil horizons was estimated according to Kitse (1978) as a function of soil specific surface area (SSA, m^2 g^{-1}) and bulk density (BD, g cm^{-3}) (Supplementary Table 2, Fig. 3) multiplied by the thickness of the soil horizon (L, cm) and corrected with the concentration of gravel (Gr, %):

$$\begin{aligned}
&\text{A horizon}: \mathrm{AWC} = \mathrm{BD}(47.7 - 18.2\mathrm{BD} - 0.04\mathrm{SSA} - 72/\mathrm{SSA})(L/10)(1 - \mathrm{Gr});\\
&\text{E horizon}: \mathrm{AWC} = \mathrm{BD}(44.3 - 18.0\mathrm{BD} - 0.08\mathrm{SSA} - 41/\mathrm{SSA})(L/10)(1 - \mathrm{Gr});\\
&\text{B(C) horizon}: \mathrm{AWC} = \mathrm{BD}(46.5 - 19.1\mathrm{BD} - 0.05\mathrm{SSA} - 64/\mathrm{SSA})(L/10)(1 - \mathrm{Gr}).
\end{aligned}$$

AWC was defined as volumetric difference between field capacity and wilting point i.e. between those water potentials. The lower limit was constantly −1,500 kPa for all soils, but the upper limit was differentiated according to soil texture: −10 kPa for sandy soils and −33 kPa for loams and clay loams. AWC was estimated for all the master horizons (Supplementary Table 2) within 75 cm soil layer ($\mathrm{AWC}_{0\text{–}75\ \mathrm{cm}}$). In order to overcome variability in sequence and thickness of master horizons, AWC was stratified into 25 cm soil layers ($\mathrm{AWC}_{0\text{–}25\ \mathrm{cm}}$, $\mathrm{AWC}_{25\text{–}50\ \mathrm{cm}}$, $\mathrm{AWC}_{50\text{–}75\ \mathrm{cm}}$). AWC was expressed in mm (or in volumetric %) of water present in a particular depth of soil. The depth of the studied soil profile (75 cm) was governed mainly from the inherent soil limits (hard rock or water table) and

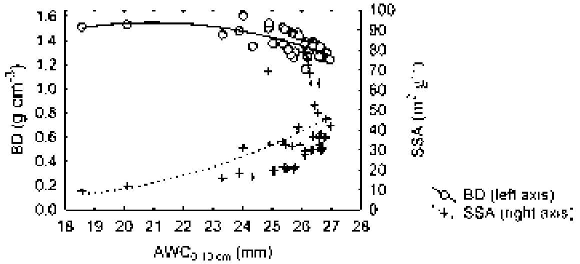

Fig. 3 AWC in the top 10 cm soil layer of 45 experimental plots, related to bulk density (BD) and soil specific specific surface area (SSA)

from the hypothetical effective rooting depth of young aspens.

In the applied AWC equation, bulk density (BD) is one of the input variables, since it is inversely related to soil total porosity. For mineral cultivated soils, which are more or less compacted, a decrease in bulk density increased field capacity and AWC as well (Fig. 3). Mean BD values were similar between soil groups in subsoil horizons, but there were differences in topsoils (Supplementary Table 2). *Gleysols*, which are more enriched with organic matter (Supplementary Table 1), had significantly lower BD values in the A-horizon compared to well-drained soils (Supplementary Table 2). That also caused a sharper boundary between the A-horizon and the following mineral subsoil. Although we estimated soil texture, the data is not shown here, however in AWC calculations it has been integrated together with organic matter into SSA. SSA of subsoil mineral layers is in average range of 16–39 $m^2\ g^{-1}$ (Supplementary Table 2) what corresponds to moderately coarse and medium textured soils.

Foliar analyses

In order to evaluate the nutritional status of the trees, foliar concentrations of major mineral nutrients (NPK) were analysed in the middle of the growing season. The leaves were taken from six sample trees from each plot according to the distribution of the breast height diameters of all the trees.

The concentration of total N in plant samples was determined by standard Kjeldahl procedure using a Kjeltec Auto 1030 Analyzer (FOSS Tecator AB, Höganäs, Sweden); P was determined spectrophotometrically from Kjeldahl digest using a FIAstar 5000 Analyzer (FOSS Tecator AB, Höganäs, Sweden). Concentration of K was determined flamephotometrically. The analyses were performed in the Laboratory of Biochemistry of the Estonian University of Life Sciences.

Statistical analyses

Descriptive statistics and simple regression models were calculated with Statistica 7 (StatSoft, Inc. 2004). Normality of the studied growth, soil and foliar variables was checked with the Shapiro-Wilk's test; soil contents of organic C, total N, extractable P and K were log-transformed. One-way Anova followed by Fisher LSD test was used for multiple comparisons of the mean foliar and growth characteristics between soil groups. Due to multicollinearity with other soil variables, organic C content was excluded from regression analysis. In the case of other studied soil variables the possible multicollinearity, as revealed from the correlation matrix of these variables, was considered to be low.

The optimal and critical levels of foliar concentration of N and AWC in the top 75 cm soil layer were predicted from regressions between tree height and these variables. Depending on the nature of the relations, linear and polynomial regressions were used. The regression outputs corresponding to the upper and lower quartile of plot mean tree heights were used respectively as optimal (sufficient) and insufficient values of the response variable.

The mean values are followed by ± standard error in the text. Level of significance $\alpha=0.05$ was applied in all cases.

Results

Tree growth and soil properties

The plot mean height of the trees and height increment of the 7th year did not vary significantly between soil groups (Table 1). However, the maximum plot mean height reached 7.4–8.0 m and the maximum height increment was 1.7–1.9 m on auto- and semi-hydromorphic soils, exceeding considerably the respective values (5.3 m and 1.1 m) on hydromorphic soils. The tallest individual tree had reached a height of 11.6 m and the greatest measured height increment of the 7th year was 3.1 m.

Between the studied growth, foliar, and soil variables, the highest share of significant correlations were observed on automorphic soils, followed by semi-hydromorphic and hydromorphic soils (Table 2). Organic C content in A-horizon, which due to multicollinearity with soil nutrients was excluded from regression analyses, showed significant positive correlations with $AWC_{0–25\ cm}$ in automorphic and semi-hydromorphic soils as well as in the combined soil data.

Soil available water content

Tree growth traits were significantly affected by AWC in automorphic soils, where AWC explained 24–56% of

Table 1 Growth characteristics of 7-yr-old hybrid aspen plantations in different soil drainage groups and on different soil types (represented by more than one experimental plot) ± S.E. (range)

Soil classification	Mean height, m	Mean height increment during the 7th season, m
Automorphic soils	4.2±0.33 (1.5–7.4)	1.0±0.10 (0.2–1.9)
Planosols	4.8±0.44 (3.4–6.6)	1.2±0.15 (0.7–1.9)
Cambisols	3.2±0.48 (1.5–5.2)	0.7±0.16 (0.2–1.4)
Arenosols	3.1±0.24 (2.8–3.3)	0.7±0.04 (0.6–0.7)
Albeluvisols	5.0±0.26 (4.7–5.2)	1.2±0.02 (1.2–1.2)
Semi-hydromorphic soils	5.0±0.38 (2.4–8.0)	1.0±0.08 (0.6–1.7)
Planosols	4.7±0.64 (2.4–6.9)	1.0±0.14 (0.6–1.7)
Cambisols	3.9±1.07 (2.8–5.0)	1.0±0.26 (0.7–1.2)
Arenosols	7.0±0.90 (6.1–8.0)	1.3±0.38 (1.0–1.7)
Luvisols	4.7±0.12 (4.6–4.8)	1.2±0.01 (1.2–1.2)
Hydromorphic soils	4.0±0.30 (3.0–5.3)	0.9±0.06 (0.6–1.1)
Gleysols	4.2±0.28 (3.3–5.3)	0.9±0.04 (0.8–1.1)
All groups	4.5±0.22 (1.5–8.0)	1.0±0.06 (0.2–1.9)

the total variation of tree height and height increment (Table 2). The simple regression residuals were further analysed in order to find out at which site conditions the regression model was more inaccurate. The model tended to underestimate the growth on *Planosols* and on soils with extractable P content in the humus horizon >800 kg ha^{-1}. The model overestimated growth on *Cambisols* and *Arenosols*, on soils with pH_{KCl} of the humus horizon >7.0 and on a site with very high bulk density of the humus layer (1.60 g cm^{-3}).

The relations between the current year height increment and AWC were stronger in a "dry" year (2006) compared to 2005 with normal precipitation rate during the growing season (Table 3).

The pairwise correlations between AWC in 25 cm soil layers and growth traits of the trees increased with depth in automorphic soils (Table 2). We further analysed how AWC changed within the 75 cm soil profile in plots grouped according to the growth speed of the trees, and which soil types and properties were characteristic to these groups. AWC in the topmost 25 cm soil layer did not vary considerably in former field soils, the distinction of sites by AWC and tree growth was clearer in deeper soil layers (Fig. 4).

In general, automorphic soils showed highest dispersion of AWC and tree height in opposite to hydromorphic soils, which showed converged pattern (Table 1, Figs. 5 and 6), however this could be due to small number of plots on hydromorphic soils. The relationships between tree growth and $AWC_{0–75\ cm}$ suggested that the sufficient $AWC_{0–75\ cm}$ level would be 154 mm (20.5 vol. %) for all studied soil groups and 157 mm (20.9 vol. %) for automorphic soils, the insufficient $AWC_{0–75\ cm}$ levels would be 138 mm (18.4 vol. %) and 121 mm (16.1 vol. %) respectively (Fig. 5).

Nutritional status of the trees

The average foliar nutrient concentrations did not vary between plots belonging to different soil moisture groups (Table 4). Foliar N was significantly related to height growth of the trees (Table 2, Fig. 6a and b). The optimal level of foliar N in the studied 7-yr-old hybrid aspen plantations was 2.7% and the insufficient level was 2.4% (Fig. 6c). Foliar N was significantly ($p<0.01$) above insufficient level on slightly acidic sites (pH 5.5±0.11) and on sites with sufficient $AWC_{0–75\ cm}$ (153±3.7 mm), and below insufficient level on soils with almost neutral reaction (pH 6.7±0.20) and insufficient $AWC_{0–75\ cm}$ (126±11.1 mm).

Discussion

Hybrid aspen growth and hydrophysical soil properties

Soil AWC in the physical sense is a static property, but the actual volume filled with water is subject to

Table 2 Simple correlations between the analysed growth, soil, and foliar characteristics in different soil groups (A—automorphic, S-H—semi-hydromorphic, H—hydromorphic soils)

Variable	Soil group	Height	Height increment in 7th yr	Foliar N	Foliar P	Foliar K	Foliar N/P	Foliar N/K
Height	A	1.00	0.95***	0.72***	0.38	0.09	−0.01	0.30
	S-H	1.00	0.73***	0.67**	−0.07	0.72***	0.48	−0.58*
	H	1.00	0.85*	−0.41	0.34	0.09	−0.66	−0.25
Height increment in 7th yr	A	0.95***	1.00	0.64**	0.42	0.22	−0.10	0.17
	S-H	0.73***	1.00	0.48*	0.07	0.55*	0.19	−0.45
	H	0.85*	1.00	−0.66	0.25	0.19	−0.71	−0.40
AWC$_{0–75\ \mathrm{cm}}$	A	0.62**	0.67***	0.53*	0.37	0.19	−0.09	0.14
	S-H	0.00	0.11	−0.02	−0.52*	−0.20	0.46	0.24
	H	0.75	0.77*	−0.11	0.62	0.17	−0.77*	−0.19
AWC$_{0–25\ \mathrm{cm}}$	A	0.36	0.39	0.23	0.26	0.25	−0.12	−0.04
	S-H	−0.07	0.10	−0.25	−0.06	−0.11	−0.11	0.06
	H	0.59	0.32	0.32	0.51	0.46	−0.41	−0.35
AWC$_{25–50\ \mathrm{cm}}$	A	0.49*	0.54*	0.49*	0.33	0.13	−0.10	0.18
	S-H	0.08	0.15	0.06	−0.44	−0.09	0.44	0.15
	H	0.81*	0.84*	−0.17	0.62	0.42	−0.82*	−0.44
AWC$_{50–75\ \mathrm{cm}}$	A	0.71***	0.75***	0.61**	0.38	0.15	−0.04	0.17
	S-H	0.17	0.01	0.18	−0.29	−0.01	0.37	0.14
	H	0.49	0.56	−0.12	0.46	−0.26	−0.57	0.22
A-horizon pH$_{\mathrm{KCl}}$	A	−0.65**	−0.65***	−0.77***	−0.27	−0.14	−0.11	−0.32
	S-H	−0.45	−0.18	−0.53*	0.30	−0.09	−0.60*	−0.09
	H	0.31	0.49	−0.60	0.15	−0.26	−0.53	0.03
A-horizon total N[a]	A	0.12	0.03	−0.12	−0.29	0.01	0.30	−0.03
	S-H	0.06	−0.30	0.07	−0.39	−0.05	0.45	0.08
	H	−0.37	−0.23	−0.10	0.14	−0.31	−0.18	0.21
A-horizon available P[a]	A	0.46*	0.49*	0.29	0.47*	0.26	−0.27	0.01
	S-H	0.14	−0.02	0.22	0.25	0.28	−0.11	−0.24
	H	0.90**	0.65	−0.08	0.62	−0.12	−0.76*	0.04
A-horizon available K[a]	A	0.31	0.33	0.06	0.29	0.51*	−0.33	−0.31
	S-H	0.09	0.01	0.19	0.12	0.02	0.01	−0.01
	H	−0.19	−0.33	0.56	0.67	0.03	−0.38	0.11

[a] These variables were log-transformed before the analysis

Significant correlations are marked as follows: $0.01< p<0.05$*; $0.001< p<0.01$**; $p<0.001$***

Table 3 Correlations between AWC and the current year height increment during a growing season with normal and insufficient precipitation on automorphic soils

Variable	Normal growing season (2005)	"Dry" growing season (2006)
AWC$_{0–75\ \mathrm{cm}}$	0.59*	0.71**
AWC$_{0–25\ \mathrm{cm}}$	0.33 ns	0.41 ns
AWC$_{25–50\ \mathrm{cm}}$	0.55*	0.67**
AWC$_{50–75\ \mathrm{cm}}$	0.71**	0.82***

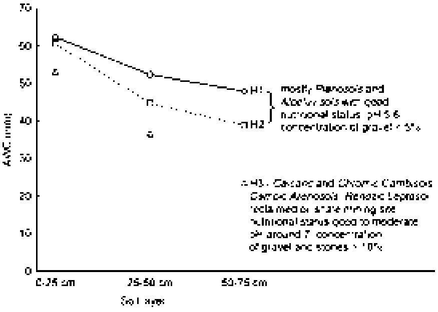

Fig. 4 The mean AWC by soil depths in plots grouped according to mean tree height (H1–good growth, H>5 m; H2–moderate growth, H=3–5 m; H3–poor growth, H<3 m; 7 plots in each group) on automorphic soils

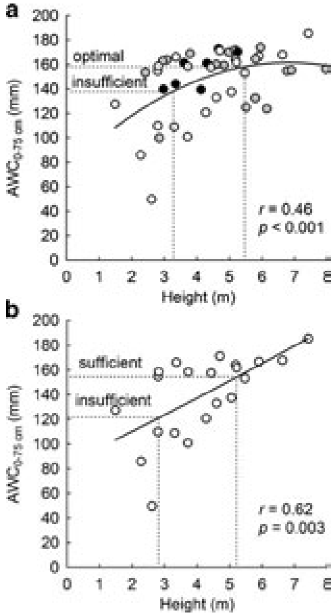

Fig. 5 The relationships between $AWC_{0-75\ cm}$ and mean height of hybrid aspens including **a**) all studied soil moisture groups: automorphic (empty circles), semi-hydromorphic (grey circles) and hydromorphic (black circles) soils and **b**) including only automorphic soils

natural changes, i.e. it is a dynamic property. Potential evapotranspiration measured in Estonian grasslands averaged *ca* 550 mm (Mander et al. 1998). Precipitation during the growing season in dry years (e.g. 2002 and 2006, Fig. 2) covered *ca* 55% and during a normal year (e.g. 2005) *ca* 80% of this demand. Thus,

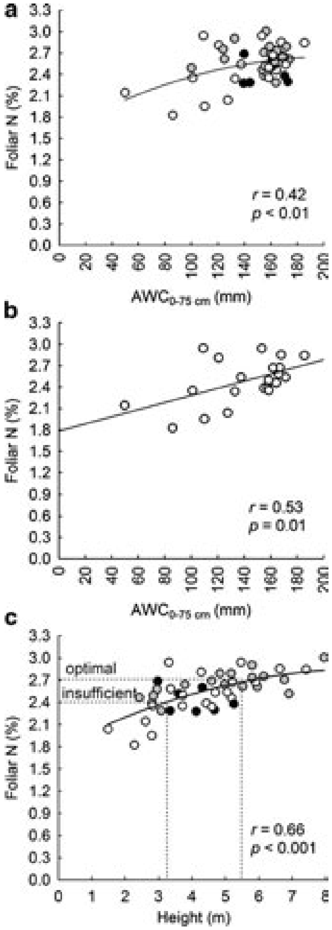

Fig. 6 The relationships between foliar N concentration and $AWC_{0-75\ cm}$ including **a**) all soil moisture groups: automorphic (empty circles), semi-hydromorphic (grey circles) and hydromorphic soils (black circles), **b**) including only automorphic soils and **c**) foliar N related to mean tree height

Table 4 Foliar concentrations of N, P and K, N/P and N/K ratios ± S.E. (range)

Soil group	Foliar N, %	Foliar P, %	Foliar K, %	N/P	N/K
Automorphic	2.5±0.06 (1.8–2.9)	0.25±0.011 (0.19–0.37)	0.78±0.027 (0.55–1.00)	10.4±0.47 (7.0–15.2)	3.3±0.16 (1.9–4.6)
Semi-hydromorphic	2.7±0.04 (2.3–3.0)	0.25±0.007 (0.21–0.31)	0.81±0.034 (0.57–1.02)	11.0±0.29 (8.9–12.5)	3.4±0.13 (2.7–4.2)
Hydromorphic	2.4±0.06 (2.3–2.7)	0.22±0.009 (0.18–0.25)	0.76±0.051 (0.59–0.97)	11.4±0.42 (9.4–12.5)	3.3±0.24 (2.6–4.3)
Total	2.6±0.04 (1.8–3.0)	0.24±0.006 (0.18–0.37)	0.79±0.019 (0.55–1.02)	10.8±0.25 (7.0–15.2)	3.3±0.09 (1.9–4.6)

rainfall does not completely cover the potential soil water storage. Moreover, precipitation during the growing season is seldom uniformly distributed, as plants would ideally need. In some circumstances not only a shortage, but also a surplus of water can occur, especially on poorly drained hydromorphic soils.

Estonian soils have developed on inhomogeneous parent materials (Fig. 1); therefore soils show great variety in physical properties (Supplementary Table 2). Relations between the studied tree growth, foliar and soil characteristics were more pronounced on automorphic soils, where AWC was significantly correlated with tree growth (Table 2). Our results showed that deep automorphic and semi-hydromorphic soils had enough capacity to store and provide water for fast growth of aspens, but this was not the case for shallow *Leptosols* and *Cambisols* (Fig. 4).

The topsoil layer of former agricultural lands has been formed by the cultivation activities (e.g. ploughing and fertilization) and its water properties vary less than in deeper subsoil layers, which could thus be also important for proper site selection while afforestating abandoned agricultural lands with aspen. In general the topmost 25 cm soil layer corresponded to the humus horizon (32±0.9 cm) of the studied field soils and was therefore rich in plant available nutrients. $AWC_{0\text{–}25\ \mathrm{cm}}$ was in the sufficient range to maintain nutrient uptake and growth of the trees, explaining the insignificant correlations between $AWC_{0\text{–}25\ \mathrm{cm}}$ and tree growth variables (Tables 2 and 3). Although the majority of aspen roots are concentrated in top soil layers (Alban 1982), water and nutrient uptake from deeper layers also plays a significant role for tree growth. Root distribution alone may not always indicate the uptake capacity of trees from deeper soil layers (Göransson et al. 2006). We did not estimate root distribution, while we assumed that $AWC_{0\text{–}75\ \mathrm{cm}}$ was attributable to the rooting depth of young hybrid aspens and no extra water from deeper than 75 cm was drawn up by aspen roots. The root system of hybrid aspen has not been described in detail, but should be similar to its parent species. *P. tremuloides* develops a heart root system on deep, well-drained soils. Fine roots are found to a depth of 0.6–0.9 m, with sinker roots descending to a depth of 3 m (Perala 1990). Fine roots of *P. tremula* may reach far from the stem in the topmost soil layer with sinker roots, occasionally going deeper (Reim 1930).

Another reason explaining the higher significance of AWC in deeper soil layers could be that topsoil dried out and $AWC_{0\text{–}25\ \mathrm{cm}}$ was depleted and the plant available water was almost exclusively stored in lower horizons. One more reason is probably that in AWC estimation we applied volume correction by the concentration of stones, that generally increased with depth. According to Estonian experience, a low stone content ≤ 10% by volume had minor influence on AWC (Bergert 1970; Kitse 1978). The limestone rock fragments do not store a considerable quantity of water, depending of weathering rate 1–5% (Bergert 1970). We presumed that higher stoniness restricts root access to scarce water captured by stones. For clay loam *Rendzic Leptosols*, when the rock fragments are neglected, the AWC can be overestimated by 39% (Cousin et al. 2003). In the current study AWC was overestimated on average by 6±1.7%, reaching 40–60% in the case of stony soils.

Soil texture traditionally has been used to infer soil hydraulic properties (Wösten and van Genuchten 1988). Automorphic soils which have more clayey subsoil overlain by somewhat lighter texture and porous humus horizons could provide more water for aspen than others. *Albeluvisols*, *Luvisols*, which had clay illuvial *argic* B-horizon and *Planosols* with abrupt textural change showed improved growth rates within our selection (Fig. 4, Table 1).

It is well established that increase in bulk density (BD) reduces root growth and thus may reduce water and nutrient acquisition. Also AWC showed a negative trend with increasing BD (Fig. 3). In denser soils, the low content of nutrients in the biomass due to hindered uptake is mostly connected with limited conditions for root development (Clark et al. 2003).

Although organic C was presented in the current study rather for characterization of the studied soils, it showed positive relation with AWC. This is consistent with Olness and Archer (2005), who showed that plant available water may increase substantially with increasing organic C when other soil factors (e.g. texture, structure, mineralogy) are constant. However in the current study organic matter was integrated in SSA that was one of the input variables in the AWC equation, thus we did not separately analyse relations between organic C and plant growth.

Perhaps, on semi-hydromorphic and hydromorphic soils the water status of trees does not so much depend on precipitation and the water holding capacity of the soil compared to well-drained automorphic soils. *Gleysols* have more static water regime, they stay longer wet in spring and consequently dry and warm up with delay in spring. However, when the ground water table is lowered via drainage, we could expect improved rainwater collection due to low position in landscape. Capillary fringe of gleyed horizons, despite their higher BD (Supplementary Table 2), could help to explain the unexpected significant correlation that was observed between height growth and AWC also in hydromorphic soils (Table 2). In addition to the texture layering that we also established on automorphic soils, looser topsoil structure (lower BD in Supplementary Table 2) appeared on drained *Gleysols*. Soil structure was crucial in characterizing hydraulic behaviour in the macropore flow region, whereas texture had major impact on those hydraulic properties controlled by micropores (Lin et al. 1999). Due to drastic pores discontinuity between humus horizon and reductomorphic mineral subsoil, if their topsoil dried up during drought, then rewetting of *Gleysols* would be remarkably slower.

The sufficient and insufficient ranges of AWC established in the current study (Fig. 5) are comparable to Sampson and Allen (1999), who found that AWC below 100 mm in the 1.25 m soil layer resulted in low productivity of loblolly pine, and AWC 125–150 mm was sufficient for high productivity. In Germany for effective root depth, the "limited" AWC was estimated in range 50–90 mm and "high" 141–200 mm (Diez and Weigelt 1987). The mean AWC in the 75 cm soil layer of Estonian field soils has been estimated at 131–150 mm (Kitse and Leis 1996), which can be considered almost sufficient for hybrid aspen.

In the studied 7-yr-old hybrid aspen plantations the above-ground biomass was still rather small, however annual increment is increasing substantially from this age upwards (Tullus et al. 2009). Thus the annual water demand is going to rise as well. The correlations between AWC and height increment of the 7th year were stronger than with total height (Table 2), indicating also the possible growing importance of AWC with age i.e. with the growing biomass of the plantation. We can conclude that xeromorphic stony (drought sensitive) soils are not suitable for SRF aspen plantations in the region (Fig. 4).

Nutritional status of 7-yr-old hybrid aspens

The nutritional status of the studied former field soils can be considered good; the average concentration of extractable P in the humus layer was 87±8.2 mg g^{-1}, which is above the optimal value of Estonian field soils (50–80 mg g^{-1}). P concentration was the highest in automorphic soils (109±13.9 mg g^{-1}) and below optimal in hydromorphic soils (49±6.7 mg g^{-1}). The average concentration of extractable K was 128±11.1 mg g^{-1}, which is also above the optimal value (120 mg g^{-1}), however in the different soil moisture groups, a value above optimal was found only in automorphic soils (154±18.9 mg g^{-1}), being below optimal in semi-hydromorphic (99±8.4 mg g^{-1}) and hydromorphic soils (117±32.9 mg g^{-1}). Our data showed that element inputs from previous agricultural management still supported native nutrient-poor soils, equally with pedogenetically nutrient-rich soils.

The optimal foliar N:P:K ratio for poplars has been estimated 100N:11P:48K (Stanturf et al. 2001). Based on our results (Table 4) the average ratio was 100N:9P:30K. Our results concerning sufficient ranges of foliar N and P were comparable to other studies with hybrid aspen (Table 5). However, foliar K was close to or below the lower limit of the sufficient range suggested by other authors. Foliar K was related to extractable K in the soil, although neither tree growth nor foliar N:K ratio were related to K content in the soil (Table 2), thus we cannot

Table 5 Nutritional status of poplar and aspen leaves according to the current study and literature

Nutrient	Source	Species	Value, %	Status for tree growth
N	current study	hybrid aspen	2.4–2.7	sufficient
	van den Burg 1985, 1990	poplar/hybrid aspen	1.7–2.5	sufficient
	Hansen et al. 1988	hybrid poplar	3	critical
	McLennan 1990	*Populus trichocarpa*	2.5	optimal
	Jug et al. 1999	hybrid aspen	2.2–2.8	sufficient
P	current study	hybrid aspen	0.25	sufficient
	van den Burg 1985, 1990	poplar/hybrid aspen	0.13–0.18	sufficient
	McLennan 1990	*Populus trichocarpa*	0.33	optimal
	Jug et al. 1999	hybrid aspen	0.26–0.32	sufficient
	van den Driessche 2000	poplar	0.25	optimal
K	current study	hybrid aspen	0.8	sufficient
	van den Burg 1985, 1990	poplar/hybrid aspen	0.8–1.5	sufficient
	Côté and Camiré 1987	hybrid aspen	1.5–2.0	sufficient
	van den Burg 1987	European aspen	0.8–1.2	sufficient
	McLennan 1990	*Populus trichocarpa*	1.9	optimal
	Jug et al. 1999	hybrid aspen	1.4–2.0	sufficient
N:P	current study	hybrid aspen	9.2–10.8	sufficient
	van den Burg 1985, 1990	poplar/hybrid aspen	9.4–19.2	sufficient
	McLennan 1990	*Populus trichocarpa*	7.6	optimal
	Jug et al. 1999	hybrid aspen	6.9–10.8	sufficient
	Stanturf et al. 2001	poplars	9.1	optimal
N:K	current study	hybrid aspen	2.9–3.4	sufficient
	van den Burg 1985, 1990	poplar/hybrid aspen	1.1–3.1	sufficient
	McLennan 1990	*Populus trichocarpa*	1.3	optimal
	Jug et al. 1999	hybrid aspen	1.1–2	sufficient
	Stanturf et al. 2001	poplars	2.1	optimal

conclude that K is limiting hybrid aspen growth. K is antagonistic to the uptake of Ca and Mg (Diem and Godbold 1993). Ca is unlikely to be limited since the former agricultural fields received frequent inputs of lime or other fertilizer containing Ca (e.g. superphosphate). Foliar K:N ratio was close to 0.30, which is somewhat lower than the optimal 0.35, what has been determined for *Picea abies* foliage (Linder 1995), but higher than in other Swedish studies, where it ranged from 0.24 for *Fagus sylvatica* up to 0.28 for *Quercus robur* (Göransson et al. 2006). Differences in observed foliar K levels could also be affected by differences in sampling and analysis methods. In the current study we collected leaf samples from the upper canopy, whereas Jug et al. (1999) collected from main shoots, supposedly from all canopy layers. For *P. tremula* it has been observed that foliar N does not significantly vary between different canopy layers, but P and K decrease towards the top of the canopy and could be 13% and 30% respectively higher in the lowermost canopy fraction (Mandre et al. 1998). There could be differences between pot (ex-situ) and field (in-situ) experiments. Also, the measure (output value) for estimation of optimum nutrient content is not always clear. In addition, genetic (clonal) background affects the phytochemistry of trees (Lindroth and Hwang 1996; Prasolova et al. 2005) and thus critical levels for foliar nutrients could vary among hybrid aspen clones selected in different regions.

Foliar N was correlated with tree growth both on auto- and semi-hydromorphic soils (Table 2), which agrees with other studies about relations between plant growth and chemistry (e.g Lu and Sucoff 2003). While foliar N concentrations on semi-hydromorphic soils were above sufficient level—2.4% (Table 4), we can conclude that N–acquisition was a more limiting factor for hybrid aspen growth on automorphic and hydromorphic soils.

The soil N content was not significantly correlated with height growth or foliar N in the studied plantations (Table 2), contrasting with previous studies in boreal native aspen stands (e.g. Chen et al. 1998). Our study did not indicate that soil N alone was a decisive limiting growth factor for young hybrid aspen plantations on previously cultivated lands in the hemi-boreal region. Growth of the trees was more dependent on nutrient uptake conditions (soil hydrophysical properties and pH) than on nutrient content itself in previous agricultural soils. While interpreting the results from the current study, we must bear in mind that there always exists some multicollinearity between soil variables. For example organic C content showed positive correlation with both AWC and N content in the A-horizons of the studied soils. According to Estonian experience (Kitse 1978), the positive relation between soil humus content and SSA will become constant (11.3 $m^2 g^{-1}$) when humus content reaches approximately 7% and the positive curvilinear relation between SSA and AWC (with constant BD) persists until SSA reaches 60 $m^2 g^{-1}$. So humus rich or fine textured soils were exceptional in our selection. We did not establish any significant relations between $AWC_{0–25\ cm}$ or N content of the A-horizon and growth of the trees. The impact of AWC on tree growth increased in deeper soil layers, where the organic matter content and its possible collinearity with AWC and N content would be negligible. Although the total and mineralisable N pool in the topsoil of cultivated land is usually lower than in forest soils, N might not be limiting for the planted trees, especially when the soils are high in other nutrients e.g. P (Falkengren-Grerup et al. 2006). Moreover, in 10-year-old afforestations of formerly cultivated lands in Finland, the topsoil contained even more N than in adjacent forest lands (Wall and Hytönen 2005). The differences in N content between continuously forested and cultivated soils could be higher regarding the organic layer, which is more decisive for plants in forest lands whereas on afforested agricultural lands the nutrients are distributed more evenly within the plough layer (Wall and Hytönen 2005). The formation of litter layer and forest floor during the further stand development could additionally improve N supply in the studied young plantations as aspen are known to be more dependent on organic N (Strong and La Roi 1985).

We analysed total N content in soil, however different soils contain various forms of organic N that differ in susceptibility to mineralization. Changes in water content also affect the N- mineralization rate of soil. The curvilinear relation between $AWC_{0–75\ cm}$ and foliar N for the whole range of soils became horizontal at *ca* 150–160 mm (Fig. 6a), which corresponded to the optimal level, based on the relation between foliar N and tree growth (Fig. 6c). If we used only automorphic soils, the relation was linear within the whole range (Fig. 6b). It has been established in earlier studies that N mineralization in well-drained field soils is essentially a linear function of soil water content in the range from wilting point to field capacity (Reichmann et al. 1966; Stanford and Epstein 1974). Generally, aerobic microbial activity is optimal at soil water potential of about −50 kPa and decreases as the soil either becomes wetter and saturated, i.e. waterlogged, or dries (Voroney 2007). Automorphic soils dry more frequently, which in turn might enhance mineralization and N uptake. Another possible explanation is that roots are more effectively spreaded at suboptimal AWC range 100–120 mm (Fig. 6b); even more efficient water use on fertile soils could be a hypothetical option (Brueck, 2008). The relations between AWC and tree growth and foliar N increased with depth (Tables 2 and 3, Fig. 4), which indicates that N uptake is not only governed by topsoil properties. In spite of high N pool and favourable AWC range, the trees growing on hydromorphic soils had lower foliar N content (Fig. 6a). This is caused by poorer drainage, as it is well known that wet and anaerobic soils inhibit nitrification (Miller and Johnson 1964). In Estonian climate the suppressed mineralization activity could be an additional factor for lower foliar N values on *Gleysols*, especially due to the delayed start of vegetation season in spring. As N mineralization is governed mainly by microbiological processes, the wider range of automorphic soils with different physical and chemical properties (including organic matter quality) creates more variable conditions for mineralization than semi-hydromorphic or hydromorphic soils (Fig. 6). For example, in calcareous grassland the N mineralization was found to be lower than in the moderately acid soils (Neitzke 1998). The relation between foliar N and AWC (Fig. 6), showed that trees growing on soils with remarkably low AWC had also low foliar N. These soils included xeromorphic *Calcaric Cambisols and Leptosols* with high pH (Supplementary Table 1), partly explaining the negative correlation between tree growth and soil pH (Table 2).

Previous agricultural land use and side effects of fertilization affect the net balance of P and K. Available P in soil was related to height growth and foliar P and available K in soil was related to foliar K on automorphic soils (Table 2). Thus we agreed with Falkengren-Grerup et al. (2006), that the N budget in formerly cultivated soils seems to be less predictable than the P budget. Generally, soil pH was in favourable range for P uptake (Supplementary Table 1). Reducing conditions could improve P uptake, as the soluble fraction in the soil increases (Scalenghe et al. 2002) and consequently this is reversed on drying. Less drainable semi-hydromorphic and hydromorphic soils having *stagnic* and *gleyic* properties favor reductive conditions in soils and could improve P uptake. The studied hydromorphic soils were low in available P (Supplementary Table 1) and there was a significant correlation between tree height and soil P (Table 2). However, the mean growth speed as well as foliar P of trees was not considerably lower on hydromorphic soils compared to semi-hydro- and automorphic soils (Tables 1 and 4); thus higher water availability could have compensated the below optimal content of nutrients in the soil. The negative correlation between soil P and foliar N/P ratio in hydromorphic soils (Table 2) reflected retarded N uptake despite improved P uptake.

The height growth of hybrid aspen was in negative correlation with soil pH (Table 2); a similar relation was observed at the age of 5 years (Tullus et al. 2007), however, no very acid soils (pH <4.0) were included in the study. pH values of the forest floor and mineral soil suggest that trembling aspen stands have a higher productivity in less acid soils (Chen et al. 1998). Our findings agree with other studies indicating the optimal soil pH for poplar and aspen to be 5.0–6.5 (Lu and Sucoff 2001; Stanturf et al. 2001). The negative correlation between soil pH and tree growth in the current study might not be a direct influence, since the more vigorous aspen growth was observed in the southern part of Estonia, where sandy soils have developed from Devonian sandstone rocks (Fig. 1) and thus usually have lower pH levels. Stony soils that have developed on Silurian and Ordovician carbonate rocks (e.g. *Calcaric Cambisols*) and which are represented in northern Estonia in combination with high pH resulted in a significantly slower growth rate (Supplementary Table 1, Figs. 1 and 4).

Management implications

The water regime, stoniness and calcareousness of parent material have been used as predictors of forest site productivity in Estonia (Lõhmus 2004). In Estonia the most productive forest soils are *Luvisols*, *Planosols* and some *Albeluvisols* and *Gleysols*. On automorphic soils tree productivity depends primarily on the subsoil texture (Kõlli 2002). Our results confirmed that similar soil-based site quality predictors can be used also for selecting suitable abandoned agricultural sites for afforestation. The most suitable soils for hybrid aspen would be *Albeluvisols*, *Luvisols* and *Planosols* (Fig. 4, Table 1).

Similar classification was evident already at the age of 5 years except for *Luvisols* (Tullus et al. 2007), where height growth has improved from age 5–7 years. *Planosols* and *Luvisols* are characterized by a sharp decrease in the hydraulic conductivity of the B-horizons, which temporarily causes the appearance of perched water, its rise towards the surface, and the presence of the capillary fringe above the free gravitational water table. Thus a short time surplus of water might rather be an advantage than a disadvantage for hybrid aspen. The fertility and available water status of *Albeluvisols* is generally considered average or below average. This was true in the case of nutrient content in the studied sites, but the $\mathrm{AWC}_{0\text{–}75\ \mathrm{cm}}$ of the studied *Albeluvisols* was among the highest (161–172 mm), thus probably compensating the lower supply of nutrients. Hybrid aspens showed very fast growth also on *Arenosols* in the semi-hydromorphic soils group. One of these sites was located in the middle of a slope, which had a positive effect on the growth of hybrid aspen; a similar effect has been observed in Finland (Yu and Pulkkinen 2003). Estonia is generally characterized by a flat surface topography, however, undulating micro-relief was quite common in the study area. Sandy soils situated on heights could suffer from water limitation during dry summers, whereas *Arenosols* with redoximorphic properties situated in lower positions remain water saturated for longer during spring and will probably draw additional precipitation water from the surroundings during the vegetation period.

The impact of AWC on tree growth was stronger in a growing season with insufficient precipitation (Table 3). This indicates a possible risk, especially when the establishment of hybrid aspen plantations coincides with a dry growing season, which could result in considerable mortality of planted trees. From this aspect semi-hydromorphic soils should be preferred. High stoniness reduces AWC in soil and thus dry automorphic field soils, as well as the stony substrate of exhausted oil shale quarries are not favourable for fast growth of hybrid aspen (Tullus et al. 2007, 2008). However, for ecological restoration of exhausted mining sites, deciduous tree species that are able to dwell in such extreme conditions should be considered from a biological diversity point of view in order to reduce the present predominance of coniferous stands in previously restored Estonian opencast oil shale mining sites (Tullus et al. 2008). On abandoned agricultural lands the proper site selection for establishing a hybrid aspen plantation should be based on maximizing the profitability of the investment, i.e. only sites that have proved suitable for fast growth and high biomass productivity of trees should be preferred. Due to high establishment cost, SRF plantations with hybrid aspen would probably not be reasonable just for their potential soil restoring effect in agriculturally degraded landscapes.

Conclusions

In general, our results about site fertility for hybrid aspen agreed with previous knowledge about aspen site preferences. Determination of AWC, pH and the content of major mineral nutrients in the soil can be seen as an effective tool for selecting the most suitable abandoned agricultural sites for establishing hybrid aspen plantations in the hemi-boreal region. The indirect estimation of AWC as a function of bulk density and soil specific surface area was found to be an effective method for characterizing soil water properties. However, in-situ measurements of soil water during the growing season need to be done for comparison for drawing final conclusions.

Subsoil properties should be considered as well for proper site selection when afforestating abandoned agricultural lands. In the current study the correlation between tree growth and AWC increased with depth within the studied 75 cm soil layer. Drought-sensitive stony soils with AWC<120 mm in the 75 cm soil layer (<16 volumetric %) have not been suitable for hybrid aspen. During the first 7 years, the fastest tree growth had occurred on automorphic and semi-hydromorphic soils with sufficient AWC (>150–160 mm in 75 cm soil layer, i.e. >21 volumetric %). On hydromorphic soils, trees had grown well but had not reached the maximum dimensions compared to more drained soils. Within the studied range of soil types, the most suitable previous agricultural soils for afforestation with hybrid aspen would be moderately drained *Albeluvisols*, *Luvisols* and *Planosols*.

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Supplementary Table 1 Chemical characteristics of the soil A-horizon in the experimental plots ± S.E.

Soil type	Plots	pH$_{KCl}$	Organic C, t ha^{-1}	Total N, t ha^{-1}	Available P, kg ha^{-1}	Available K, kg ha^{-1}
Automorphic soils						
Albeluvisols	2	4.8 ± 0.09	36.3 ± 1.80	5.1 ± 1.23	254 ± 44.1	359 ± 58.5
Arenosols	2	5.8 ± 0.43	39.1 ± 2.18	3.4 ± 0.01	660 ± 140.1	412 ± 103.2
Cambisols	7	6.7 ± 0.20	56.1 ± 15.68	6.4 ± 1.36	340 ± 74.7	686 ± 227.9
Leptosols	1	7.2	19.6	1.9	38	110
Phaeozems	1	6.3	40.3	5.1	194	691
Planosols	7	5.8 ± 0.16	46.7 ± 4.56	5.0 ± 0.37	596 ± 119.5	768 ± 129.2
Umbrisols	1	5.1	109.7	8.1	1529	1158
Semi-hydromorphic soils						
Albeluvisols	2	4.4 ± 0.33	72.2 ± 1.10	7.0 ± 2.11	237 ± 146.9	334 ± 147.1
Arenosols	2	5.0 ± 0.68	38.3 ± 4.25	3.6 ± 0.34	501 ± 176.8	328 ± 71.1
Cambisols	2	6.0 ± 0.45	80.8 ± 37.22	7.6 ± 3.16	377 ± 173.7	741 ± 6.3
Luvisols	2	5.7 ± 0.13	46.2 ± 16.65	4.5 ± 1.56	288 ± 72.6	423 ± 123.2
Planosols	8	5.7 ± 0.16	57.6 ± 7.13	6.5 ± 1.12	258 ± 40.0	397 ± 67.4
Umbrisols	1	5.1	79.8	16.3	1314	1577
Hydromorphic soils						
Fluvisols	1	4.8	72.9	9.6	129	1092
Gleysols	6	6.1 ± 0.38	76.8 ± 13.42	7.5 ± 1.27	210 ± 40.2	357 ± 92.4
Moisture groups						
Automorphic	21	6.1 ± 0.17 b[1]	49.9 ± 6.30 a	5.3 ± 0.54 a	483 ± 79.5 b	651 ± 95.8 a
Semi-hydromorphic	17	5.5 ± 0.16 a	59.8 ± 5.80 ab	6.7 ± 0.91 a	364 ± 70.2 ab	494 ± 81.9 a
Hydromorphic	7	5.9 ± 0.37 ab	76.2 ± 11.36 b	7.8 ± 1.11 a	198 ± 35.9 a	462 ± 130.8 a
All Groups	45	5.8 ± 0.12	58.8 ± 4.09	6.2 ± 0.47	394 ± 47.7	563 ± 58.2

[1] letters denote significant differences in group means according to Fisher LSD test

Supplementary Table 2 Physical characteristics (*L* – thickness of the horizon, BD – bulk density, SSA – soil specific surface area, AWC – available water content) of the major soil horizons within 75 cm soil layer in the experimental plots ± S.E. (range)

Soil horizon	Plots	*L*, cm	BD, $g\ cm^{-3}$	SSA, $m^2\ g^{-1}$	AWC, mm	AWC, vol.%
Automorphic soils						
A	21	32 ± 1.4 (22–45)	1.39 ± 0.02 (1.25–1.60) b[1]	34.9 ± 3.69 (11.5–75.6) a	77.7 ± 5.04 (16.7–115.5)	23.4 ± 0.92 (7.6–26.1) a
E	13	26 ± 3.1 (4–44)	1.56 ± 0.04 (1.32–1.83) k	19.7 ± 3.68 (3.3–41.4) k	42.8 ± 6.30 (7.2–85.4)	16.4 ± 1.34 (7.4–24.3) k
B(C)[2]	17	32 ± 3.3 (10–53)	1.54 ± 0.04 (1.27–1.80) x	24.4 ± 4.15 (3.0–53.6) x	45.1 ± 6.57 (14.9–88.1)	15.9 ± 1.28 (6.3–23.3) x
Semi-hydromorphic soils						
A	17	36 ± 2.9 (25–75)	1.37 ± 0.02 (1.24–1.51) ab	30.5 ± 2.80 (9.6–52.2) a	86.7 ± 4.76 (66.5–132.6)	24.8 ± 0.55 (17.7–27.0) a
E	10	17 ± 2.2 (10–31)	1.54 ± 0.02 (1.45–1.70) k	15.6 ± 2.66 (3.8–30.6) k	27.2 ± 3.83 (12.9–52.7)	17.6 ± 1.14 (9.9–21.2) k
B(C)[2]	14	34 ± 2.3 (17–45)	1.55 ± 0.03 (1.23–1.69) x	35.9 ± 6.84 (2.2–81.3) x	57.4 ± 5.95 (25.3–85.7)	17.1 ± 1.22 (6.0–22.3) x
Hydromorphic soils						
A	7	32 ± 2.2 (25–42)	1.29 ± 0.03 (1.16–1.37) a	61.5 ± 8.97 (27.4–89.4) b	80.4 ± 6.27 (60.3–107.7)	25.4 ± 0.30 (24.1–26.6) a
E	2	34 ± 4.0 (30–38)	1.56 ± 0.09 (1.48–1.65) k	19.1 ± 9.00 (10.1–28.1) k	62.9 ± 15.69 (47.2–78.6)	18.2 ± 2.47 (15.7–20.7) k
B(C)[2]	7	32 ± 5.4 (7–47)	1.52 ± 0.04 (1.38–1.74) x	38.9 ± 15.46 (5.6–127.5) x	57.2 ± 10.42 (5.7–89.9)	16.7 ± 1.57 (8.2–19.7) x

[1] letters a, b and c denote significant differences in mean soil properties in A-horizon, letters k, l and m in E-horizon and letters x, y and z in B(C)-horizon according to Fisher LSD test. Thickness of the horizon and AWC in mm were not compared because only the part of the lower-most horizon within 75 cm soil layer was studied

[2] only part of the B- or C-horizon that was within 75 cm soil layer was included in the calculations

III

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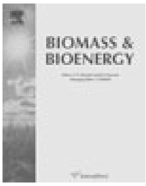

Above-ground biomass characteristics of young hybrid aspen (*Populus tremula* L. x *P. tremuloides* Michx.) plantations on former agricultural land in Estonia

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ABSTRACT

Fifty biomass production model trees were analysed in 7-yr-old commercial hybrid aspen plantations established on abandoned agricultural land in Estonia. Above-ground leafless biomass (ALB) of the model trees varied from 0.1 to 9.8 kg DM. The ALB of plantations with a density of 880–1340 trees ha^{-1} growing on former field soils was between 2.18 and 8.54 t DM ha^{-1}. The amount of nitrogen accumulated in the ALB varied between 14.4 and 48.5 kg ha^{-1}, the amount of phosphorus, between 1.7 and 5.9 kg ha^{-1}, and the amount of potassium, between 6.5 and 21.9 kg ha^{-1}. The removal of major mineral nutrients from the site with the removal of woody biomass in 7-yr-old plantations would be relatively small, constituting 0.5–3.4% of the nutrient pool in the humus layer of the previously fertilized field soils. The stembark content decreases rapidly until the DBH reaches 4 cm, which can be considered a target diameter for the hybrid aspen coppicing system.

1. Introduction

As one of the most crucial challenges of the new millennium, mankind is critically reconsidering its energy production and consumption in order to reduce the use of fossil fuels, the emission of greenhouse gases and the share of nuclear energy. The need to raise the share of energy from renewable resources, including biomass energy, has led among other things to the spread of short-rotation plantation forestry (SRF) out from southern Europe into the boreal areas including the Baltic Sea region. Being a member of the European Union since 2004, Estonia has to follow EU energy policy and raise the share of energy from renewable resources to 20% by 2020 [1–3]. Another application of SRF in Estonia and also in other countries of the region is derived from the need to find alternative uses for abandoned agricultural land.

Poplars, aspens and willows are considered the most suitable species for SRF in boreal regions because they combine fast growth rate with good cold hardiness [4,5]. The hybrid between *Populus tremula* and *Populus tremuloides* has proved to be a suitable deciduous species for management in short rotations of 20–30 yrs for the production of pulpwood in the boreal region [6,7]. Even shorter rotations are suggested for the successive vegetatively regenerating hybrid aspen stands for the production of biofuels [8,9]. Regenerating hybrid aspen stands have shown high biomass production rates at a young age in Scandinavia, with mean annual increment reaching 7.9–9.5 t DM ha^{-1} yr^{-1} [4,9,10]. In Estonia approximately 700 ha

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of hybrid aspen plantations have been established since 1999, mostly on abandoned agricultural lands but also for the reclamation of an exhausted oil shale quarry [11,12]. The initial growth of trees has been highly variable, depending significantly on physicochemical soil properties; in well suited site conditions hybrid aspen has shown fast growth in Estonia [12]. The current study provides the first overview of biomass productivity and biomass characteristics of hybrid aspen plantations in Estonian conditions.

An important issue in managing SRF plantations is nutrient accumulation in biomass, its removal from the ecosystem by harvest and the consequent need for fertilization especially after many successive harvests [5,13,14]. Thus low concentrations of nutrients in stems and branches are generally considered to be more desirable. The results from Sweden suggest that regenerating hybrid aspen stands are highly productive with no fertilizer applications, similar to estimated yields of fertilized willow stands [9]. In the current study we evaluated the share of major mineral nutrients accumulated in the above-ground biomass in 7-yr-old commercial hybrid aspen plantations compared to the respective nutrient's pool in the humus layer of the previously fertilized field soils. Although this age constitutes only one third of the predicted 20–30 yrs rotation period in plantations where the initial aim has been pulpwood production, it could be a possible age for the first bioenergy harvest followed by successive root-sucker generations.

While evaluating the quality of woody biomass for energy the preference of a higher share of wood and a lower share of bark is generally acknowledged. Due to its chemical composition, bark has high ash content and several pollutants are released during bark combustion. Ash content in the stems of common deciduous (including *P. tremula*) and coniferous tree species in Scandinavia is positively correlated with bark content and negatively with stem (branch) diameter [15]. For short-rotation poplar and willow stands it has been observed that bark content decreases rapidly until the tree reaches a certain size, after which the decrease slows down [16,17]. We studied the relations between bark content of stems and the size of hybrid aspens.

The aims of the study were: (a) to determine the above-ground leafless biomass production and biomass allocation of young hybrid aspens; (b) to determine the concentrations of dry matter, NPK and calorific values in different parts of the studied model trees and to study relations between these properties and the growth rate of the trees; (c) to estimate the leafless biomass, calorific value and NPK removal by harvest in 7-yr-old commercial hybrid aspen plantations; (d) to provide background data for the fertilization need in bioenergy plantations based on analysis of major mineral nutrients stored in biomass and in soil.

2. Material and methods

2.1. Study area

The study was carried out within the network of long-term experimental plots in commercial hybrid aspen (*P. tremula* L. x *P. tremuloides* Michx.) plantations [12]. Fifty experimental plots within 24 hybrid aspen plantations on former agricultural land were included in the study (Fig. 1). The plantations were

Fig. 1 – Locations of the plantations ($n = 24$) and number of analysed model trees corresponding to the number of experimental plots within the plantation.

established in 1999 and 2000 using 1-yr-old micropropagated plants belonging to 27 clones [12].

2.2. *Model trees for estimation of biomass and wood properties*

One model tree was selected from each experimental plot ($n = 50$) from 7-yr-old hybrid aspen plantations (Fig. 1) on the basis of DBH from the upper half of the DBH distribution of all the trees within the plot. Model trees were cut in winter (January), so that this would coincide with the normal harvest time, which in hemi-boreal Estonia is preferably winter, when the land is frozen. Before fractionating, several growth characteristics of the model trees were measured (Table 1).

All model trees were divided into the following components: current-year top of the stem (referred as top shoot in the current study), stem, current-year shoots and older branches. Fresh weight of each component was estimated. For determination of proportions and dry matter content of the stemwood and stembark, sample stem disks with thickness of 5–10 cm (up to 20 cm in very small trees) were taken from the base and 1.3 m height. For model trees taller than 3 m an additional sample was taken from 50% height. Sub-samples were taken from each compartment for determination of dry matter content and other wood properties. The dry weight of the samples was measured after drying at 70 °C to constant weight. To estimate dry mass of the top shoot, current-year shoots and old branches, the respective fresh mass was multiplied by dry matter content. As the trees were rather small-dimensioned and dry matter content of stemwood did not differ significantly between three locations along the stem, and that of stembark varied only slightly, the data from the breast height sample was used for calculating the respective values for the whole stem in the current study. To estimate the above-ground biomass of the growing trees and tree fractions in relation to DBH, the power function was used following the example of other similar studies [18,19]:

$$\mathrm{ALB} = b_0 \times \mathrm{DBH}^{b}{}_{1}, \qquad (1)$$

where ALB = above-ground leafless biomass of the tree or tree component, b_0 and b_1 – parameter estimates (Table 2), DBH – diameter of the stem at breast height. A measure of the fit of the non-linear regression was based on the coefficient of determination: $R^2 = 1 - (\mathrm{SSE/SStotal\ (corrected)})$. Regression lines between the observed and predicted biomass values of the model trees are shown in Fig. 2.

Table 1 – Growth characteristics of the 7-yr-old hybrid aspen model trees.

Characteristic	N	Mean ± S.E.	Range
Total height, m	50	4.19 ± 0.25	1.70–8.80
Top shoot length, m	50	0.82 ± 0.06	0.21–1.80
First living branch, m	50	0.69 ± 0.04	0.20–1.30
Diameter of the crown, m	50	1.45 ± 0.08	0.40–3.50
Diameter of the stem above bark at base, cm	50	4.69 ± 0.30	1.30–10.10
Diameter of the stem above bark at breast height, cm	50	3.14 ± 0.25	0.85–7.45
Diameter of the stem above bark at 50% height, cm	30[a]	2.93 ± 0.17	1.50–4.85

a Measured only for trees higher than 3 m.

Table 2 – Parameters of regression equation (1) based on data from 50 model trees: b_0 and b_1 – parameter estimates, R^2 – coefficient of determination.

Compartment	Parameter	Parameter estimates	Standard errors of parameters	R^2
Whole tree	b_0	107.7192	8.7322	0.99
	b_1	2.2371	0.0452	
Current-year shoots[a]	b_0	18.8190	5.4865	0.77
	b_1	1.6511	0.1696	
Old branches	b_0	23.3737	6.0997	0.90
	b_1	2.1606	0.1461	
Stem	b_0	61.2077	7.6889	0.99
	b_1	2.3856	0.0695	

a Including current-year top of the stem.

The power function was used also to describe the non-linear regression between wood or bark content in the stems and DBH of the model trees.

Albeluvisols and Planosols have proved suitable for growing hybrid aspen in Estonia [11,12]. In traditional forestry these soils correspond to *Oxalis* and *Oxalis–Myrtillus* forest site types [20]. We used the constructed equation (1) to determine the above-ground leafless biomass in twelve 7-yr-old hybrid aspen plantations in above-mentioned site conditions, where the DBH of all the trees had previously been recorded within 0.1 ha experimental plots (Table 3). The average plantation area was 12 ± 3.1 ha, varying from 2 to 33 ha. The DBH range of the observed trees (0.2–10.5 cm) was comparable to the model trees (0.9–7.5 cm), only on four experimental plots more than three trees had DBH over 7.5 cm.

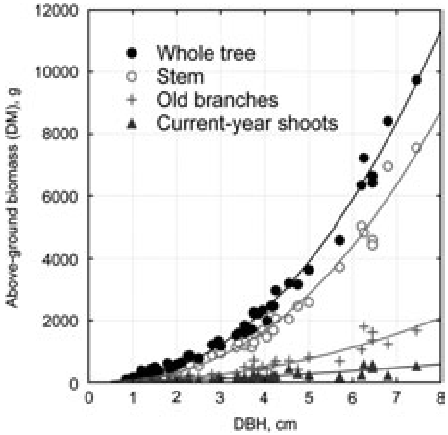

Fig. 2 – Observed (markers) and predicted values (regression lines) for above-ground biomass of the model trees.

Table 3 – Site characteristics of 12 commercial hybrid aspen plantations corresponding to *Oxalis* (OX) and *Oxalis–Myrtillus* (OXMT) forest site types.

Plot name[a]	Soil type [21]	Site type	n Trees ha^{-1}	DBH ± S.E. cm	Major mineral nutrients pool in the soil humus horizon		
					Total N t ha^{-1}	Extractable P kg ha^{-1}	Extractable K kg ha^{-1}
102/HHB3	*Mollic Planosol*	OX	1110	6.5 ± 0.13	4.8	808.8	721.7
102/HHB5	*Mollic Planosol*	OX	1280	5.5 ± 0.19	6.0	1109.2	1085.4
108/HHB15	*Glossic Albeluvisol*	OX	1050	4.2 ± 0.17	6.4	210.1	417.6
110/HHB19	*Gleyi-Mollic Planosol*	OXMT	1250	5.6 ± 0.10	13.1	311.2	260.2
112/HHB26	*Gleyi-Mollic Planosol*	OXMT	1170	5.5 ± 0.13	5.5	176.3	425.0
115/HHB31	*Glossic Albeluvisol*	OX	880	4.2 ± 0.16	3.9	298.3	300.6
116/HHB34	*Mollic Planosol*	OX	1040	3.5 ± 0.13	3.8	286.2	457.2
120/HHB40	*Gleyic Albeluvisol*	OXMT	1340	4.9 ± 0.16	9.1	89.7	480.9
121/HHB41	*Mollic Planosol*	OX	880	4.0 ± 0.15	5.7	233.4	278.9
123/HHB43	*Gleyic Albeluvisol*	OXMT	1180	4.3 ± 0.13	4.8	383.4	186.8
125/HHB48	*Gleyic Planosol*	OXMT	1190	5.9 ± 0.21	5.4	503.3	748.5
126/HHB50	*Gleyi-Mollic Planosol*	OXMT	1070	4.5 ± 0.18	4.1	150.2	301.5

a Plot names according to NOLTFOX on-line database (http://noltfox.metla.fi/).

2.3. *Concentrations of mineral nutrients and calorific values of plant samples*

The stem disks (separately wood and bark), current-year top of the stem and representative sub-samples from current-year shoots and older branches were milled to 0.5 mm with equipment Retsch SM 100 standard (© Retsch GmbH, Germany) and taken to the laboratory for chemical and calorific analyses.

The concentration of total nitrogen in plant samples was determined by standard Kjeldahl procedure using "Kjeltec Auto 1030"; phosphorus was determined spectrophotometrically from Kjeldahl digest using "FiaStar 5000". Concentration of potassium was determined flamephotometrically.

For determination of calorific values (kJ g^{-1}) of stemwood, stembark, current-year shoots and old branches, triplicate samples from the corresponding components of 11 model trees (every 5th model tree according to ranking by DBH, altogether 132 samples) were analysed using adiabatic measurement mode with the IKA calorimeter system C 5003 control [22]. In order to evaluate the energetic values of hybrid aspen plantations the dry masses of tree compartments were multiplied with respective calorific values; for the stems the calorific value of the 1.3 m sample was used assuming that the energetic value of wood does not depend on the relative height of the sample [23,24].

The analyses of NPK and calorific values were performed in the Laboratory of Biochemistry and the Laboratory of Wood Properties of the Estonian University of Life Sciences.

2.4. *Soil properties*

In order to evaluate the share of nutrients removed from the site with harvest, we analysed the concentrations of major mineral nutrients in the soil humus horizon and calculated the nutrient pools in the soil (Table 3) as follows: Npool = Ahor × Abulk × Nconc × (1 − Gr), where Npool = nutrient's pool in the humus horizon, Ahor = depth of the humus horizon, Abulk = bulk density of the humus horizon, Nconc = concentration of the nutrient and Gr = concentration of gravel (soil particles with diameter >2 mm).

Concentrations of total nitrogen (N) and extractable phosphorus (P) and potassium (K) in the soil humus layer were determined by the Laboratory of Agrochemistry of the Agricultural Research Centre in Saku [http://pmk.agri.ee], using methods: total N – ISO 11261; P, K, – Mehlich III. The depth, bulk density and gravel content of the humus layer had been recorded as part of the previous study in the network of experimental areas and the respective methodology is described in detail elsewhere [12].

2.5. *Statistical analysis*

Parameter estimates for the power equation (1) were obtained with proc NLIN using SAS for Windows 9.1.3 [25]. Statistica 7 [26] software was used for estimating descriptive statistics and simple regression coefficients between biomass characteristics and DBH. One-way ANOVA followed by Tukey HSD test was used for multiple comparison of the mean biomass characteristics between tree compartments. Mean values are followed by ±standard error of the estimate in the text. Level of significance $\alpha = 0.05$ was applied in all cases.

3. Results

3.1. *Above-ground leafless biomass characteristics*

The mean dry matter content in the above-ground part of the hybrid aspen model trees varied significantly between tree compartments (Table 4). The dry matter content in the analysed compartments was not related to DBH of the model trees.

The highest share of above-ground biomass was contained in stems: 73.2 ± 0.89% (varying between 58.0 and 86.3%), followed by branches: 18.2 ± 0.84% (6.3–32.2%) and current-year shoots (incl. top shoot): 8.6 ± 0.47 (2.7–18.2%). The share of stem and branches was not related to the size of the model tree (Fig. 3). The share of stembark from the total stem biomass excluding the top shoot was significantly related to the DBH of the model tree (Fig. 4).

Table 4 – Dry matter content in the analysed model trees.

Compartment	Dry matter content, %	
	Mean ± S.E.	Range
Top shoot	47.2 ± 0.45 b	35.5–59.1
Current-year shoots	51.7 ± 0.22 cd	47.7–55.4
Old branches	50.0 ± 0.26 c	43.9–54.3
Stemwood at base	41.9 ± 0.49 a	36.3–53.7
Stemwood at 1.3 m	41.0 ± 0.41 a	34.7–49.6
Stemwood at 50% height	39.6 ± 0.45 a	35.1–43.6
Stembark at base	52.8 ± 0.31 de	47.0–58.3
Stembark at 1.3 m	53.9 ± 0.90 e	47.1–65.3
Stembark at 50% height	50.8 ± 0.52 cd	44.3–54.3
Whole tree	46.0 ± 0.26	42.1–50.4

Letters denote significant differences according to Tukey HSD test.

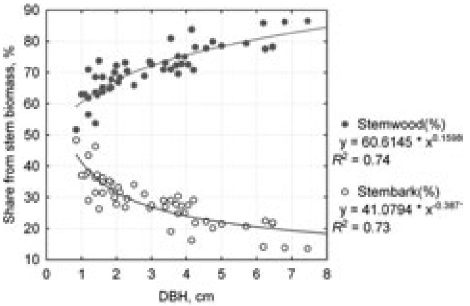

Fig. 4 – Non-linear regression between wood and bark content in the stem and DBH of the model trees.

The data obtained from the model tree analysis was used for estimating the respective ALB characteristics for twelve 7-yr-old commercial hybrid aspen plantations (Table 5).

The total ALB in 7-yr-old hybrid aspen plantations was significantly correlated with mean single tree ALB ($r = 0.98$, $p < 0.001$) and plantation density ($r = 0.69$, $p = 0.01$).

3.2. *Nutrient accumulation in above-ground biomass*

The concentrations of major mineral nutrients in above-ground parts of the model trees (Table 6) and twelve 7-yr-old hybrid aspen plantations (Table 5) were estimated. Approximately 61% of NPK was contained in the stems (wood and bark), leaving 39% for the branches (Fig. 5). The correlations between nutrient concentrations and DBH of the model trees are given in Table 7. The content of NPK per dry matter unit in the whole above-ground part of the model trees was significantly related to DBH (Fig. 6).

The concentrations of NPK in different above-ground parts of the model trees were compared to the respective concentrations in the soil humus layer. Most of the relations were not significant at $p < 0.05$, except the concentration of P in the current-year shoots and the concentration of K in old branches, which had a weak significant relation with the respective concentrations in the soil ($r = 0.45$, $p = 0.001$ and $r = 0.32$, $p = 0.02$ respectively). The mean DBH and total above-ground leafless biomass in 7-yr-old hybrid aspen plantations were positively correlated with the content of nitrogen accumulated in biomass ($r = 0.76$, $p = 0.004$ and $r = 0.75$, $p = 0.005$ respectively), expressed as the percentage of the nitrogen pool in the soil humus layer.

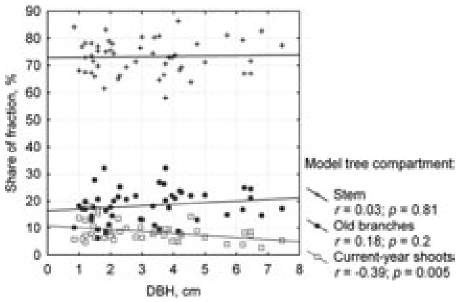

Fig. 3 – The relations between DBH and distribution of above-ground biomass.

3.3. *Calorific value of biomass*

Calorific values differed significantly between tree compartments (Table 8). Calorific value of stemwood was significantly related to the DBH of the model tree ($r = -0.61$, $p = 0.05$); no significant correlations with the size of the tree were observed for calorific values of other components at $p < 0.05$. More than half of the energetic value of ALB in 7-yr-old hybrid aspen plantations was accumulated in the stemwood, followed by branches and stembark (Table 5).

Table 5 – Biomass characteristics estimated for twelve 7-yr-old hybrid aspen plantations, ALB – above-ground leafless biomass, DM – dry matter, CAL – calorific value.

Characteristic	Unit	Mean ± S.E.	Range
ALB of the plantation	t DM ha^{-1}	5.17 ± 0.67	2.18–8.54
ALB of single tree	kg DM	2.97 ± 0.05	0.03–25.9
ALB of single stem	kg DM	2.21 ± 0.04	0.02–20.53
N accumulated in ALB	kg ha^{-1}	30.75 ± 3.64	14.44–48.48
	kg t^{-1}	6.08 ± 0.09	5.62–6.62
P accumulated in ALB	kg ha^{-1}	3.71 ± 0.45	1.69–5.93
	kg t^{-1}	0.73 ± 0.01	0.70–0.77
K accumulated in ALB	kg ha^{-1}	13.91 ± 1.65	6.54–21.93
	kg t^{-1}	2.75 ± 0.04	2.58–3.00
N_{ALB}/N_{soil}	%	0.54 ± 0.07	0.27–1.01
P_{ALB}/P_{soil}	%	1.44 ± 0.36	0.48–4.80
K_{ALB}/K_{soil}	%	3.35 ± 0.46	1.43–7.00
CAL plantation	GJ ha^{-1}	101.11 ± 13.17	42.82–166.88
CAL shoots	GJ ha^{-1}	6.45 ± 0.68	3.38–9.62
CAL branches	GJ ha^{-1}	19.17 ± 2.40	8.41–31.08
CAL stembark	GJ ha^{-1}	18.55 ± 1.89	10.00–27.24
CAL stemwood	GJ ha^{-1}	56.94 ± 8.23	21.03–98.94

Table 6 – The concentrations of major mineral nutrients in above-ground parts of the model trees.

Compartment	N, %		P, %		K, %	
	Mean ± S.E.	Range	Mean ± S.E.	Range	Mean ± S.E.	Range
Top shoot	1.21 ± 0.031 c	0.75–1.78	0.16 ± 0.003 c	0.11–0.23	0.35 ± 0.016 b	0.15–0.89
Current-year shoots	1.17 ± 0.017 c	0.91–1.41	0.12 ± 0.003 b	0.07–0.16	0.48 ± 0.007 c	0.39–0.58
Old branches	0.93 ± 0.020 b	0.56–1.24	0.13 ± 0.003 b	0.09–0.18	0.37 ± 0.006 b	0.31–0.47
Stemwood	0.24 ± 0.013 a	0.14–0.34	0.04 ± 0.002 a	0.03–0.05	0.12 ± 0.001 a	0.11–0.13
Stembark	1.35 ± 0.043 d	0.77–2.06	0.14 ± 0.007 b	0.05–0.26	0.60 ± 0.016 d	0.39–0.90

Letters denote significant differences according to Tukey HSD test.

4. Discussion

4.1. Productivity and management

Above-ground leafless biomass (ALB) production in sparse (880–1340 trees ha^{-1}) 7-yr-old hybrid aspen plantations was rather low. Total ALB of the fastest growing plantations exceeded 8 t DM ha^{-1} with an energetic value of 150 GJ ha^{-1} (Table 5). It is comparable with the annual production rate in young regenerating hybrid aspen root-sucker stands [4,9,10] or in willow and poplar plantations [27,28]. Previously published biomass data from 7-yr-old hybrid aspen plantations was not found for comparison. The mean leafless dry weight of a single 7-yr-old hybrid aspen in our study – 2.97 kg DM (Table 5) was higher than that recorded in a 8 to 9-yr-old root-sucker stand of *P. tremula* (1.2–2.5 kg DM, [19]), or in 8-yr-old *Betula pendula* stands (0.3–1.8 kg DM, [29]). In the mentioned studies, the total biomass production ha^{-1} exceeded our estimates due to considerably higher stand densities. However, the annual biomass production is speeding up also in the studied plantations. For example a current-year production of over 6 t DM ha^{-1} has been estimated in a 9-yr-old hybrid aspen plantation in Estonia (Tullus, unpublished). The acceleration of growth at an early age has been found in previous studies with fast-growing broadleaves [30].

A higher planting density than the currently used 1100–1600 plants ha^{-1} in Estonia and Scandinavia [9,12], is not economically justified due to the high cost of micropropagated hybrid aspen plants (€0.7 plant^{-1}). However, 4200–5555 plants ha^{-1} has been recommended in Germany for aspen short-rotation coppice plantations [8]. Establishment grants and/or cheaper hybrid aspen propagation methods, e.g. using root cuttings [31], would allow to increase the initial spacing for bioenergy production in short rotations. Grants and subsidies to support the establishment of short-rotation plantations and to promote the harvest of woody biomass for energy are a common practice in Europe [32–34]. In Estonia the establishment of willow short-rotation plantations for energy purposes is subsidized since 2008, however no other tree species are currently subsidized. A denser stand achieves higher biomass productivity in a shorter time, but trees in such plantations are likely to be exposed to early competition and density-dependent mortality [4]. Thus, for pulpwood production systems, the current planting densities would be sufficient. In the current study the number of trees ha^{-1} was significantly correlated with the total ALB of the plantation but not with single tree ALB ($r = 0.54$, $p = 0.07$). Thus competition-driven mortality of trees and a consequent need for a thinning had not appeared in sparse 7-yr-old plantations. As there are no mature hybrid aspen stands in Estonia we can predict the annual returns from the first 25-yr rotation based on production figures taken from literature. Provided that the yield of hybrid aspen plantation at harvest is 250–300 m^3 ha^{-1} pulpwood [6,10] then according to the present prices of plantation establishment, harvest and pulpwood the annual returns would be €137–175 ha^{-1} yr^{-1}. This is roughly comparable with studies from Finland and Sweden [6,35], which reported annual returns of approximately €170–180 ha^{-1} from the first rotation in hybrid aspen or poplar plantations, but with lower initial spacing (800–1100 plants ha^{-1}).

4.2. Biomass properties

The mean dry matter (DM) content in ALB was 46% (Table 4), which is in accordance with other studies with winter-cut model trees [8,36]. Even lower DM content of hybrid aspen has been reported at an age of four years: 36% [37]. The DM content of stemwood in our study (41%) was considerably lower than reported for aspen in summer: 63% [15]. In general the high water content of wood at harvest time is considered one of the most important quality problems of energy wood from poplar plantations [36].

The average share of current-year shoots and branches in the total ALB was 26.8 ± 0.89% being slightly higher than the 23–24% reported in other studies [19,38]. The allocation of above-ground biomass of poplars could be affected by clone and spacing, whereas the share of stems could be higher with denser spacing [4,39]. Spacing was relatively sparse in the

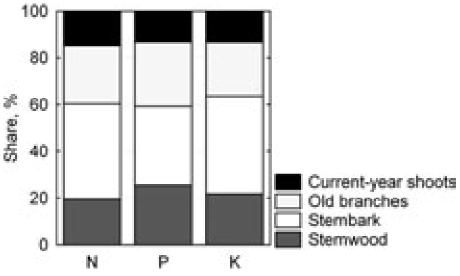

Fig. 5 – Distribution of NPK among the above-ground tree parts.

Table 7 – Correlation coefficients between the concentrations of NPK in model tree compartments and DBH.

Compartment	N		P		K	
	r	*p*	*r*	*p*	*r*	*p*
Top shoot	0.17	0.24	0.26	0.07	0.05	0.75
Current-year shoots	0.13	0.38	0.12	0.40	0.10	0.50
Old branches	–0.38	0.01	–0.22	0.13	–0.31	0.03
Stembark	–0.56	<0.001	–0.66	<0.001	–0.24	0.10
Stemwood	–0.86	<0.001	–0.69	0.003	0.23	0.38

Table 8 – Calorific values of model tree compartments.

Tree compartment	Calorific value, kJ g^{-1}	
	Mean ± S.E.	Range
Stemwood	19.33 ± 0.05 a	19.05–19.72
Stembark	19.98 ± 0.10 bc	19.32–20.43
Old branches	19.68 ± 0.08 b	19.19–20.18
Current-year shoots	20.28 ± 0.08 c	19.84–21.02

Letters denote significant differences according to Tukey HSD test.

studied plantations, which could partly explain the slightly higher portion of current-year shoots and branches.

The analysis of bark content in stems revealed that it dropped significantly to 24% when the DBH of model trees reached 4 cm, the following decrease in bark content with growing DBH was slower (Fig. 4). Similarly, it has been found that bark content in young poplar stems stabilized at 17.5% when DBH reached 4 cm [17]. In a willow plantation the respective diameter at 55 cm has been found to be 2 cm, when bark content stabilizes at 20% [16]. Trees exceeding a certain size limit at harvest ensure higher stemwood content in biomass, resulting in lower ash content and lower emission of pollutants during combustion. We conclude that for the hybrid aspen energy wood coppicing system, 4 cm DBH could be a reasonable target diameter. In addition less major nutrients per dry weight of biomass are removed from the plantation with bigger trees (Fig. 6). The harvest of the sparse first generation plantation does not provide considerable amounts of biomass when the mean DBH of trees is around 4 cm (Tables 3 and 5). At the same time the total biomass volume in a 4-yr-old regenerating root-sucker stand has been estimated at 46 $m^3\,ha^{-1}$ in Sweden [40]. At this age (2–4 yrs) a strong thinning is suggested (89% of the number of trees, 87% of the volume) providing potential energy wood and leaving some trees growing for pulpwood in a longer rotation.

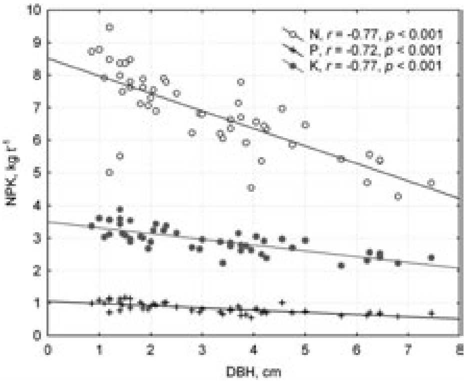

Fig. 6 – The relationships between the content of major mineral nutrients in the biomass and the DBH of the model trees.

In addition to identifying the moment when the competition-driven self-thinning occurs, also the average size of harvested trees should be considered in order to ensure the better quality of the energy wood. For a hybrid aspen energy wood coppice system the rotation period of less than 10 yrs has been suggested [8,9]. In the planted hybrid aspen stands the mean DBH of just 1.6 cm has been measured in Estonia at age 5 with the fastest growing plantations reaching 3.9 cm [12]. In the current study the mean DBH in 7-yr-old plantations varied from 3.5 to 6.5 cm (Table 3). Thus the 4 cm target diameter could be achieved rather in 5 or more years in the planted stand. Root suckers usually grow faster in the first years than planted trees while they can use the existing root system from the previous generation. In Sweden the mean DBH of 2.9 cm has been measured in 4-yr-old and about 5 cm in 5-yr-old hybrid aspen root-sucker stand [10,40]. We can conclude that the 4 cm target diameter is thinkable also in the dense sucker stand. At the same time in the dense sucker stand the trees would probably have greater height to diameter ratio than in sparse planted stand and biomass model trees from root-sucker stands should be analysed in order to establish more accurate target diameter for the coppice system based on above-ground biomass and bark content in it.

Calorific values of hybrid aspen stemwood (19.33 ± 0.05 kJ g^{-1}) and stembark (19.98 ± 0.10 kJ g^{-1}) in our study are comparable to the results in a 35-yr-old natural *P. tremula* stand, where a calorific value of 19.38 ± 0.05 kJ g^{-1} has been estimated for stemwood and 20.22 ± 0.13 kJ g^{-1} for stembark [24]. In our study the calorific values differed significantly between tree compartments, following the sequence: current-year shoots $\geq$ stembark $\geq$ old branches $>$ stemwood (Table 8). The calorific values of bark and branches exceed that of stemwood due to differences in chemical composition [23,24]. Besides the high calorific value of stembark, the ash content in aspen bark is considerably higher than in stemwood (0.4% vs 4.1% [15]), confirming also that a higher content of stemwood in aspen biomass for energy should be preferred.

4.3. *Nutrient removal and fertilization need*

We studied the concentration and content of three major mineral nutrients (N, P, K) in different above-ground parts of the tree. They are all known as seasonally mobile elements in biomass, which are retranslocated during the summer from foliage to other parts of the tree, where they are stored during winter time [36,41,42]. In 7-yr-old plantations 36–41% of nutrients accumulated in biomass were located in the current-year shoots and old branches (Fig. 5), which agree with a previous study in young hybrid aspen stands where nutrient removal in branches was 50% or more of the removal in stems, although this share will decrease in older stands [40]. The lowest concentrations and contents of NPK were estimated for stemwood (Table 6, Fig. 5). The nutrient content in one unit of dry biomass (Table 5) was in a comparable range with the respective values in a young silver birch stand [29]. Thus there is no difference in the potential nutrient removal between these two fast-growing deciduous trees that are recommended for afforestation of abandoned agricultural land.

According to previous studies the nutrient concentrations in hybrid aspens do not vary between trees of different sizes [40]. In our study the size of the model trees was not correlated with NPK concentrations in current-year shoots and branches and with K concentration in stemwood and stembark (Table 7). The concentration of N and P in stemwood and stembark was significantly higher in smaller trees, which can be explained by the fact that nutrient concentration increases with relative height of the sample along the stem [41]. As the samples were taken from a height of 1.3 m height, in case of the smallest model trees this was greater than 50% of their height.

In general SRF plantations in the boreal region require fertilization [5]. However, hybrid aspen has demonstrated high biomass productivity also in unfertilized sites [9]. The plant–soil studies in 5-yr-old hybrid aspen plantations on abandoned agricultural land have indicated the importance of soil moisture regime, dominant profile texture and the concentration of extractable P for tree growth at an early age [12]. In the current study the concentrations of N and P in current-year shoots and branches were significantly related to the respective nutrients pool in the humus horizon, and the share of N accumulated in biomass from the soil N pool was significantly related to plantation ALB, confirming the importance of soil fertility for hybrid aspen. During the following stand development, nutrient mineralization from increasing litter amounts should help to balance the nutrient requirements of the trees: in general the forest floor under deciduous trees has shown high N mineralization rates [43,44]. Probably the fertilization need will be higher in short-rotation coppice systems where nutrient removal with successive harvests exceeds the share of nutrients returned into the soil through litter and weathering. We found that the share of NPK accumulated in the above-ground biomass of 7-yr-old plantations growing on similar sites and in similar nutrient acquisition conditions (Table 3) constituted on average 0.5–3.4% of the corresponding nutrient pool in the soil (Table 5). Thus the potential nutrient removal with harvest at this age would not result in considerable nutrients loss from the site and consequent fertilization need. At the same time the mineral nutrient pool in the studied soils varied considerably (Table 3) probably mainly due to different fertilization practices during the previous agricultural land use. The highest removal was found for K (varying between 1.4 and 7.0%). Bearing in mind that in our study the total biomass of sparsely spaced planted plantations was four times lower than that reported for the potential regenerating root-sucker stand at energy wood harvest, this could lead to the need for K compensation.

5. Conclusions

Although the above-ground biomass quantities in sparsely spaced 7-yr-old commercial hybrid aspen plantations were rather small, the size of individual trees confirmed the suitability of hybrid aspen for energy forestry in hemi-boreal Estonia.

Approximately 73% of above-ground leafless biomass was allocated in the stems and this share was not related with the size of the trees. The share of bark and wood in the stems was significantly correlated with the DBH. The bark content decreased and the wood content increased significantly until the DBH reached 4 cm, after that the change slowed down.

In order to ensure better quality of biomass for energy the DBH of hybrid aspens at energy wood harvest should be at least 4 cm. In addition, fewer nutrients per dry weight of biomass are removed from the site with larger trees. The major mineral nutrients pool in the humus layer of the previous field soils has met the nutrient demand of young trees and the need for fertilization has not emerged so far.

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IV

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EARLY GROWTH AND FLORISTIC DIVERSITY OF HYBRID ASPEN (*POPULUS X WETTSTEINII* HÄMET-AHTI) PLANTATIONS ON A RECLAIMED OPENCAST OIL SHALE QUARRY IN NORTH-EAST ESTONIA

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*The early growth of the trees, foliar and soil properties, and floristic diversity were studied in 5-year-old hybrid aspen plantations in four sites: A1-levelled oil shale quarry spoil (*Calcaric Regosol*), A2-levelled quarry spoil covered with the mixture of removed former* Calcaric Cambisol *horizons, B1-former arable land on* Calcaric Cambisol, Chromic Cambisol *and* Rendzic Leptosol*, B2-former arable land on* Mollic Planosol. *In the quarry area trees had grown significantly faster in site A2. Overall fastest growth was observed on former arable land (B2). Significantly higher pH and lower values of P in the substrate and of foliar N and P were estimated in A1. TWINSPAN classification and DCA ordination showed substantial differences in vegetation composition between the sites. Vegetation of the quarry site A2 resembled more to B1 and B2 than to A1.*

Introduction

Land disturbed or destroyed by mining and similar activities is an inevitable part of civilization [1]. Estonian oil shale opencasts quarries are usually reclaimed as forest lands, a few areas also as agricultural lands. Altogether

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10 347 ha of the reclaimed areas had been afforested by 2006 [2]. Approximately 86% of the reclaimed areas have been afforested with Scots pine (*Pinus sylvestris* L.) [3]. In addition some other local tree species such as silver birch (*Betula pendula* Roth.) and black alder (*Alnus glutinosa* (L.) Gaertn.) and a number of exotic species (mainly *Picea*, *Pinus*, *Larix*, also *Populus* spp) have been used. 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 [3]. On the other hand, it can be argued that large monocultural pine stands present a high fire hazard and they are threatened by pests [3]. Wider use of silver birch and black alder, due to its fast growth and meliorative properties, is recommended for such areas [3–7].

A suitable species for afforestation of quarry spoils should be able to grow on poor and dry soil, establish vegetation cover as quickly as possible, prevent erosion or nutrient leaching and improve the soil organic matter status and microbial biomass. Notwithstanding, some tree species might also differ in their influence on soil biological activities, such as the presence of mychorrhizae or the composition of microbial communities, which in turn may affect soil chemistry [8]. For example the specific root area and length has been found to be significantly higher under alder than under pine trees [9].

Hybrid aspen (*Populus x wettsteinii* Hämet-Ahti) is an artificial cross between European aspen (*P. tremula* L.) and North-American trembling aspen (*P. tremuloides* Michx.). It has been most widely studied and cultivated in Sweden and Finland, both on agricultural and forest land, and has shown higher biomass productivity compared to its parent species in boreal conditions [10, 11]. The results from Lusatian lignite mining region in Germany have indicated 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 [12]. Hybrid poplars have been found to have good potential for reforestation of reclaimed surface-mined lands also in the Appalachian coal producing region in the USA [13].

Considering possible environmental impacts of monospecific plantations with exotic tree species, cultivation of hybrid aspen is not recommended on traditional forest lands in Estonia [14]. At the same time it can be seen as an alternative deciduous tree for afforestation of abandoned agricultural land. Opencast mining is carried out in large areas and the environmental impact of reforesting ecologically degraded landscapes with exotic tree species on the adjacent natural ecosystems is considered to be smaller.

Since 1999 hybrid aspen has been cultivated on former arable land in Estonia. The early growth of hybrid aspen on abandoned agricultural land in Estonia has been highly variable. Trees have grown faster on automorphic and semi-hydromorphic soils; hydromorphic clay soils have been less favourable [15]. In 2000 two experimental plantations with hybrid aspen were established in Aidu oil shale opencast. In the current paper we evaluate the early growth results from these plantations and compare them to the plantations growing on former arable land.

To achieve a successful restoration of exhausted mining areas, the soil has to be remediated and the vegetation re-established [16]. With the formation of permanent plant cover, skeletal quarry detritus, which is a disintegrated rock debris in areas of opencast oil shale mining, can develop into the soil of a productive forest ecosystem [5, 17–20]. Vegetation restoration on levelled quarry spoil is a successional process, depending on different factors. The substrate of exhausted oil shale opencasts is very unfavourable for reoccupation by plants, especially due to its uttermost dryness and the extreme temperatures of its surface [21]. Easily acquirable water for plants is basically absent in the top layers of quarry spoil, or appears in small quantities only in spring and autumn [22]. In primary successions, community development accompanies the development of the habitat. The establishment of different species can be determined by chance, the state of the habitat, and interactions between new species and those already present [23].

From a successional point of view, the current study focuses on four sites that are basically at the same stage on a time scale (5-year-old forest plantations) but in substantially different ecological conditions. Development of vegetation in levelled quarry spoil follows primary succession. In another site, quarry spoil has been covered with previously removed soil offering more favourable conditions for vegetation development. The vegetation analysis of plantations on former arable land in two sites as an example of secondary succession was included for comparative purposes. The differences between the sites in terms of species composition, species richness, diversity and life-history characteristics were investigated.

The principal aim of the study was to analyse ecologic relations that determine the growth speed of hybrid aspens and formation of plant cover in reclaimed quarry sites and on similar former arable soils. The nutrition conditions of the trees, fertility and productive capacity of the studied sites are characterized according to interactions between chemical soil properties, foliar and growth properties of the trees and floristic diversity of the field layer.

The objectives of this study were: (i) to describe the early growth of hybrid aspen in two sites on reclaimed oil shale opencast and compare it with the results from automorphic arable soils in two sites: in the same region with the quarry area and in South-Estonia; (ii) to study relations between tree growth, foliar and soil properties and define the most limiting growth factors for hybrid aspen in reclaimed quarry areas; (iii) to describe and compare the floristic diversity and vegetation structure in plantations established on reclaimed quarry and on abandoned agricultural land.

Materials and methods

Study area

The study focuses on two hybrid aspen plantations established for the reclamation of Aidu oil shale opencast in spring 2000 (Table 1). Micropropagated plants belonging to clones C05-99-8 until C05-99-34 were used. The first plantation had been established directly on levelled quarry spoil. The spoil is a heterogeneous mixture of Ordovician limestone and Quaternary sediments and contains over 75% of rubble and limestone blocks. The other plantation lies on part of the opencast that had been reclaimed as agricultural land. Before mining the topsoil from 12 different soil types suitable for reclamation [24] was removed and put into storage piles. In this paper, the term "topsoil" is considered synonymous with zone of organic-C accumulation and illuvation in the natural soil. After levelling of the exhausted quarry spoil it was covered by previously removed soil with the approximate depth of 40–60 cm [4]. Four experimental plots were created randomly within the first plantation and three within the second plantation (Table 1). The hybrid aspen plantations from Aidu opencast were compared to plantations established on abandoned agricultural land, where a network of 51 permanent experimental plots has been created in Estonia [15]. For comparison, three plots in the same region with the quarry sites and four plots from plantations on South-Estonian *Planosols*, where hybrid aspen has shown good growth potential [15], were selected (Table 1). All the soil types included in group B1 (Table 1) existed in

Table 1. **Characteristics of the study area. Site codes: A1– levelled quarry spoil, A2 – levelled quarry spoil covered with the former soil, B1 – former arable land on *Calcaric Cambisol*, *Chromic Cambisol* and *Rendzic Leptosol* in North-Estonia, B2 – former arable land on South-Estonian *Planosols*. Analysed properties: T – tree growth, S – soil, L – tree leaves, P – vascular plant cover**

Plantation	Site code	Plot	Location	Soil type according to WRB [26]	Analysed properties
Aidu 1	A1	1	59°19'N, 27°03'E	*Calcaric Regosol*	T, S, L, P
Aidu 1	A1	2	59°19'N, 27°03'E	*Calcaric Regosol*	T, S, L, P
Aidu 1	A1	3	59°19'N, 27°03'E	*Calcaric Regosol*	T, S, L, P
Aidu 1	A1	4	59°19'N, 27°03'E	*Calcaric Regosol*	T, S, L, P
Aidu 2	A2	1	59°20'N, 27°04'E	*Calcaric Cambisol* mixt.[a]	T, S, L, P
Aidu 2	A2	2	59°20'N, 27°04'E	*Calcaric Cambisol* mixt.[a]	T, S, L, P
Aidu 2	A2	3	59°20'N, 27°04'E	*Calcaric Cambisol* mixt.[a]	T, S, L, P
Sõeru	B1	1	58°53'N, 24°42'E	*Chromic Cambisol*	T, S, P
Sõeru	B1	2	58°53'N, 24°42'E	*Rendzic Leptosol*	T, S, P
Mikkeri	B1	3	59°30'N, 26°35'E	*Calcaric Cambisol*	T, S, P
Sikka	B2	1	58°14'N, 27°19'E	*Mollic Planosol*	T, S, L, P
Sikka	B2	2	58°14'N, 27°19'E	*Mollic Planosol*	T, S, L, P
Laaska	B2	3	58°20'N, 26°33'E	*Mollic Planosol*	T, S, L, P
Laaska	B2	4	58°20'N, 26°33'E	*Mollic Planosol*	T, S, L, P

[a] Mixture of removed former *Calcaric Cambisol* horizons

the quarry area before mining [24]. We limited our selection in all sites, so that available moisture content in 75 cm soil depth would remain <150 mm as calculated by Kitse and Leis [25].

In the following text the studied sites are referred to as codes (A1, A2, B1, B2) which are explained in Table 1.

Dendrometric characteristics

Total tree height at the end of the fifth growing season and height increment of the fifth year were measured for all the trees within the studied experimental plots. All the studied plantations are quite sparsely spaced and tree canopies have not closed yet. Therefore it was decided to rely only on the height growth of the trees for evaluating their growth speed and production potential and not to include biomass calculations per unit area in the current study.

Soil properties

From plots within site A1, which lies on levelled quarry spoil with available moisture being as low as 9 mm per 100 mm soil depth [27], the fine earth fraction between rock debris was taken for analysis. In the case of A2 samples from the top of mixed layer of former *Calcaric Cambisol* were analysed. The total nitrogen was determined by the Kjeldahl procedure. To analyse available phosphorus and potassium, Mehlich 3 extracant was used. The pH in 1M KCl suspensions was measured in the ratio 10 g : 25 ml. The soil samples were analysed in the Laboratory of Agrochemistry of Agricultural Research Centre in Saku.

Leaf properties

Ten model trees, based on the distribution of diameter at breast height (DBH), were selected from sites A1, A2 and B2 from each plot, altogether 110 trees. 15 leaves were collected from each model tree from the middle part of the canopy. After drying at +70 °C the leaves were weighed, single leaf blade area was measured with WINFOLIA ver. 5.0a (Regent Instruments Inc.) software and leaf weight per area (LWA, g m^{-2}) was derived. Foliar concentrations of NPK of all model trees were determined.

Floristic data

A transect of four 2×2 m experimental plots was created within each experimental area in order to analyse the vascular plant cover of the studied hybrid aspen plantations. Altogether 28 plots were established in plantations of Aidu opencast and 28 plots on former arable land. On every plot a species list of vascular plant and moss species was compiled following the guidebooks [28, 29]. The total percentage cover and percentage cover of individual species were recorded. Vascular plant species were grouped into life form and seed dispersal mode categories according to Lindacher [30] and into life-span categories following Krall *et al.* [31]. When one species was listed as belonging to more than one category, all of these categories were taken into account.

Data analysis

Statistical analyses of the growth traits, and foliar and soil properties were carried out with Statistica 7 [32]. One-way ANOVA was used to test the significance of differences between site means of growth traits, and foliar and soil properties. Tukey HSD multiple comparison test was applied to determine significant differences between group means after one-way ANOVA. Distance weighted least squares fitting procedure was used for smoothing the distribution curves of tree height (stiffness 0.25). Level of significance $\alpha = 0.05$ was applied in all cases.

Statistical analysis of plant cover was carried out with PCORD-4 [33] and Statistica 7. Species richness (S), evenness (E) and Simpson's diversity index (D) were calculated for all plots and compared between the sites with one-way ANOVA. Floristic data was classified with TWINSPAN clustering method [34] using the default options and 5 pseudospecies cut levels; the maximum level of divisions was 6. Detrended Correspondence Analysis (DCA, [35]) was applied with default options in order to analyse the positioning of species and plots from four different sites along the ordination axes. Logarithmic transformation of the data was applied prior to TWINSPAN and DCA.

Results and discussion

Dendrometric characteristics

Trees had grown significantly faster during the first five years in the former quarry site where levelled spoil had been covered with removed soil (A2) compared to the plantation that had been established directly on levelled quarry spoil (A1). The height of the trees varied from 0.2 to 3.6 m in A1 and from 0.8 to 4.0 m in A2. The height increment of the fifth year varied from 0.1 to 0.7 m in A1 and from 0.2 to 0.9 m in A2. The comparison of main dendrometric characteristics between studied sites in the Aidu opencast and on former arable land is given in Table 2.

A few experimental plantations with poplars and their hybrids have been established on levelled oil shale opencasts in Estonia in the 1960ies [6, 36]. The early growth results have been considered quite promising although the aim has been to use poplars as pioneer species and to replace them in the course of time with more perspective species, e.g. silver birch and *Larix* spp [37]. But in terms of the whole rotation period, the use of poplars has not justified itself due to considerable damage by tree trunk rot [6]. In two

Table 2. **Comparison of tree height (H) and height increment of the fifth year (Z) in hybrid aspen plantations in studied sites ± 1 standard error**

Site	Plots	Trees	H (m)	Z (m)
A1	4	161	1.1 ± 0.05 c[a]	0.3 ± 0.01 c
A2	3	54	2.0 ± 0.08 b	0.4 ± 0.02 b
B1	3	302	2.0 ± 0.05 b	0.5 ± 0.02 b
B2	4	334	3.4 ± 0.04 a	0.9 ± 0.01 a

[a] Letters within each column denote significant differences between means determined by Tukey HSD test (p <0.05) after one-way ANOVA.

experimental poplar plantations established on levelled oil shale opencasts in 1962 and 1964 the mean height at age 5 was estimated 2.1 and 3.2 m; the mean height increment was 0.3 and 0.8 m respectively [7, 36]. According to unpublished data provided by Elmar Kaar the following traits have been recorded for a poplar stand in mining area at age 25: height: 21.7 m, DBH: 26.5 cm, growing stock: 281 m^3 ha^{-1}**.** We can see that height and height increment of 5-year-old poplar stands and the hybrid aspen in quarry site A2 (Table 2) are roughly comparable. At the same time the poplar stands had been established directly on quarry spoil.

The distribution of hybrid aspens by height is shown in Fig. 1. We can observe clear difference between sites A1, A2 and B2. The distribution curves of tree height in sites A2 and B1 are more overlapping although trees higher than 4 m were missing in the quarry site. There was also no statistically significant difference in mean values of H and Z between sites A2 and B1 (Table 2). Thus the growth rate of hybrid aspens in quarry site covered with previously removed soil has been comparable with the results from former arable land on similar soil in the same region.

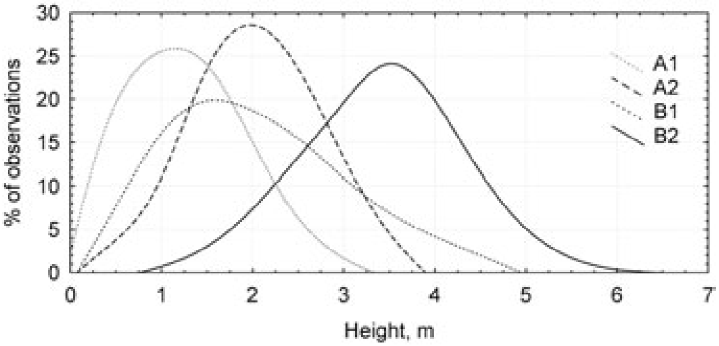

Fig. 1. Distribution of the trees by height in studied sites.

Soil properties

Significant differences were observed in concentrations of macronutrients (NPK) and in pH of the upper part of the quarry soils and humus horizons of former arable soils (Fig. 2).

Quarry spoil, as fresh calcareous parent material for soil development, had the highest pH value, in the other soils pH decreased according to soil development and decreasing of parent material calcareousness from North- to South-Estonia. The early growth of hybrid aspen has been found to be in negative correlation with pH of the arable soils in Estonia [15]. Generally the biogenic elements, such as N and P, are more depending on organic matter content of soil than geogenic K which is more related to clay minerals [38]. The highest total nitrogen content was discovered in quarry area which was covered with former soil (Fig. 2). The lowest phosphorus content was found in fresh spoil. The other soils were characterized by good phosphorous supply. Hybrid aspen growth on bare quarry spoil was obviously limited by N and P deficiencies. There were no differences in potassium content between soils; the availability level could be considered as an average. As generally known, available nutrients for root uptake during growing season depend on both nutrient pools and soil moisture. We should consider that element concentrations are expressed as content per unit weight of fine earth, not storage per unit area or volume, which reduces the potential of bare spoil to supply nutrients even more.

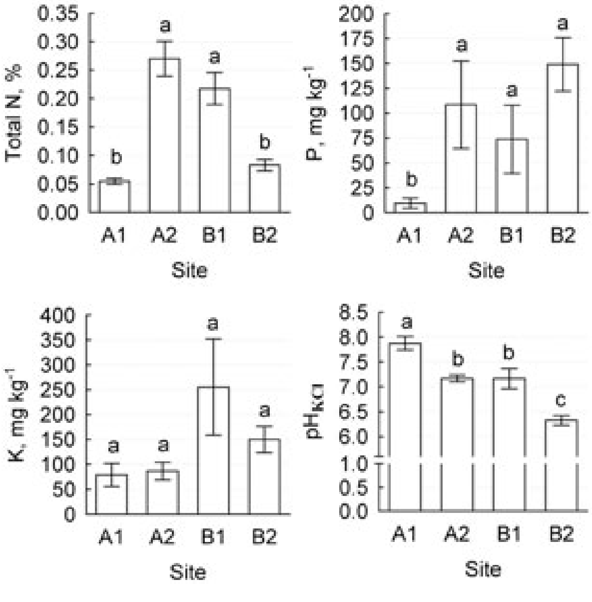

Fig. 2. Comparison of the concentrations of total N, extractable P and K and pH of the substrate between studied sites. Whiskers denote ± 1 standard error, letters denote significant differences between means determined by Tukey's test ($p < 0.05$) after one-way ANOVA.

The formation of organo-mineral soil layers is of prime importance for the reestablishment of the ecosystem. By restoring the topsoil we increase soil water holding capacity and increase biological potential. Topsoil that is replaced on levelled spoil does not have the same integrity of structure, porous continuity trough profile as is seen in naturally developed soils. However, the initial average height growth of trees is similar between sites A2 and B1 (Table 1), moreover, the tree height variability is even lower on restored soil (Fig. 1). Thus reshaping the soil banks to a gently undulating topography, changing subsoil properties and replacing topsoil creates quite homogenous initial growth environment for aspen plantation. Fear that the storage of topsoil in deep piles for years reduces the functional capacity of soil microorganisms is not so serious. The nitrogen potential of the removed soil has been preserved well in soil depots, as the vitality of *Azotobacteria* has survived well and the content of ammonium nitrogen inside soil depot has even increased [39]. This could explain the significantly higher concentration of N in site A2 (Fig. 2).

Leaf properties

The foliar concentrations of main mineral nutrients (NPK) and the sizes of leaves differed significantly between model trees taken from hybrid aspen plantations of Aidu opencast and abandoned agricultural land (Fig. 3, Table 3).

Plant nutrition in different sites depends of several factors, e.g. from physiological status of trees, from chemical soil properties and from climatic factor. Therefore it is also complicated to draw firm conclusions. Generally, sufficient nutrient supply may increase and shortage may reduce foliar nutrient concentration. At the same time nutrients are not independent from each other and can interact with other elements. The lowest nitrogen content of aspen leaves growing on site A1 (Fig. 3) reflects well the poor nitrogen and water supply from the quarry spoil (Fig. 2). As we do not know present Ca data of soil, we can be indirectly guided by pH values (Fig. 2). While

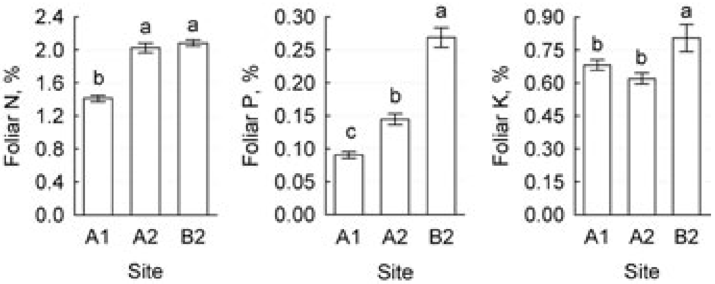

Fig. 3. Comparison of the foliar concentrations of NPK of hybrid aspens between studied sites. Whiskers denote ± 1 standard error; letters denote significant differences between means determined by Tukey's test ($p < 0.05$) after one-way ANOVA.

Table 3. **Comparison of foliar characteristics in plantations of Aidu mine and abandoned agricultural land (B2) ± 1 standard error**

Site	Plots	Model trees	Single leaf:		
			weight, g	blade area, cm^2	LWA[b], g/m^2
A1	4	40	0.15 ± 0.006 b[a]	14.7 ± 0.58 b	101.1 ± 0.91 a
A2	3	30	0.17 ± 0.004 b	17.2 ± 0.43 b	97.1 ± 1.34 b
B2	4	40	0.23 ± 0.012 a	22.5 ± 1.09 a	102.0 ± 0.94 a

[a] Letters within each column denote significant differences between means determined by Tukey's test ($p < 0.05$) after one-way ANOVA.

[b] LWA – leaf weight per area.

phosphorus uptake is more dependent on root development and $CaCO_3$ content, we can see that these conditions are most favourable for aspen in arable soils and worst in calcareous spoil. *Populus* species are colonized by both arbuscular and ectomycorrhizal fungi [40, 41]. Both types of mycorrhizal fungi can facilitate uptake of nutrients required for young tree growth, but in some periods they can act as inhibitors, as they form a sink that competes for carbon. It should be noted that capability for mycorrhiza development by mycobionts is probably worse in bare spoil without humus horizon. The potassium content in leaves is more evenly distributed than phosphorus. Although available potassium content of studied soils is even (Fig. 2), the highest K content was estimated for B2 (*Mollic Planosols*) with lower pH value (Fig. 2). As known, potassium moves into roots better in moist soils, and potassium availability is relatively weak in calcareous environment because of Ca/K antagonism [42].

The leaves were significantly bigger in plantations on former arable soils compared to the plantation with reestablished soil in Aidu opencast (Table 3), although the concentration of N was two times lower in former arable site B2 and concentrations of P and K were comparable in all soils (Fig. 2). It has been long recognized that plants growing under soil moisture or nutrient shortage have smaller leaves and lower growth rates than plants growing under more favorable conditions. The lower LWA in site A2 indicates differences in water supply, soil reaction or microclimate between sites. The bigger leaves on abandoned fields are as ashy as those growing on spoil. The size of the leaves has been regulated by abiotic conditions, as of water and perhaps nitrogen supply as well, while the light conditions are presumably comparable in the studied sites.

Usually the spoils or minesoils are chemically or physically less desirable growth environment than the native soils [43, 44]. North-Estonian abandoned oil shale opencast areas have high forestry potential [19]. Reeder and Berg [45] indicated that net N mineralisation and nitrification are generally smaller in geologic materials than in soils, and that a smaller portion of the total N in geogenic materials is potentially mineralizable. Nitrogen deficiency can be overcome in the short term by the application of industrial or organic fertilizers, and in the long term by the introduction of nitrogen-fixing plant species [23]. Since the spoil is calcareous, nitrate is preferable to ammonia in order to avoid NH_3 volatilization. The studies of Scots pine needles in Estonian oil shale opencast areas [46, 47] have shown the deficiency of N, P and K, optimal concentration of Mg and optimal or overabundant concentration of Ca in needles.

Fertilizing with N or NP or NPK has had a positive effect on the growth of Scots pine on such lands [46]. Our study showed significant deficiency of N in the substrate (Fig. 2) and N and P in the leaves (Fig. 3) of hybrid aspens growing on quarry spoil compared to trees growing on quarry spoil covered with soil and on former arable land.

Floristic diversity

Altogether 113 vascular plant and 19 moss species were described on 56 plots within 14 experimental areas in the hybrid aspen plantations of Aidu opencast and on former agricultural land. Out of the 113 vascular plant species, 6 species (*Achillea millefolium* L., *Artemisia vulgaris* L., *Deschampsia cespitosa* (L.) P. Beauv., *Sonchus arvensis* L., *Taraxacum officinale* Weber ex Wigg. s.l., *Tussilago farfara* L.) were found in all four sites (A1, A2, B1 and B2). They are all widespread perennials in Estonia [28, 31]. None of the moss species was common to all sites. *Ceratodon purpureus* (Hedw.) Brid. was the most common moss species in site A1. The same species has been described as the first bryophyte to colonise levelled oil shale mining landscapes in Estonia [21].

The total percentage cover of the field layer was > 60% in all sites with continuous A-horizon but over two times lower on quarry spoil in site A1 (Table 4). Species richness was significantly higher in B2. The highest values for species evenness (E) and Simpson's diversity index (D) were recorded on quarry spoil. In such ecologically extreme conditions individual species have not yet succeeded to dominate over others.

The studies have shown that natural forestation of abandoned oil shale opencasts usually produces a mixed stand with lower productivity compared to artificial afforestation [30]. At the same time the analysis of vegetation restora-

Table 4. **Comparison of the average total percentage cover of the field layer, species richness (S), evenness (E) and Simpson's diversity index (D) between studied sites, ±1 standard error**

Site	% cover	S	E	D
A1	27 ± 6.0 c[a]	12.5 ± 0.77 b	0.89 ± 0.019 a	0.86 ± 0.011 a
A2	82 ± 1.0 a	15.3 ± 0.92 b	0.77 ± 0.016 b	0.81 ± 0.017 ab
B1	60 ± 3.2 b	14.6 ± 1.28 b	0.69 ± 0.026 b	0.74 ± 0.032 b
B2	75 ± 1.8 ab	20.5 ± 1.08 a	0.71 ± 0.025 b	0.78 ± 0.029 ab

[a] Letters within each column denote significant differences between means determined by Tukey HSD test ($p < 0.05$) after one-way ANOVA.

tion on oil shale opencasts in Estonia has indicated that spontaneous succession on calcareous and stony spoils may have several advantages in terms of increased plant diversity [48]. The study of long-term vegetation recovery on reclaimed coal surface mines in the eastern USA [49] indicated that the vegetation composition in the reclaimed sites is following a successional trajectory towards the surrounding forests and some reclamation efforts (e.g. retention of nearby seed sources) should be considered in order to accelerate the process. The plantations that we focused on in the current study are situated quite near to the edge of the opencast and are surrounded by exhausted areas that have been reclaimed as agricultural and forest lands during the past 40 years. Therefore the availability of nearby seed sources was good.

Despite the environmental differences between the sites, the division of vascular plant species by life form followed rather similar patterns (Table 5). In our study, development of vegetation cover represented primary succession in site A1 and that on former arable land (B1, B2) represented secondary succession. The study of changes in species traits during succession in the Czech Republic has also indicated that trends of life-history characteristics of constituent species did not differ significantly between primary and secondary series after the first 10 years of succession [50]. All sites were dominated by hemicryptophytes (Table 5). A similar trend has been observed by Wiegleb and Felinks [51], who studied the chronosequence of early primary succession in post-mining landscapes of eastern

Table 5. **Division of vascular plant species into life form, dispersal mode and life-span categories in studied sites**

Life form:	1[a]	2	3	4	5	6	H	L
A1 (%)	8	5	14	49	14	10	–	–
A2 (%)	–	–	9	67	17	–	–	7
B1 (%)	3	–	9	52	13	13	2	8
B2 (%)	4	1	8	58	11	12	–	6
Dispersal mode:	I[b]	II	III	IV	V			
A1 (%)	14	48	2	29	7			
A2 (%)	17	33	6	32	12			
B1 (%)	16	36	4	35	9			
B2 (%)	18	33	6	33	10			
Life-span:	A[c]	B	P	T	S			
A1 (%)	12	15	52	15	6			
A2 (%)	8	8	84	–	–			
B1 (%)	17	15	62	6	–			
B2 (%)	16	8	69	6	1			

[a] Life form categories: 1 – phanerophytes; 2 – nanophanerophytes; 3 – chamaephytes; 4 – hemicryptophytes; 5 – geophytes; 6 – therophytes; H – half parasites; L – lianas

[b] Dispersal mode categories: I – autochorous; II – anemochorous; III – hydrochorous; IV – zoochorous; V - anthropochorous

[c] Life-span categories: A – annuals; B – biennials; P – perennials; T – trees; S – shrubs

Germany and found that hemicryptophytes dominated on all study sites, even in pioneer stands. The comparison of vascular plant species from the four sites with respect to seed dispersal mode and life-span revealed also similarities. As a difference, higher proportion of woody plants in A1 could be pointed out. Seeds of woody plants from A1 are mainly wind-dispersed that facilitates their arrival. Their germination on uncolonized spoil is easier as the competition with tall herbaceous plants is missing.

According to classification (TWINSPAN) and ordination (DCA) the vegetation composition of 5-year-old hybrid aspen plantation in the quarry site with reestablished soil was more similar to the plantations on former arable soils than to the plantation on quarry spoil (Fig. 4).

Consequently covering of the quarry spoil with a previously removed soil had promoted vegetation restoration. We must consider that, besides providing a more fertile growth environment, the reestablished soil could contain seed bank from the pre-mining period. At the same time soil removal, loading and transport into storage, and its use for recovering the area after mining is used mainly when the aim is to reclaim the area as arable land and this is a very expensive process when compared with reforestation of bare quarry spoil [52].

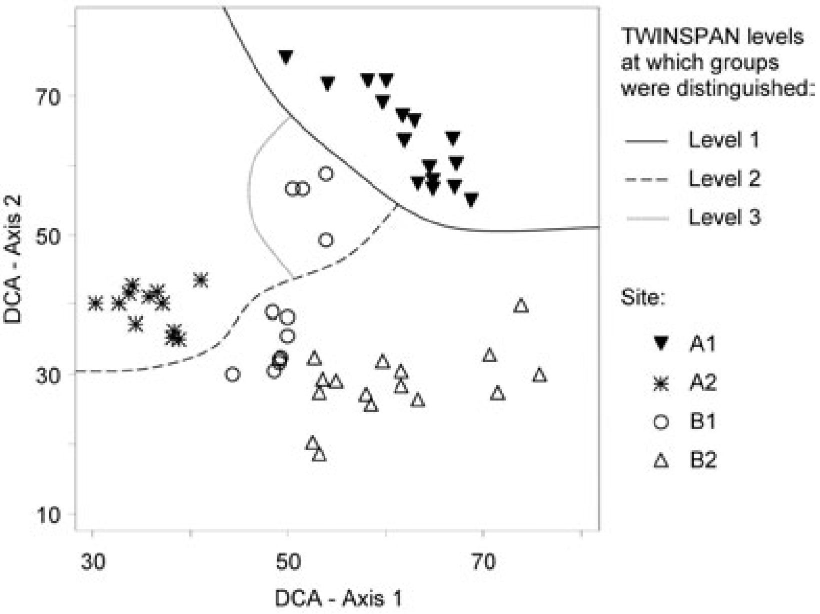

Fig. 4. Biplot of DCA Axis 1 (Eigenvalue = 0.42) and Axis 2 (Eigenvalue = 0.42) scores for 56 plots at four sites, with TWINSPAN classification groupings.

Conclusions

The early growth speed of hybrid aspens in the extreme substrate conditions of the levelled quarry spoil is significantly slower compared to the results from the quarry area covered with the former soil and from former arable soils. The growth rate of hybrid aspens in quarry site covered with previously removed soil has been comparable with the results from former arable land in the same region but it is significantly slower compared to the results from South-Estonian *Planosols* where hybrid aspen has shown promising growth potential on former arable land.

Significant deficiency of P in the substrate and N and P in tree leaves was observed in plantations established on bare quarry spoil, resulting in below optimal growth speed of hybrid aspens. It could be overcome by fertilization during the early growth stage.

Covering the spoil with former soil after mining can be seen as a promoting but expensive tool for ecological restoration of exhausted oil shale opencasts. It accelerates the development of the ground vegetation and creates a more fertile environment for forest plantations. During the five year time span the vegetation of the site with reestablished soil resembled that of former agricultural land.

Despite the relatively slow growth speed of hybrid aspen during the first five years after planting in the reclaimed quarry areas, the monitoring should proceed through the whole rotation period. The study of the suitability of using deciduous trees for reclamation of quarry areas should continue in Estonia in order to reduce the environmental risks caused by the large share of monocultural Scots pine plantations in the mining region.

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LIST OF PUBLICATIONS

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4. **Tullus, A.** 2005. Puupõllud hübriidhaavaga: lootused ja kartused. Eesti Loodus, 4, 44–46.

5. **Tullus, A.,** Vares, A. 2004. Hybrid aspen in Estonia: 5 years experience in plantation forestry. Baltic Timber Journal, 4(19), 38–40.

6. Vares, A., **Tullus, A.** 2003. Milliseid lehtpuukultuure rajada endistele põllumajandusmaadele. Eesti Mets, 1, 37–40.

7. Vares, A., **Tullus, A.,** Raudoja, A. 2003. Hübriidhaab: ökoloogia ja majandamine. Tartu: Triip, 112 lk.

APPROPATION

International conferences and meetings

Oral presentations

1. 17.11.2009. **Tullus, A.,** Kanal, A., Tullus, H., Soo, T. The importance of available water content in previous field soils for tree growth and nutritional status in young hybrid aspen plantations. International Workshop on Environmental Stress and Forest Ecosystem. RMK central office, Tallinn.

2. 28.11.2007. **Tullus, A.** Site conditions for hybrid aspen on former agricultural lands. Forestry adapted to future demand on energy and environment. Baltic Forest Seminar, Bispgarden, Sweden.

3. 5.09.2006. **Tullus, A.** Ecology and management of hybrid aspen. Post-graduate course: "Tree Canopy – Structure and Functioning – from Below and Above", Järvselja, Vihula.

4. 28.05.2005. **Tullus, A.** Hybrid aspen plantations in Estonia. Joint workshop of three International Poplar Commission (IPC) Working Parties in Estonia, Tartu.

5. 12.05.2004. **Tullus, A.,** Tullus, H., Vares, A., Kanal, A. Hybrid aspen plantations as a new promising biomass resource in Estonia. 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy.

Visual presentations

1. 2.-4.09.2009. Tullus, H., **Tullus, A.,** Soo, T. Hybrid aspen plantations as a new pulp resource in boreal conditions. The 2nd Nordic Wood Biorefinery Conference (NWBC), Finlandia Hall, Helsinki, Finland.

2. 10.-12.06.2009. Soo, T., **Tullus, A.,** Tullus, H., Roosaluste, E. Ordination of floristic data from young deciduous forest plantations using Non-metric Multidimensional Scaling (NMDS). NBBC09 2nd Nordic-Baltic Biometric Conference, Tartu.

3. 2.-6.06.2008. Tullus, H., **Tullus, A.,** Soo, T. Hybrid aspen plantations as new biomass resource in boreal Estonia. The 16th European Biomass Conference & Exhibition - "From Research to Industry and Markets", Feria Valencia, Spain.

4. 17.-20.10.2008. Tullus, H., **Tullus, A.,** Soo, T., Vares, A. Plantation forestry in boreal conditions: new experience in Estonian forestry. El 2º Simposio Iberoamericano de Eucalyptus globulus, organizado por la CÁTEDRA ENCE de la Universidad de Vigo. Pontevedra, Spain.

5. 17.-21.10.2005. **Tullus, A.,** Tullus, H., Vares, A., Kanal, Soo, T. Initial experience with short rotation hybrid aspen plantations in Estonia. – 14th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection. Paris, France.

Local conferences and meetings

Oral presentations

1. 12.03.2009. **Tullus, A.** Hübriidhaava kasvatamisest Eestis. ELUS-i metsandussektsiooni koosolek. Metsamaja, Tartu.

2. 10.05.2007. **Tullus, A.** Hübriidhaava ökoloogia ja majandamine. Metsanduse eriala doktorantide ettekannete päev. Metsamaja, Tartu.

3. 29.04.2005. **Tullus, A.,** Vares, A. Hübriidhaava kultuurid Eestis. SA Keskkonnainvesteeringute Keskuse projekti „Noorte hübriidhaava istanduste kasvukäik ja seda mõjutavad tegurid" seminar. Tartu.

4. 17.03.2005. **Tullus, A.** Hübriidhaava kasvatamise ökonoomiline analüüs. EPMÜ Metsandus- ja maaehitusinstituudi metsakorralduse valdkonna seminar. Tartu.

5. 26.10.2004. **Tullus, A.** Hübriidhaava kasvatamise tulemused maailmas ja Eestis. Eesti Teaduste Akadeemia üliõpilaskonverents. Tallinn.

6. 22.04.2004. **Tullus, A.,** Vares, A. Hübriidhaava (*Populus* x *wettsteinii*) kasv Eestisse rajatud istandustes. EPMÜ Metsandusteaduskonna õppurite ettekannete päev. Tartu.

Visual presentations

1. 12.11.2009. **Tullus, A.,** Jänes, E., Tullus, H., Soo, T. Noorte hübriidhaava- ja arukasekultuuride tootlikkuse võrdlus. Taastuvate energiaallikate uurimine ja kasutamine XI (TEUK XI). Eesti Maaülikool, Tartu.

2. 13.11.2008. **Tullus, A.,** Tullus, H., Soo, T. Hybrid aspen: a new bioenergy and pulpwood resource. Taastuvate energiaallikate uurimine ja kasutamine X (TEUK X). Eesti Maaülikool, Tartu.

3. 27.-29.02.2008. **Tullus, A.,** Tullus, H., Soo, T. Kiirekasvulise hübriidhaava kasutusvõimalused taastuvenergiaallikana ja uurimine Eestis. Konverents „Biomass ja bioenergia 2008”. Eesti Näituste messikeskus, Tallinn.

4. 12.10.2006. **Tullus, A.,** Soo, T., Tullus, H., Vares, A. Hübriidhaab taastuvenergia allikana. Taastuvate Energaallikate uurimine ja Kasutamine VIII (TEUK VIII). Eesti Maaülikool, Tartu.

5. 10.03.2005. **Tullus, A.,** Tullus, H., Vares, A., Kanal, A. Plantatsiooniline metsandus Eestis: hübriidhaab. Teaduskonverents Agronoomia 2005. Eesti Põllumajandusülikool, Tartu.