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ORIGINAL PAPER

Effects of soil preparation methods and plant types on the establishment of poplars on forest land

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Abstract

- **Key message The success of poplar plantations on forest land was affected by soil preparation, plant type, site, and clone. Mounding in combination with large plant types (rooted plants or long cuttings) of site-adapted clones achieved the highest survival and growth.**
- ***Context*** Poplars (*Populus* species and hybrids) are fast-growing trees used to make various products. In north European countries, they are mainly grown on agricultural land, but interest in planting poplars on forest land has increased.
- ***Aims*** Plant damage and mortality problems occur on forest land, probably due to soil conditions and competing vegetation. It is therefore of interest to investigate whether combinations of soil preparation methods and plant materials can improve establishment.
- ***Methods*** At three sites in southern Sweden, the effects of four soil preparation treatments (no soil preparation, patch scarification, mounding, soil inversion) in combination with three plant types (short cuttings, long cuttings, rooted plants) were studied.
- ***Results*** Survival and growth were significantly influenced by site, soil preparation method, plant type, and their interactions. Mounding resulted in the best overall performance on all sites. Interactions between site and plant type revealed differences in growth dependent on site conditions, but rooted plants and long cuttings were in general most successful. Patch scarification and short cuttings were associated with lower survival and growth.
- ***Conclusion*** Soil preparation is needed to support survival and early growth, but the combination of method and plant type must be adapted to site conditions. The choice of clones should also be considered.

Keywords Clone · Cutting · Growth · *Populus* species · Survival · Site properties

1 Introduction

There is much interest in growing *Populus* spp. in temperate and boreal zones of the world. This started with the increasing demand for wood products after World War II, leading to a worldwide spread of fast-growing poplars (Isebrands and Richardson 2014). The pulp and paper industry needed raw material and this was also the main reason for the breeding work with *Populus* spp. that started in Sweden in the 1940s (Johnsson 1953). Subsequently, this work and cultivation of the genus have gradually increased, but with a focus on bioenergy in northern latitudes (Rytter et al. 2013; Stener and Westin 2017; Tullus et al. 2013). Present political goals

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stress that a large part of the future energy supply must be obtained from renewable sources (e.g., European Commission 2015). From a north European perspective, one of the main sources will most certainly be forests (Rytter et al. 2015; Rytter et al. 2016). In addition, the Nordic countries have a vision to become carbon neutral by 2050 (IEA 2013; Nordenergi 2010), and hence, interest in fast-growing tree species, e.g., *Populus* spp., is high in the region.

Until now, poplars have mainly been planted on agricultural land in Sweden. The interest in using these species and their hybrids also on forest land increased after the storms in 2005 and 2007, but problems with damage and low plant survival have been reported (Engerup 2011). The aim was to use alternative tree species to the commonly planted Norway spruce (*Picea abies* (L.) Karst.) and to increase the proportion of deciduous tree species. In addition, the area of forest land that can be used for biomass production is far larger than the area of surplus agricultural land (Larsson et al. 2009). Little is known about reforestation with poplars on forest land at northern latitudes in Europe and more research is needed in this field.

The establishment failures are probably caused by differences in site properties and establishment strategies between agricultural land and forest land. Forest land has, in general, a lower nutrient status and lower soil pH and is stonier compared to agricultural land. Poplars need fertile and well-aerated soils with adequate water availability to realize their high growth potential (Rytter et al. 2011; Stanturf and van Oosten 2014). It has been recommended that poplar should be established on soils where the pH is above 5 (e.g., Boysen and Strobl 1991; Ericsson and Lindsjö 1981; Stanturf and van Oosten 2014). Fertile soil conditions are also favorable for weeds that compete for water, nutrients, and light. Weed control and soil preparation that improve soil physical properties are therefore of great importance when planting poplar. Vegetation control on agricultural land commonly includes chemical herbicides, e.g., glyphosate, but can also be done mechanically (Hansen et al. 1983; Persson et al. 2015; Stanturf and van Oosten 2014). The use of herbicides is restricted on forest land in Sweden and alternative methods to improve soil conditions and remove competing vegetation are needed. Therefore, to succeed on forest land, a suitable soil preparation method must be employed and combined with appropriate plant material. For conifers, this is fairly well known (Grossnickle and El-Kassaby 2015; Johansson et al. 2007; Thiffault et al. 2014), and results from Canada have shown that soil preparation can be an effective measure for poplar establishment (Bilodeau-Gauthier et al. 2011).

The general effects of all soil preparation methods are decreased competition from surrounding vegetation, release of nutrients, and increased soil temperature (Löf et al. 2012; Nilsson et al. 2010). Common soil preparation methods on forest land in Sweden are disk trenching and mounding, but soil inversion and patch scarification are also used (Nilsson et al. 2010). Disk trenching is the most common method and it is performed by using rotating disks in continuous rows. Patch scarification generates a similar result, but leaves undisturbed areas in between. Mounding is the second most common method and creates elevated planting spots. The method is often used on mesic to moist soils to improve soil moisture conditions and reduce oxygen limitation at the plant level. Soil inversion creates a planting spot at the same level as the surrounding soil by turning the soil upside down and then placing it back into the original hole. Thus, different soil preparation methods affect the height of the planting spot and soil moisture conditions in the rooting zone.

One way to reduce establishment costs related to poplar plants is to use cuttings instead of rooted plants. Unrooted cuttings of varying lengths are commonly planted worldwide, while in Sweden, it is more common to use rooted cuttings, either as containerized or bare-rooted plants. It has been reported that increased soil temperatures and soil moisture positively affect the rooting of dormant poplar cuttings (Hansen 1986; Landhäusser 2003; Zalesny et al. 2005), while longer cuttings have shown better survival, more roots, and higher shoot growth compared to shorter cuttings (Allen and McComb 1956; Burgess et al. 1990; Schuler and McCarthy 2015; Vigl and Rewald 2014). Böhlenius and Övergaard (2015) found that cuttings (30 cm) grew better than bare-rooted plants on agricultural land if the soil was prepared to reduce competing vegetation.

Knowledge concerning the establishment of poplars on agricultural land is not always applicable on forest land, and data pertaining to the effects of soil preparation and plant types on growth are still lacking. Thus, the aim of this study was to investigate the effects of different plant types and soil preparation methods when establishing poplars (from the *Aigeiros* (Duby) and *Tacamahaca* (Spach) sections) on forest land in southern Sweden. The hypotheses were

1. Survival and growth are influenced by the site
2. Soil preparation will enhance plant survival
3. Larger plant types will have higher survival and growth than short cuttings
4. In line with results from conifer studies, interactions between soil preparation and plant type will probably be found, indicating that smaller plant types need more intensive soil preparation methods.

2 Materials and methods

2.1 Study sites and experimental design

The study was established on relatively fertile forest land at three different sites in southern Sweden (Table 1). The Brattön

Table 1 Site characteristics

Variable	Site		
	Brattön	Dimbo	Duveholm
Coordination[a]	58° 35′ N, 11° 50′ E	59° 07′ N, 15° 43′ E	58° 58′ N, 16° 09′ E
Elevation[a]	135	90	55
Soil structure	Clay-silt moraine	Sandy moraine and surged gravel	Glacial clay and silty moraine
Soil moisture	Mesic-moist	Mesic	Mesic
Prec. (mm)	900	500	500
Temp. (°C)	6	6	6
Veg. (days)	190	190	180
pH[b]	4.7	4.5	5.3
C_{Tot}	4.3	1.6	1.5
N_{Tot}	0.32	0.09	0.12
$\mathrm{P_{AL}}$	26	11	21
$\mathrm{K_{AL}}$	62	9	70
$\mathrm{Ca_{AL}}$	145	85	1138
$\mathrm{Mg_{AL}}$	44	11	162

Annual precipitation (Prec.), annual mean temperature (Temp), and length of annual vegetation period (Veg.) for the area are averages for the period of 1961–1990 from the Swedish Meteorological and Hydrological Institute (SMHI). pH and nutrient figures were taken from Hjelm and Rytter (2016). Total C and N contents (percent of dry matter) are given for each site, while P, K, Ca, and Mg are plant-available content (mg g^{-1} dry matter) determined using the ammonium lactate (AL) method

[a] WGS84 coordinate system; °N, °E, and elevation (meters above sea level)

[b] pH recorded in distilled H_2O

site had the highest annual precipitation. Brattön was also the most nitrogen rich site and parts of the site were classified as moist. Dimbo was the least fertile site, with the lowest soil pH and a coarse soil texture. Duveholm had the highest calcium content and soil pH. The sites were previous Norway spruce stands clear-felled in the winter of 2012–2013.

The Brattön site was divided into four blocks and the other two sites were divided into five blocks (each 50 × 30 m). The blocking was based on differences in topography and soil moisture within the sites. The blocks contained four plots with the different soil preparation treatments: (1) control with no soil preparation, (2) patch scarification, (3) mounding, and (4) soil inversion (Fig. 1). All soil preparation treatments were performed using an excavator and were randomly applied within the blocks with three rows for each treatment. Patch scarification was carried out by removing the humus layer in patches, leaving undisturbed areas in between. Mounding was conducted by creating elevated planting spots with the excavated soil turned upside-down and put on the side of the hole. Soil inversion was performed by excavating the soil, turning it over, and putting it back in the original hole. Within each soil preparation treatment, the following plant types were randomly assigned to one row each: (a) short cuttings (ca. 20 cm), (b) long cuttings (ca. 50 cm), and (c) containerized plants from rooted cuttings (hereafter called poplar plants). Each row contained 24 cuttings or plants of 12 clones, two individuals of each, randomly distributed (Table 2). All clones were

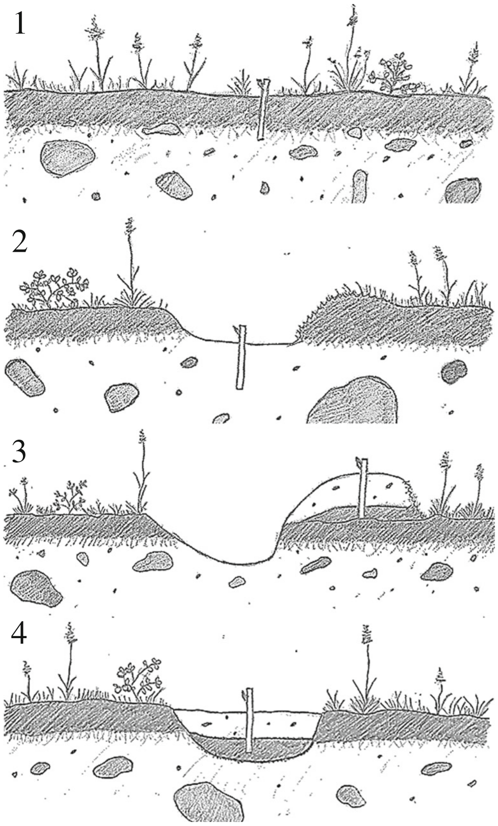

Fig. 1 Illustration of soil preparation methods. *1* = no soil preparation (control), *2* = patch scarification, *3* = mounding, and *4* = soil inversion. All soil preparation was performed with an excavator. Illustration: R. Mc Carthy

Table 2 Information on the clones used in the study

Clone number	Skogforsk ID	Taxon[a]	Additional information
1	S21K766049	*P. trichocarpa*	
3	S21K766003	*P. maximowiczii* × *P. nigra*	Commercial name “Rochester”
4	S21K82604	*P. trichocarpa*	
5	S21K766048	*P. trichocarpa*	
6	S23K9040086	*P. maximowiczii* × *P. trichocarpa*	
7	S23K9040089	*P. maximowiczii* × *P. nigra*	
8	S23K9040073	*P. trichocarpa*	
9	S23K9040025	*P. trichocarpa*	
10	S23K9040019	*P. trichocarpa*	
11	S23K9040011	*P. trichocarpa*	
12	S23K9040006	*P. trichocarpa*	
14	S216PPL52	*P. trichocarpa*	

All clones were commercially available in Sweden. The clone number is the identifier used in this study, and Skogforsk ID is the identifier used by the Forestry Research Institute of Sweden (Skogforsk)

[a] *P. maximowiczii* (Henry), *P. nigra* (Linneaus), and *P. trichocarpa* (Torrey & Gray)

selected from material commercially available in Sweden. The experiment included a total of 4032 plants.

The cuttings came from 1-year-old shoot cut during the winter of 2012–2013, and the poplar plants came from 1-year-old shoots that were planted as cuttings in containers and grown in a nursery the year before planting. All plant types were stored in a freezer (−2 to −4 °C) during the winter of 2012–2013.

Soil preparation and fencing, to prevent browsing damage, were undertaken before planting took place in late May and early June 2013 on the fresh clear-cuts, from where the slash was removed after harvest. Stumps were left on the site. The frozen cuttings were first placed in cold storage for 2 weeks and then stood in water for approximately 24 h before planting. Short cuttings were planted by inserting the cutting straight into the soil with one bud left above the soil surface. A pole was used to form a hole into which the long cuttings were planted. We aimed to keep one third of their length above the soil surface. Possible air pockets were then eliminated by treading. Containerized plants were placed in cold storage for 2 weeks and then planted with a conventional planting tool (Pottiputki). The spacing was approximately 2 × 2 m, but differed somewhat depending on suitable planting spots. After planting, the mean height above the soil surface was 5 cm with mean top diameter 6.1 mm for short cuttings, 19 cm with top diameter 7.5 mm for long cuttings, and 47 cm with a mean basal diameter of 3.5 mm for poplar plants. The clone identity was recorded for each plant.

2.2 Measurements

After each growing season during three consecutive years, the total height (from the soil surface to the base of the highest living bud) of all plants was measured and any new damage was recorded. Damage was recorded in four classes: undamaged, lightly damaged, severely damaged (damage with a negative effect on plant height between years), and dead or dying. In addition, the cause of damage was noted (e.g., browsing by moose, competing vegetation or damage by voles). If the cause was difficult to determine, it was recorded as unknown. The proportion of damage was calculated for each year and only new damage for each specific year was included, while calculations of survival were accumulated over the years and included all initial plants.

At the Dimbo site, wind-thrown trees damaged the fence during the winters 2013 and 2014. Even though the fence was repaired, there was browsing damage and this adversely affected the height growth of the plants.

2.3 Analyses

In the first year, height growth was calculated as the difference between the initial height of the cutting (cm above soil surface) or plant (cm to base of highest bud) and the height at the end of the year. The following years, height growth was calculated as the difference in height from the previous year. Height growth and total plant height were only analyzed for undamaged and lightly damaged plants. In addition, total heights of plants in these categories were compared to total plant heights of all living plants in the third year. Survival of individual clones was estimated across the sites.

After 3 years, survival was analyzed with a split-split-plot generalized mixed model using a binomial distribution with logit link in PROC GLIMMIX, SAS 9.4 (SAS Institute, Cary, NC, USA) (Eq. 1). Height growth and total plant height were analyzed with a split-split-plot mixed model in R using the package “lmerTest” (Bates et al. 2015; Kuznetsova et al. 2016; R Core Team 2016) (Eq. 2). Survival of clones was analyzed over the means of plant type and soil preparation with a split-plot mixed model (Eq. 3). Satterthwaite's approximation was used to determine appropriate degrees of freedom in all analyses. The experimental unit used was based on 24 plants in all models. Significance levels for all analyses were set to an alpha value of 0.05, and where significant effects were found, least squares means were compared pairwise, and the differences were adjusted according to Tukey's test.

$$\begin{aligned}\mathrm{logit}\left(\eta_{ijkl}\right) &= \log\left(\eta_{ijkl}/\left(1-\eta_{ijkl}\right)\right)\\ &= \mu + \mathrm{Site}_i + \mathit{block}_{ij} + \mathrm{Soil}_k\\ &\quad + (\mathrm{Site}\times\mathrm{Soil})_{ik} + \mathit{block}_{ij}\times\mathrm{Soil}_k\\ &\quad + \mathrm{Plant}_l + (\mathrm{Site}\times\mathrm{Plant})_{il}\\ &\quad + (\mathrm{Soil}\times\mathrm{Plant})_{kl}\\ &\quad + (\mathrm{Site}\times\mathrm{Soil}\times\mathrm{Plant})_{ikl} + e_{ijkl} \qquad (1)\end{aligned}$$

where η is a sample proportion with the number of dead plants divided by the total number of plants in the trial (Eq. 1), μ is the overall mean, Site is the fixed effect of the site (i = 1–3), block_{ij} is the random effect of block (j = 1–5) within site, Soil is the fixed effect of soil preparation method (k = 1–4), Plant is the fixed effect of plant type (l = 1–3), and e_{ijkl} is the random error term assumed to be normally distributed with mean 0 and constant variance. The interactions between all fixed factors were also included in the model.

$$\begin{aligned}y_{ijkl} &= \mu + \mathrm{Site}_i + \mathit{block}_{ij} + \mathrm{Soil}_k + (\mathrm{Site}\times\mathrm{Soil})_{ik}\\ &\quad + \mathit{block}_{ij}\times\mathrm{Soil}_k + \mathrm{Plant}_l + (\mathrm{Site}\times\mathrm{Plant})_{il}\\ &\quad + (\mathrm{Soil}\times\mathrm{Plant})_{kl} + (\mathrm{Site}\times\mathrm{Soil}\times\mathrm{Plant})_{ikl}\\ &\quad + e_{ijkl} \qquad (2)\end{aligned}$$

where y_{ijkl} is the observed stand characteristic. The other variables are as described in Eq. 1.

$$\begin{aligned}y_{ijf} &= \mu + \mathrm{Site}_i + \mathit{block}_{ij} + \mathrm{Clone}_f + (\mathrm{Site}\times\mathrm{Clone})_{if}\\ &\quad + e_{ijf} \qquad (3)\end{aligned}$$

where y_{ijf} is the observed survival (%), clone is the fixed effect of clone (f = 1–12), and e_{ijf} is the random error term. The other variables are as described in Eq. 1.

3 Results

3.1 Survival and damage

After the first year, the overall plant survival was 81–100% (Fig. 2). More plants died in the second year (survival ranged between 23 and 91%), especially where there was patch scarification and when short cuttings were planted (Fig. 2). Statistical analysis of survival was performed using data for the third year. Differences in survival as an effect of site, soil preparation method, plant type, and interactions between these variables were found (Table 3). The Dimbo site had a significantly higher survival rate than both Duveholm and Brattön for all soil preparations and plant types (Fig. 2 and Table 4). The effects of soil preparation differed between sites (Table 4), although looking at the main effects of soil preparation, mounding, followed by soil inversion, had the highest survival (mean survival was 61% with mounding, 55% with soil inversion, 43% with patch scarification, and 43% in the control). Short cuttings exhibited relatively low survival at all sites (Fig. 2 and Table 4). With respect to the main effect of plant type, poplar plants had the highest survival rate (61%), followed by long cuttings (56%) and short cuttings (35%).

Within the sites, clones differed in survival success ($p < 0.0001$; Fig. 3). Clone 4 had in general a high survival rate. Clones 7 and 14 exhibited the lowest survival rates. It should be noted that this analysis was done with averages over four soil preparation treatments (1–4) and three plant types (a–c).

Over 3 years, plant damage occurred at all sites (Fig. 4). Of the plants at Brattön and Duveholm, 84 and 75%, respectively, were undamaged after the first year. At Dimbo, only 52% of the plants were undamaged. After the second year, a lot of new damage was observed, especially at Brattön and Duveholm. In year 3, the percentage of plants without new damage increased to 83% at Dimbo and Duveholm, and to 54% at Brattön (Fig. 4).

At Dimbo, some trees fell onto the fence during the first 2 years, and browsing by ungulates was the major cause of damage (31 and 26% of the plants in years 1 and 2, respectively). At Duveholm, voles were responsible for the highest proportion of damage (30% of all plants in year 2). Other causes of damage that could be identified were climate (e.g., frost) and weed competition.

3.2 Height growth and plant height

All plant types differed from each other in height at planting ($p < 0.0001$), and this height was the starting point for growth calculations. Analyses of height growth and plant height were performed on data relating to living plants that were undamaged or only lightly damaged.

Annual height growth (cm year^{-1}) was influenced by site, soil preparation method, plant type, and the interactions between these variables (Tables 3 and 4 and Fig. 5). Site effects interacted with soil preparation or plant type in all 3 years (Table 3). Plants at Duveholm more frequently had faster growth and greater height than at Brattön and Dimbo (Table 4 and Fig. 5).

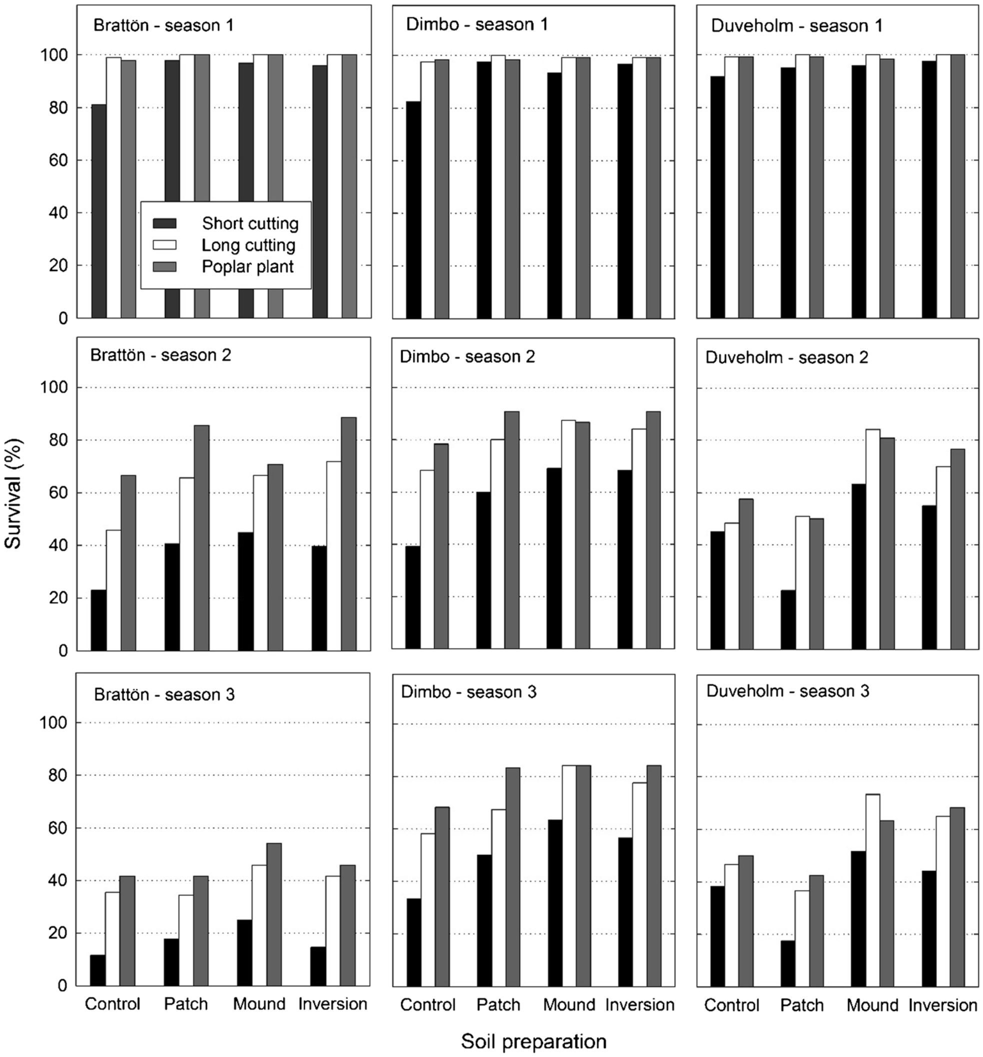

Fig. 2 Survival (%) of poplars for each site (Brattön, Dimbo, and Duveholm) and year (1–3), soil preparation method (*x* axis), and plant type (*bars*). Plant types were short cuttings (ca. 20 cm), long cuttings (ca. 50 cm), and containerized plants

Mounding was associated with faster growth and greater plant height than the other soil preparation treatments in year 1 (Fig. 5a). Plants grown in soil inversion had the second fastest growth, while plants in patch scarification had the slowest. In the second year, mounding and soil inversion were associated with the fastest growth at Dimbo, but no soil preparation effects were seen on growth at the other two sites. The total plant height was higher in mounding plots than in the control and patch scarification plots. In the third year, results diverged with respect to growth and plant height among soil preparation treatments at the sites (Table 4 and Fig. 5a). Examining soil preparation as the main effect showed that patch scarification resulted in the slowest growth of plants and the shortest plants in the third year.

In the first year, the two types of cuttings exhibited the fastest growth, but the total plant height was greatest for the poplar plants followed by long cuttings (Fig. 5b). In the second year, poplar plants and long cuttings performed best at Duveholm, but no other growth effects of plant type were observed. However, the total plant height was still highest for poplar plants followed by long cuttings. The same situation among plant types was observed for growth in the third year (Table 4 and Fig. 5b). Depending on site, the total plant height and height growth was highest for poplar plants alone or together with long cuttings during the last year of the study.

4 Discussion

Significant influences of site, soil preparation method, and plant type on the establishment of poplars on forest land were revealed in this study. Statistically, the sites represented a fixed effect and were chosen for their reasonably high fertility, which is regarded as a requirement for growing poplars (e.g., Boysen and Strobl 1991; Rytter et al. 2011). Nevertheless, differences in site conditions existed. For example, precipitation and water table were higher at the westernmost site, Brattön, there were differences in nutrient availability, and Duveholm had the highest soil pH. In addition, Duveholm and Brattön had more clay in the soil, while

Table 3 Analyses of variance with mixed models for survival, height growth, and total plant height at three sites, with four soil preparation methods (soil), and three plant types (plant)

Source of variation	*df*	Year 1 (*p* value)[a]	Year 2 (*p* value)[a]	Year 3 (*p* value)[a]
Survival				
Site	2			*0.0008*
Soil	3			*<0.0001*
Plant	2			*<0.0001*
Site × soil	6			*0.0234*
Site × plant	4			*0.0350*
Soil × plant	6			0.3999
Site × soil × plant	12			0.6233
Height growth				
Site	2	*<0.0001*	*0.0017*	*0.0020*
Soil	3	*<0.0001*	0.1034	*0.0063*
Plant	2	*<0.0001*	*0.0012*	*0.0012*
Site × soil	6	0.2205	*0.0006*	*0.0249*
Site × plant	4	*0.0002*	*<0.0001*	*0.0093*
Soil × plant	6	0.1498	0.8787	0.7009
Site × soil × plant	12	0.3659	0.6345	0.0723
Total plant height				
Site	2	*<0.0001*	*<0.0001*	*0.0005*
Soil	3	*<0.0001*	*0.0015*	*0.0012*
Plant	2	*<0.0001*	*<0.0001*	*<0.0001*
Site × soil	6	0.2744	0.0714	*0.0068*
Site × plant	4	*0.0002*	*0.0208*	*0.0052*
Soil × plant	6	0.1645	0.4506	0.8165
Site × soil × plant	12	0.5448	0.1081	0.2097

Analyses of heights were performed for three consecutive years. Soil preparation methods were control, patch, mounding, and soil inversion. Plant types were short poplar cutting, long poplar cutting, and containerized poplar plant

df degrees of freedom

[a] Significant p values are highlighted in italic for an α level of 0.05

Dimbo contained more sand. These circumstances probably affected plant performance on each site, as discussed below. The site effects resulted in interactions with both soil preparation and plant type and these interactions had a stronger influence than soil preparation and plant type interactions, which were the factors presumed to have an effect according to hypothesis 4.

Survival was generally high after the first year, but dropped considerably during the period between the first and second inventories. One major reason is probably that the second study period included the first winter, which occurred between the first and second measurements, and may have caused severe stress to the young plants. Frost damage and unfavorable temperatures will lead to a decrease in survival (Landhäusser 2003). However, weed competition during the second year may also have resulted in plant mortality. Weed competition is a general problem on agricultural land (see Böhlenius and Övergaard 2015; Broeckx et al. 2012). Results from the literature have shown that removal of woody and herbaceous vegetation also promotes growth of poplar on forest land (Bilodeau-Gauthier et al. 2011; Czapowskyj and Safford 1993), and it has been reported that poplars are sensitive to both aboveground and belowground competition from weeds (Bilodeau-Gauthier 2011; Coll et al. 2007). Since all sites in this study were relatively fertile, there was already a high abundance of vegetation by the second year after planting. Both herbaceous and woody species were found around the plants and the effect of soil preparation decreased over the study period. Mounding turned out to be the most effective soil preparation at all the sites in terms of survival, but was not linked to such clear effects on growth and height of the remaining plants after 3 years.

A thick organic layer may influence survival and growth negatively (e.g., Lafleur et al. 2015) and removal or treatment of this layer will increase the potential for success. Soil preparation is performed to facilitate and ensure plant establishment on forest land without using herbicides. However, different soil preparation methods, like those used in this study, should be adapted to specific soil conditions. As an example, both the Brattön and Dimbo sites had areas with high soil

Table 4 Mean survival, height growth, and total plant height of poplars after 3 years of growth in southern Sweden

Treatment	Site								
	Brattön			Dimbo			Duveholm		
	Survival (%)	Growth (cm year^{-1})	Height (cm)	Survival (%)	Growth (cm year^{-1})	Height (cm)	Survival (%)	Growth (cm year^{-1})	Height (cm)
Soil preparation									
Control	29.5 a	44.2 a	124.4 ab	53.3 b	40.7 bc	90.0 b	45.0 ab	85.0 a	208.4 a
Patch	31.3 a	37.6 a	113.2 ab	66.9 a	34.8 c	88.1 b	32.2 b	67.0 b	177.6 b
Mound	41.7 a	43.8 a	135.3 a	77.2 a	53.1 ab	121.3 a	62.8 a	81.0 ab	204.2 ab
Inversion	34.0 a	34.8 a	103.2 b	72.8 a	59.5 a	126.8 a	59.2 a	76.7 ab	198.5 ab
Plant type									
Short cutting	17.2 b	38.4 a	105.6 b	50.8 b	46.2 a	94.4 b	37.9 b	68.7 b	170.8 c
Long cutting	39.3 a	40.0 a	115.9 b	71.9 a	47.1 a	107.9 a	55.4 a	82.2 a	204.3 b
Poplar plant	45.8 a	41.9 a	135.5 a	80.0 a	47.7 a	117.5 a	56.0 a	81.4 a	216.4 a

Three sites were prepared with four soil preparation methods and planted with three plant types. Different letters represent significant differences of least squares means within each site and respective treatment according to Tukey's test ($\alpha < 0.05$)

moisture. This resulted in water-filled patches in the patch scarification treatment, since the planting position became lower than the surrounding ground. This caused problems with both weed competition and oxygen deficiency rather than improving the microenvironment, and consequently affected survival. The survival in plots with different soil preparation methods ranged from around 30% in the control and patch scarification treatments at Brattön to 77% in the mounding treatment at Dimbo. Although poplars can be quite tolerant of high water tables, this comes at the cost of decreased root and shoot growth (Dickmann et al. 2001), which is essential for a fast establishment. Consequently, as hypothesized, mounding was in general the best method due to the elevated and drier planting spot, which also reduced competition from weeds. Elevated spots, like the mounds, have been shown to be colonized later (Örlander et al. 1990). The advantages of mounding in reducing competing vegetation are also in line with results reported by Bilodeau-Gauthier et al. (2011) on boreal soils in Canada. Mounding also results in an increased temperature in the plant soil zone, which results in improved

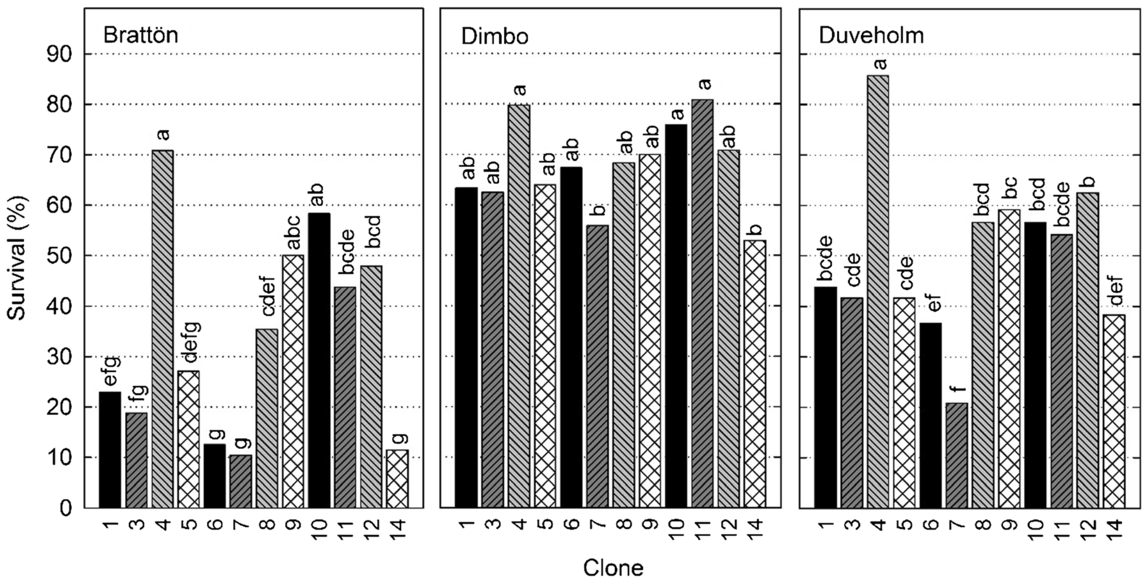

Fig. 3 Survival (%) of poplar clones at the three study sites after 3 years of growth in southern Sweden. Nine of the clones were *P. trichocarpa* (clones 1, 4, 5, and 8–14), two *P. maximowiczii* × *P. nigra* (clones 3 and 7), and one *P. maximowiczii* × *P. trichocarpa* (clone 6). Clones were in the form of three plant types: short cuttings, long cuttings, and containerized plants

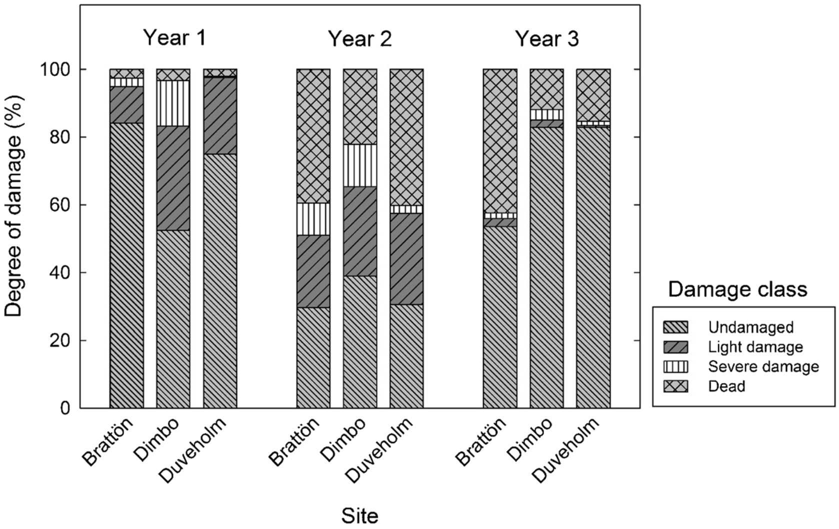

Fig. 4 Degree of damage to plants (%) recorded in four classes after each of 3 years (1–3) at the three sites. All plants were included in year 1 ($N = 4032$) and then dead plants from the previous year were removed

rooting of poplar cuttings (Hansen 1986; Landhäusser 2003; Zalesny et al. 2005) as well as faster establishment and increased growth of conifer plants (Nilsson et al. 2010). In addition, mounding loosens the soil, which encourages the root growth of poplars (Bilodeau-Gauthier et al. 2013). Since mounding was related to the best combination of survival and plant height, this method seems to be useful for establishing poplar stands on forest land where the conditions are similar to those on the Dimbo and Duveholm sites. On the other hand, the survival rate at Brattön was low even when this method was used (42%). This suggests that other species, like black alder (*Alnus glutinosa* (L.) Gaertn.) with higher tolerance to high water tables, should be planted rather than poplars on this type of partly wet soil. The soil inversion method can be used on most forest soils. Positive effects of soil inversion have been found for several experiments with conifer seedlings (Johansson et al. 2007; Johansson et al. 2013). The advantages of soil inversion shown for conifer seedlings were not obvious for the poplars in this study, maybe because of the soil moisture conditions and the fast colonization of vegetation.

In terms of survival and plant height, short poplar cuttings performed poorly at all sites and the larger plant types had an advantage. These results support hypothesis 3. Previous studies have reported better survival for longer cuttings compared to shorter ones, both in nursery and greenhouse conditions

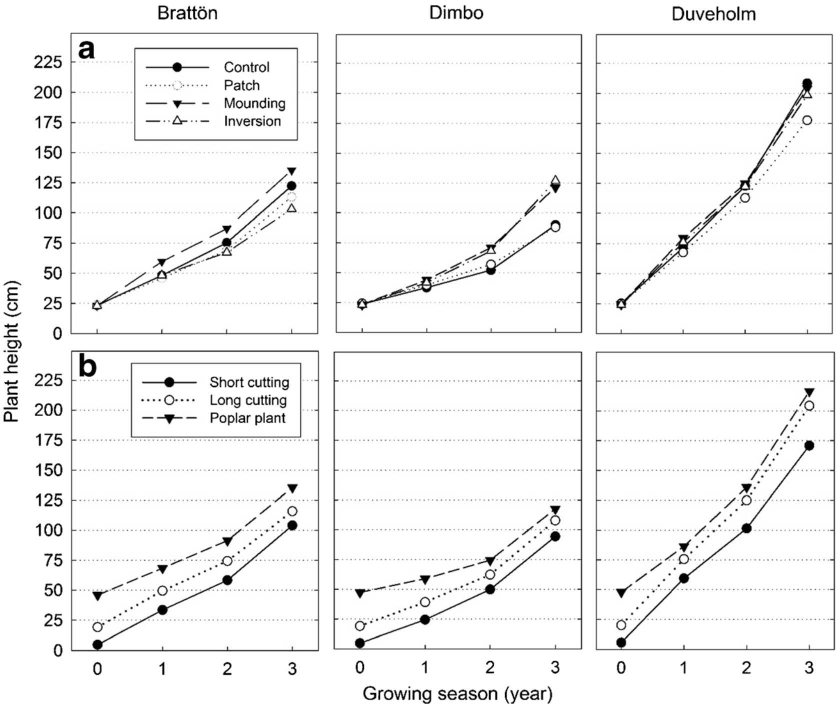

Fig. 5 Plant height (cm) of poplars during 3 years at the three sites (Brattön, Dimbo, and Duveholm). **a** Mean height of plants planted with four soil preparations: control, patch scarification, mounding, and soil inversion. **b** Mean height of three plant types: short poplar cutting (ca. 20 cm), long poplar cutting (ca. 50 cm), and containerized poplar plant. Mean height in year zero represents the aboveground portion of the cutting or plant at the time of planting

(Allen and McComb 1956; Burgess et al. 1990; Vigl and Rewald 2014) and in field experiments (Rossi 1991). Forest land is often more difficult to prepare and has different soil properties compared to agricultural land, resulting in less favorable conditions for plant establishment. Results from this study showed an average survival for short cuttings of 35% after 3 years, and at one site, the figure was below 20%. This indicates that short cuttings should not be recommended for the establishment of poplar on forest land. Long cuttings, on the other hand, were more successful and achieved a survival level similar to that of the rooted poplar plants. This is probably a result of the larger size of the cutting (i.e., diameter and length), providing carbohydrates and moisture during root and shoot initiation (DesRochers and Thomas 2003; Dickmann et al. 1980; Haissig 1974; Kaczmarek et al. 2014; Zalesny et al. 2003). The height above the soil surface was probably also a positive factor, conferring an advantage over competing vegetation in this study. At the same time, it is important to find a proper balance between the parts of the cutting placed above and below the ground (Kaczmarek et al. 2014). The long cuttings had the advantage of a large belowground part which made it possible to initiate roots over a large soil depth, thus reducing sensitivity to drought (Rossi 1991; Schuler and McCarthy 2015).

In our study, the cuttings exhibited fast initial growth. A high initial growth rate of poplar cuttings in comparison with bare-root plants has been reported on agricultural land by Böhlenius and Övergaard (2015). This suggests that poplar plantations should ideally be planted with long cuttings or rooted plants. The slower start of poplar plants indicated that they needed to extend their existing root system before shoot growth could accelerate. Better balanced plants with respect to shoot to root ratio may reduce this planting shock.

Soil acidity should also be considered when planting poplar on forest land. In this study, the sites had a soil pH that ranged from 4.5 to 5.3. The plants at the Duveholm site, with the highest pH, showed the highest growth rates. This is in agreement with, for example, the studies of Hjelm and Rytter (2016) and Böhlenius et al. (2016). The survival did not follow this trend as Dimbo, with the lowest pH, had the highest survival rates and Duveholm the lowest. Survival may not be closely related to pH, and the low survival at Duveholm could instead be explained by vole damage (over 30%), partly as a consequence of more competitive vegetation. It has been reported that populations of voles are related to the amount and composition of ground vegetation (Hytönen and Jylhä 2005; Manson et al. 2001).

Since this study only included two ramets per clone in each experimental unit, the design for studying clones was weak. However, trends in clone survival could be identified, but it should be noted that the figures for poplar clones included averages over three plant types and four soil preparation treatments. Nevertheless, poplar clone 4, a *P. trichocarpa*, was successful with an overall survival close to 80%. The plant material was selected for good performance on agricultural land with mild climate in southern Sweden. By planting this material on forest land, the survival results were more varied and the need for clonal tests on forest land is obvious. The first step in testing poplar clones on forest land has recently begun in Sweden (Stener and Westin 2017), and the results provide evidence of poplar's sensitivity to climate and soil acidity.

In conclusion, by selecting well-tested clones, using long cuttings or rooted plants, undertaking necessary protection measures against herbivores, and preparing the soil in accordance with needs dictated by the site conditions, poplars can be established on forest land. Interacting site effects had a large influence on survival and growth, but in general, mounding enhanced plant survival and growth during the study period. Poplar plants and sometimes long cuttings exhibited the highest survival and growth, while short cuttings performed much less well.

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Compliance with ethical standards

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References

Allen RM, McComb AL (1956) Rooting of cottonwood cuttings. Occasional Paper 151, USDA Forest Service, Southern Forest Experiment Station

Bates D, Mächler M, Bolker BM, Walker SC (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–51. doi:10.18637/jss.v067.i01

Bilodeau-Gauthier S (2011) Shoot and root responses of hybrid poplars to interspecific competition and soil fertility. Dissertation, Université du Québec à Montréal

Bilodeau-Gauthier S, Paré D, Messier C, Bélanger N (2011) Juvenile growth of hybrid poplars on acidic boreal soil determined by environmental effects of soil preparation, vegetation control, and fertilization. For Ecol Manag 261:620–629. doi:10.1016/j.foreco.2010.11.016

Bilodeau-Gauthier S, Paré D, Messier C, Bélanger N (2013) Root production of hybrid poplars and nitrogen mineralization improve following mounding of boreal Podzols. Can J For Res 43:1092–1103. doi:10.1139/cjfr-2013-0338

Böhlenius H, Övergaard R (2015) Exploration of optimal agricultural practices and seedling types for establishing poplar plantations. Forests 6:2785–2798. doi:10.3390/f6082785

Böhlenius H, Övergaard R, Asp H (2016) Growth response of hybrid aspen (*Populus* × *wettsteinii*) and *Populus trichocarpa* to different pH levels and nutrient availabilities. Can J For Res 46:1367–1374. doi:10.1139/cjfr-2016-0146

Boysen B, Strobl S (1991) A grower's guide to hybrid poplar. Ontario Ministry of Natural Resources, Brockville

Broeckx LS, Verlinden MS, Ceulemans R (2012) Establishment and two-year growth of a bio-energy plantation with fast-growing *Populus* trees in Flanders (Belgium): effects of genotype and former land use. Biomass Bioenergy 42:151–163. doi:10.1016/j.biombioe.2012.03.005

Burgess D, Hendrickson OQ, Roy L (1990) The importance of initial cutting size for improving the growth performance of *Salix alba* L. Scand J For Res 5:215–224. doi:10.1080/02827589009382607

Coll L, Messier C, Delagrange S, Berninger F (2007) Growth, allocation and leaf gas exchanges of hybrid poplar plants in their establishment phase on previously forested sites: effect of different vegetation management techniques. Ann For Sci 64:275–285. doi:10.1051/forest:2007005

Czapowskyj MM, Safford LO (1993) Site preparation, fertilization, and 10-year yields of hybrid poplar on a clearcut forest site in eastern Maine, USA. New For 7:331–344

DesRochers A, Thomas BR (2003) A comparison of pre-planting treatments on hardwood cuttings of four hybrid poplar clones. New For 26:17–32

Dickmann DI, Phipps H, Netzer D (1980) Cutting diameter influences early survival and growth of several *Populus* clones. Research Note NC-261, USDA Forest Service, North Central Forest Experiment Station

Dickmann DI, Isebrands JG, Blake TJ, Kosola K, Kort J (2001) Physiological ecology of poplars. In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J (eds) Poplar culture in North America. NRC Research Press, Ottawa, pp 77–118

Engerup P-O (2011) Föryngring med poppel och hybridasp på skogs- och åkermark. Master thesis, Swedish University of Agricultural Sciences, Alnarp

Ericsson T, Lindsjö I (1981) Tillväxtens pH-beroende hos några energiskogsarter. Teknisk rapport 11, Projekt Energiskogsodling (ESO). Swedish University of Agricultural Sciences, Uppsala

European Commission (2015) The Paris protocol: a blueprint for tackling global climate change beyond 2020. Brussels

Grossnickle SC, El-Kassaby YA (2015) Bareroot versus container stocktypes: a performance comparison. New For 47:1–51. doi:10.1007/s11056-015-9476-6

Haissig BE (1974) Metabolism during adventitious root primordium initiation and development. N Z J For Sci 4:324–337

Hansen EA (1986) Planting date affects survival and height growth of hybrid poplar. For Chron 62:164–169. doi:10.5558/tfc62164-3

Hansen E, Moore L, Netzer D, Ostry M, Phipps H, Zavitkovski J (1983) Establishing intensively cultured hybrid poplar plantations for fuel and fiber. General Technical Report NC-78, USDA Forest Service, North Central Forest Experiment Station

Hjelm K, Rytter L (2016) The influence of soil conditions, with focus on soil acidity, on the establishment of poplar (*Populus* spp.) in northern Europe. New For 47:731–750. doi:10.1007/s11056-016-9541-9

Hytönen J, Jylhä P (2005) Effects of competing vegetation and post-planting weed control on the mortality, growth and vole damages to *Betula pendula* planted on former agricultural land. Silva Fenn 39:365–380. doi:10.14214/sf.374

IEA (2013) Nordic energy technology perspectives: pathways to a carbon neutral energy future. IEA Publications, Paris

Isebrands JG, Richardson J (2014) Poplars and willows: trees for society and the environment. CABI, Boston

Johansson K, Nilsson U, Allen HL (2007) Interactions between soil scarification and Norway spruce seedling types. New For 33:13–27. doi:10.1007/s11056-006-9010-y

Johansson K, Nilsson U, Örlander G (2013) A comparison of long-term effects of scarification methods on the establishment of Norway spruce. Forestry 86:91–98. doi:10.1093/forestry/cps062

Johnsson H (1953) Hybridaspens ungdomsutveckling och ett försök till framtidsprognos. Svenska Skogsvårdsföreningens Tidskrift 51:73–96

Kaczmarek DJ, Rousseau RJ, Wright JA, Wachelka BC (2014) The influence of alternative plant propagation and stand establishment techniques on survival and growth of eastern cottonwood (*Populus deltoides* Bartr.) clones. New For 45:487–506. doi:10.1007/s11056-014-9411-2

Kuznetsova A, Brockhoff PB, Christensen RHB (2016) lmerTest: tests in linear mixed effects models. R package version 2.0–33. http://CRAN.R-project.org/package=lmerTest

Lafleur B, Cazal A, Leduc A, Bergeron Y (2015) Soil organic layer thickness influences the establishment and growth of trembling aspen (*Populus tremuloides*) in boreal forests. For Ecol Manag 347:209–216. doi:10.1016/j.foreco.2015.03.031

Landhäusser SM (2003) Effect of soil temperature on rooting and early establishment of balsam poplar cuttings. Tree Planters' Notes 50:31–34

Larsson S, Lundmark T, Ståhl G (2009) Möjligheter till intensivodling av skog. Slutrapport från regeringsuppdrag Jo 2008/1885, Swedish University of Agricultural Sciences, Umeå

Löf M, Dey DC, Navarro RM, Jacobs DF (2012) Mechanical site preparation for forest restoration. New For 43:825–848. doi:10.1007/s11056-012-9332-x

Manson RH, Ostfeld RS, Canham CD (2001) Long-term effects of rodent herbivores on tree invasion dynamics along forest-field edges. Ecology 82:3320–3329. doi:10.2307/2680155

Nilsson U, Luoranen J, Kolström T, Örlander G, Puttonen P (2010) Reforestation with planting in northern Europe. Scand J For Res 25:283–294. doi:10.1080/02827581.2010.498384

Nordenergi (2010) A CO_2-neutral vision for the Nordic countries for 2050: the Nordic perspective. Nordenergi Secretariat, Frederiksberg

Örlander G, Gemmel P, Hunt J (1990) Site preparation: a Swedish overview. FRDA report 105. Forestry Canada, Victoria

Persson P-O, Rytter L, Johansson T, Hjelm B (2015) Handbok för odlare av poppel och hybridasp. Jordbruksverket, Jönköping

R Core Team (2016) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna **https://www.R-project.org/**

Rossi P (1991) Length of cuttings in juvenile development of a hybrid poplar clone. New For 5:211–218. doi:10.1007/bf00028112

Rytter L, Johansson T, Karačić A, Weih M, Börjesson P, Fogdestam N, Hannerz M, Ingvarsson P, Rosenqvist H, Stener L-G (2011) Orienterande studie om ett svenskt forskningsprogram för poppel. Arbetsrapport Nr 733. Skogforsk, Uppsala

Rytter L, Johansson K, Karlsson B, Stener L-G (2013) Tree species, genetics and regeneration for bioenergy feedstock in northern Europe. In: Kellomäki S, Kilpeläinen A, Alam A (eds) Forest bioenergy production: management, carbon sequestration and adaptation. Springer, New York, pp 7–37

Rytter L, Andreassen K, Bergh J, Ekö P-M, Grönholm T, Kilpeläinen A, Lazdiņa D, Muiste P, Nord-Larsen T (2015) Availability of biomass for energy purposes in Nordic and Baltic countries: land areas and biomass amounts. Balt For 21:375–390

Rytter L, Ingerslev M, Kilpeläinen A, Torssonen P, Lazdina D, Löf M, Madsen P, Muiste P, Stener L-G (2016) Increased forest biomass production in the Nordic and Baltic countries: a review on current and future opportunities. Silva Fenn 50:1–33. doi:10.14214/sf.1660

Schuler JL, McCarthy W (2015) Development of eastern cottonwood cuttings as modified by cutting length and surface area available for rooting. New For 46:547–559. doi:10.1007/s11056-015-9482-8

Stanturf JA, van Oosten C (2014) Operational poplar and willow culture. In: Isebrands JG, Richardson J (eds) Poplars and willows: trees for society and the environment. CABI, Boston, pp 200–257

Stener L-G, Westin J (2017) Early growth and phenology of hybrid aspen and poplar in clonal field tests in Scandinavia. Silva Fenn 51:1–22. doi:10.14214/sf.5656

Thiffault N, Jobidon R, Munson AD (2014) Comparing large containerized and bareroot conifer stock on sites of contrasting vegetation composition in a non-herbicide scenario. New For 45:875–891. doi:10.1007/s11056-014-9443-7

Tullus H, Tullus A, Rytter L (2013) Short-rotation forestry for supplying biomass for energy production. In: Kellomäki S, Kilpeläinen A, Alam A (eds) Forest bioenergy production: management, carbon sequestration and adaptation. Springer, New York, pp 39–56

Vigl F, Rewald B (2014) Size matters?—the diverging influence of cutting length on growth and allometry of two *Salicaceae* clones. Biomass Bioenergy 60:130–136. doi:10.1016/j.biombioe.2013.11.020

Zalesny RS Jr, Hall RB, Bauer EO, Riemenschneider DE (2003) Shoot position affects root initiation and growth of dormant unrooted cuttings of *Populus*. Silvae Genet 52:273–279

Zalesny RS Jr, Hall RB, Bauer EO, Riemenschneider DE (2005) Soil temperature and precipitation affect the rooting ability of dormant hardwood cuttings of *Populus*. Silvae Genet 54:47–58