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Impact of seedling type on early growth of poplar plantations on forest and agricultural land

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ABSTRACT
Today, most poplar plantations in the temperate region are established on abandoned marginal agricultural land, but there is great potential for planting poplars on forest land as the available area is large and does not compete with food production. The objective of this study was to examine how different planting types (un-rooted cuttings, bare-rooted and containerized plants) affect the establishment and early growth of poplar plants on forest and agricultural sites. Our results suggest that on the agricultural site, survival and growth during the first two years are not influenced by plant type. However, at the forest sites, survival of rooted plants was superior compared to un-rooted cuttings. The height and biomass (stem and root) increment of bare-rooted plants was low; greater height and biomass growth was found for containerized plants. Container sizes had no effect on height growth, but leaf and stem biomasses were higher if the largest containers were used. When using the largest containers, concentrations of macronutrients (N, P) were increased compared to bare-rooted plants. Thus, these results suggest that practices for establishing poplar plantations of agricultural land include planting of un-rooted cutting, but on forest land, a plant grown in a container of 470 ml should be used. Together, this can reduce the cost of establishment, increase the available area for poplar plantations and have an impact on poplar plantation economics in Sweden.

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Introduction

There is increasing demand for forest biomass as a replacement for oil and coal products. Plantations of fast growing broadleaved species, such as poplars, have an important role in this transition and could be one way to reduce pressure on forest fuel from natural forests (Paquette & Messier 2009). In several parts of the world, the most appropriate fast growing tree species belong to the genus *Populus*. Thus, poplar plantations are being established across large areas in temperate regions of the world, mainly on abandoned agricultural land (Christersson 2008, 2010; Tullus et al. 2011). Failure of establishment of poplar plantations is often associated with inappropriate soil management techniques and vegetation control, or a combination of these as poplars are sensitive to competing vegetation during their establishment period (Coll et al. 2007; Otto & Zanin 2010; Tullus et al. 2011).

Seedling establishment depends on two factors: environmental conditions and seedling quality at the time of planting (Grossnickle 2005). How the newly transplanted seedling responds to the environment and starts to grow new roots into the surrounding soil determines whether the seedling survives the planting procedure (Grossnickle 2005). New root growth during the first growing season in the field has been known for long time to be extremely important for seedling growth (Wakeley 1954; Stone 1955). The ability of a seedling to utilize soil water is affected by root hydraulic conductivity, root–soil contact, and root system size and distribution (Grossnickle 2005). Typically, newly planted seedlings have limited root system permeability and/or root–soil contact and restricted root placement that together can limit water uptake from the soil (Kozlowski & Davies 1975; Rietveld 1989; Burdett 1990). Thus, fast development of the roots after planting is critical for ensuring good seedling establishment. It is important for the transplanted seedling to have high initial height growth to reduce the period when it is sensitive to factors causing stress, among which drought, competing vegetation and browsing are common (Nilsson et al. 2010). Poplars are fast growing, with a rotation period of 10–25 years depending on planting density and location (Tuskan 1998; Stanturf & van Oostem 2014) with variations according to final products and local climate conditions.

A fast and secure establishment procedure will reduce the cost and enhance the income from such plantations. Therefore, this should be ensured in the regeneration phase. The choice of location (agricultural or forest) dictates the soil preparation method and vegetation control technique, but the choice of seedling type could also be important. This is the case for Norway spruce, depending on climatic conditions at the regeneration area and the soil preparation method used (Thiffault 2004; Johansson et al. 2007). Generally, containerized seedlings out-perform bare-rooted plants under field conditions (McDonald 1991; Nilsson & Örlander 1995; Thiffault et al. 2003). However, Mohammed et al. (2001) reported that in some cases bare-rooted seedlings exhibited deeper root depth, better soil-to-root contact and anchorage compared

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to containerized seedlings. Other authors have concluded that it is not clear whether bare-rooted plants perform better than containerized plants (reviewed in Grossnickle 2000). Container size could also influence seedling growth as demonstrated for Norway spruce and Scots pine (Johansson et al. 2014). Thus, for other tree species, including poplars, container size and plant type might influence plant growth when transplanted to the field. Poplars can initiate adventitious roots from their stems, so stem cuttings can be used as transplants for establishing poplar plantations (Hartmann & Kester 1975; DeBell & Harrington 1997; Hofmann-Schielle et al. 1999), but containerized or bare-rooted plants can also be used. Rooted plants differ from cuttings in several respects: they have developed roots and substantial above-ground parts, while cuttings have no roots and very small above-ground parts. Plants of different stock types, that is, bare-rooted or containerized, are grown under different conditions and therefore have diverse attributes, of which differences in morphology and physiology are probably important. Containerized plants usually have many new and actively growing roots (Grossnickle 2012), while bare-rooted plants have suberized roots that are less effective in water uptake. The bare-rooted plants also have relatively larger above-ground parts than containerized plants and this could also influence plant establishment. How poplar plant types (un-rooted cuttings, bare-rooted plants or plants grown in containers of different sizes) influence poplar growth is unknown, thus there is a knowledge gap regarding the establishment of poplars when different plant types are used on different sites. The study described herein examined how plant development was influenced by five different plant types established on agricultural and forest sites. Comparing the effect of these plant types on survival, plant growth and nutrient content should provide important information about the interaction between plant type and planting site.

Materials and methods

Site description and soil treatment

The experiment was established at one agricultural and two forest sites located in the southernmost part of Sweden. The sites are: agricultural (Alnarp, 55°39′38.6″N 13°5′8.2″E), forest (Tönnersjöheden, 56°42′7.0″N 13°6′21.4″E) and forest (Sävsjöström, 56°59′5.6″N 15°28′55.3″E). At the agricultural site, the soil was plowed then harrowed and the vegetation was manually controlled during the experimental period. The forest sites differed in site index: G34 (dominant height of spruce at 100 years of age corresponding to a mean production of 12.6 m^3 ha^{-1} year^{-1}) at Tönnersjöheden and T22 (dominant height of pine at 100 years of age corresponding to 5.1 m^3 ha^{-1} year^{-1}) at Sävsjöström. We refer to Tönnersjöheden as G34 and Sävsjöström as T22 hereafter. The annual precipitation and mean temperature were about 800 mm and 8°C at Alnarp, 1000 mm and 8°C at Tönnersjöheden, and 800 mm and 5°C at Sävsjöström (SMHI). After planting the first year, 15 May and to October, maximum and minimum temperature at the closest weather stations to each experimental site varied between 3.8°C to 32.1°C Alnarp, 2.7–27.5°C Tönnersjöheden and 1.6–27.9°C at Sävsjöström. The weakly precipitation varied between 0 and 4.6 mm at Alnarp, 0.4 and 10 mm at Tönnersjöheden and 0 and 6.4 mm Sävsjöström. The weather stations are located 20 km from Alnarp, 16 km Tönnersjöheden and 19 km Sävsjöström. At the forest sites, G34 was dominated by spruce (*Picea abies* (L). Karst) and T22 was dominated by Scots pine (*Pinus sylvestris* L.) prior to cutting. The ground vegetation on the clear cuts was dominated by grass. To reduce browsing by deer and moose, the experimental areas were fenced. The soil at the agricultural site is silty clay and at the forest sites it is podzolic moraine. Inverse soil scarification was conducted with an excavator at the forest sites.

Plant material

Hybrid poplar (*Populus trichocarpa* × *Populus maximowiczii*), clone OP42 was selected for this study due to its commercial availability, good rooting capacity and performance. Five types of planting material were used: bare-rooted plants, un-rooted cuttings and plants grown in containers of three sizes (470, 250 and 90 ml). The bare-rooted plants were purchased from Svenska skogsplantor, Hallsberg, Sweden. The container-grown plants were produced as follows: in July dormant cuttings (length 15 cm and with a diameter of 7–10 mm) were planted in plastic containers of three sizes (470, 250 and 90 ml). The soil used was a plant nursery soil mixture (Hammenhög, Åby, Sweden) pH 5.5–6.5, N–P–K 11–5–8% + micronutrients, peat 83% clay 5%, gravel 7% and hydrograins 5%, and the plants were grown during the summer. The un-rooted cuttings were harvested in winter and stored together with container-grown plants at +4°C until planting. The plant types are referred to as follows: bare-rooted plants – BR, Un-rooted cuttings – CU, plants grown in plastic containers of 470 ml – C470, 250 ml – C250 and 90 ml – C90. All of the containers were cylinder shaped, C470 with a height of 20 cm and diameter of 5.5 cm, C250 height of 16 cm and diameter of 4.5 cm and C90 with height of 9.5 cm and diameter of 3.5 cm. At the time of planting, the mean height, diameter, stem, root biomasses and shoot-to-root ratio (S:R) were determined. A summary of these parameters is shown in Table 1. Before planting, the un-rooted cuttings were soaked in water for 24 h. Planting for the experiment was undertaken in May.

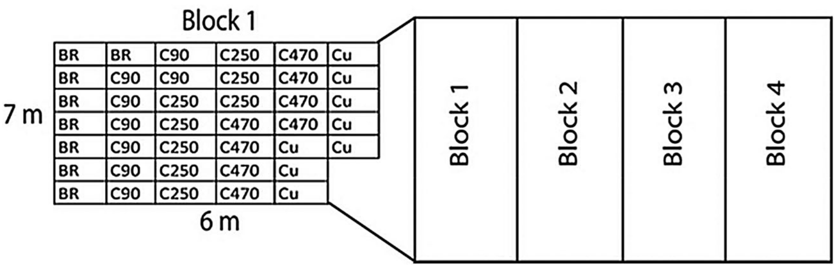
Experimental design

On each of the sites (forest and agricultural), there were four blocks. In each block, five randomly distributed plots containing the different plant types were established. In each plot, eight plants of each type were manually planted 1 m apart. The transplants were: un–rooted cuttings and rooted plants, bare-rooted and containerized plants grown in containers of different sizes. Figure 1 illustrates the experimental design of agricultural site Alnarp.

Table 1. Plant properties before planting.

	Biomasses and shoot-to-root ratio												Height and diameter					
Plant type	Stem		SE	Root		SE	Shoot:root		SE	Height		SE	Diameter		SE
BR	20.3	±	0.6	7.0	±	1.1	2.9	±	0.35	78	±	1.8	7.6	±	0.4
C470	1.1	±	0.1	0.3	±	0.12	3.6	±	0.94	37	±	1.2	3.3	±	0.1
C250	1.0	±	0.03	0.15	±	0.04	6.8	±	2.07	25	±	2.0	2.7	±	0.2
C90	0.6	±	0.05	0.17	±	0.07	4.1	±	1.45	25	±	1.9	2.7	±	0.1

Notes: The table includes stem and root biomasses. Shoot-to-root ratio (S:R), height and diameter of the different plant types. The transplanted plant types are: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants and C90 – 90 ml container-grown plants. Plant biomasses are in gram (g), height (cm) and diameter (mm). Data shown are means $n = 5$.



BR	BR	C90	C250	C470	Cu
BR	C90	C90	C250	C470	Cu
BR	C90	C250	C250	C470	Cu
BR	C90	C250	C470	C470	Cu
BR	C90	C250	C470	Cu	Cu
BR	C90	C250	C470	Cu	
BR	C90	C250	C470	Cu	

Figure 1. Illustration of experimental design exemplified by Alnarp (Agricultural site). The figure shows the four blocks and distribution of the plant types within block 1. In blocks 2–4 the plant types are distributed randomly. The plant types are: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants, C90 – 90 ml container-grown plants and CU – un-rooted cuttings.

Collection of plant data

Total stem height and ground-line diameter (10 cm above the soil surface) were recorded at the beginning of October after the first and second growth periods. For determination of biomass, one seedling per type and plot was randomly selected and harvested in September after the first growth period. The plants were separated into leaf, stem and roots. The roots were washed and, like the leaves and stems, dried at 70°C for 48 h before being weighed. For analysis of nitrogen (N), phosphorus (P) and potassium (K) contents, one fully developed leaf with no damage, from the upper part of each plant in each plot was sampled early in August the same year as planning took place. The leaves were analyzed as composite samples per plot according to Leco AN 203 821–394, ISO 16634 (Nitrogen) and NMKL 161, 198, mod (minerals) in the analytical laboratory of Eurofins, Kristianstad, Sweden. Total N were calculated by multiplication of individual leaf biomass with N concentration from that particular plant.

Statistical analysis

To test the effects of the plant types on the measured variables, the general linear model and mixed model procedures, implemented in SAS (SAS Institute Inc., Cary, NC), were used. Plant type was set as the main factor and block as a random factor. Tukey's test at the 5% level was used to determine significant differences (Quinn & Keough 2002). All tested variables were examined for distribution, residuals and homoscedasticity using the UNIVARIATE procedure and transformed when necessary to obtain an even variable distribution. The response factor y was transformed as follows: y^2 for allocation to stem, diameter growth year one and P concentration (P) at T22; $1/y$ for biomass allocation to stem on agricultural land (Alnarp), allocation to leaf and K concentration at T22 and height growth year one at G34. When none of these transformations produced a satisfactory variable distribution, the Wilcoxon rank method was used for analysis (Wonnacott & Wonnacott 1985).

Results

Plant mortality, height, diameter and biomass growth at the agricultural site

At the agricultural site, high numbers of surviving plants were found after the first and second years, varying between 100% and 93% for both years, with no differences between the

Table 2. Seedling survival one and two years after planting.

		Agricultural site						Forest site G34						Forest site T22					
Time of planting	Plant type	Year one		SE	Year two		SE	Year one		SE	Year two		SE	Year one		SE	Year two		SE
Spring 2013	BR	93	±	10a	93	±	10a	94	±	7a	80	±	16a	97	±	6a	75	±	14a
	C470	96	±	7a	96	±	7a	94	±	7a	89	±	14a	94	±	7a	75	±	10a
	C250	93	±	9a	93	±	9a	83	±	16ab	77	±	19a	94	±	7a	77	±	12a
	C90	97	±	6a	97	±	6a	91	±	19a	51	±	9b	88	±	14a	77	±	16a
	CU	100	±	0a	100	±	0a	22	±	8b	3	±	6c	53	±	12b	3	±	6a

Notes: The table incudes planting time, experimental location and plant type. The transplanted plant types are: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants, C90 – 90 ml container-grown plants and CU – dormant cuttings. Plants survival is percent (%) of transplanted plants. Data shown are means $n = 4$. Different letters indicate statistical differences $p = .05$.

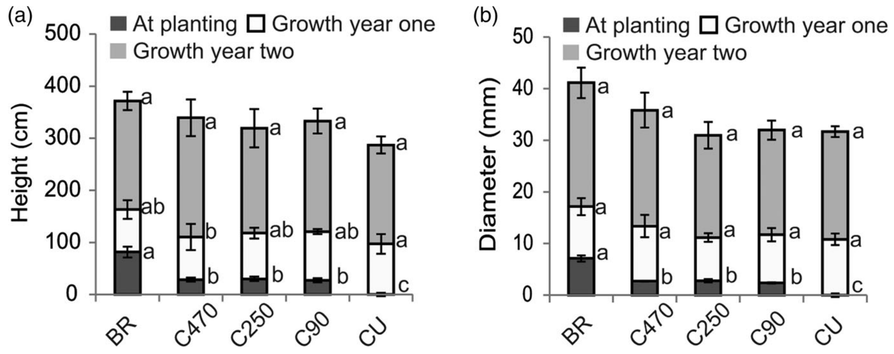


Figure 2. Height and diameter growth at the agricultural site. Height (a) and diameter growth (b) were recorded at the end of the first and second growth periods for all the different plant types: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants, C90 – 90 ml container-grown plants and CU – un-rooted cuttings. Values with the same letters are not significantly different at the $p = .05$ level: means ($n = 4$), error bars indicate standard error.

plant types (Table 2). After the first and second years of growth, the different plant types reached a similar growth; height 81–114 cm in year one and 200–214 cm in year two and diameter 8–11 mm in year one and 26–20 cm in year two (Figure 2). Biomasses varied for stem (range 162–100 g), root (range 34–26 g), leaf (range 68–47 g) and shoot-to-root ratio (range 0.24–0.15). Biomass allocation to different tissue varied for stem (range 61–54%), root (range 29–25%) and leaf (17–13%). There was no significant difference between plant types, either for biomasses or allocation.

Plant mortality at forest sites

At the forest sites, a high percentage of the transplanted rooted plants (bare-rooted and containerized) survived the first year of growth, varying between 94–83% (G34) and 97–88% (T22) (Table 2). After the second year of growth, C90 plants had the highest mortality (49%) among rooted plants when planted at forest site G34 (Table 2). Survival of the other rooted plants varied between 89% for C470 plants and 77% for C250 plants, with no difference between the plant types. At the other forest site, T22, 77–75% of the rooted plants survived (Table 2) with no difference between the plant types. In contrast to rooted plants, high mortality of transplanted un-rooted cuttings was found after the first and second years. For this reason, un-rooted cuttings planted at forest sites are excluded from further analysis.

Plant height and diameter growth at the forest sites

Height growth of bare-rooted plants was 2 and 5 cm at G34 and T22, respectively, after the first year (Figure 3(a)), but after the second year, no height growth could be detected at any of the sites. A similar result was found for diameter growth at G34, with a 1 mm diameter increase during the first year and no diameter growth after the second year (Figure 3(d)). At T22, plants increased their diameter during both years (Figure 3(c)). For containerized plants, we recorded height growth at both forest sites and in both years after planting. After the first year, height growth varied between 31 and 24 cm at T22 and 20 and 8 cm at G34. In the second year, height growth varied between 26 and 18 cm at T22 and 42 and 31 cm at G34. However, no significant differences in height growth between the container sizes could be found at either of the forest sites or in the years. Diameter growth responded in a similar way, with increased diameter at both sites and in both years. These results demonstrate that early growth of poplars at forest sites is dependent on the plant type used.

Biomass production and biomass allocation of plants grown at forest sites

Before planting, the stem biomass of containerized plants varied between 1.1 g for C470 and 0.6 g for C90 and the root biomass from 0.3 g for C470 to 0.15 g for C250 (Table 1). One year after planting at T22, plants from the largest containers, C470, had the highest leaf and stem biomasses of the containerized plants, reaching 11 g of leaves and 24 g of stem, while plants from containers C250 and C90 had lower but similar leaf and stem biomasses (Figure 4(a) and 4(c)). However, no significant difference was found for the root biomass of container-grown plants. At G34, biomasses (stem, leaf and root) gradually increased with container size with significant differences between C470 and C90 (Figure 4(d)–(f)). For bare-rooted plants, root biomass before planting was 7.0 g and stem biomass 20.3 g (Table 1). One year after planting, the root and stem weights had changed little, with root biomass of 8.4 g at T22 and 5.3 g at G34 and stem biomass of 17 g at T22 and 19 g at G34. At forest site T22, no difference in root-to-shoot ratio or biomass allocation was found for containerized plants (Figure 5(a) and 5(c)). Allocation to the roots of bare-rooted plants was higher compared to containerized plants, as was the root-to-shoot ratio (Figure 5(a) and 5(c)). At forest site G34, root-to-shoot ratio gradually increased with container size, with significant differences between C470 and C90. Of the container-grown plants, C90 had the highest allocation to stem and the lowest allocation to the roots and leaves (Figure 5(d)). For C470 and C250 plants, there were no differences in allocation to root, stem or leaves.

Analysis of macronutrients

At forest site T22, the highest concentration of N for containerized plants was found in C470, while C250 and C90 had similar levels (Figure 6(a)). For plants grown at G34, no

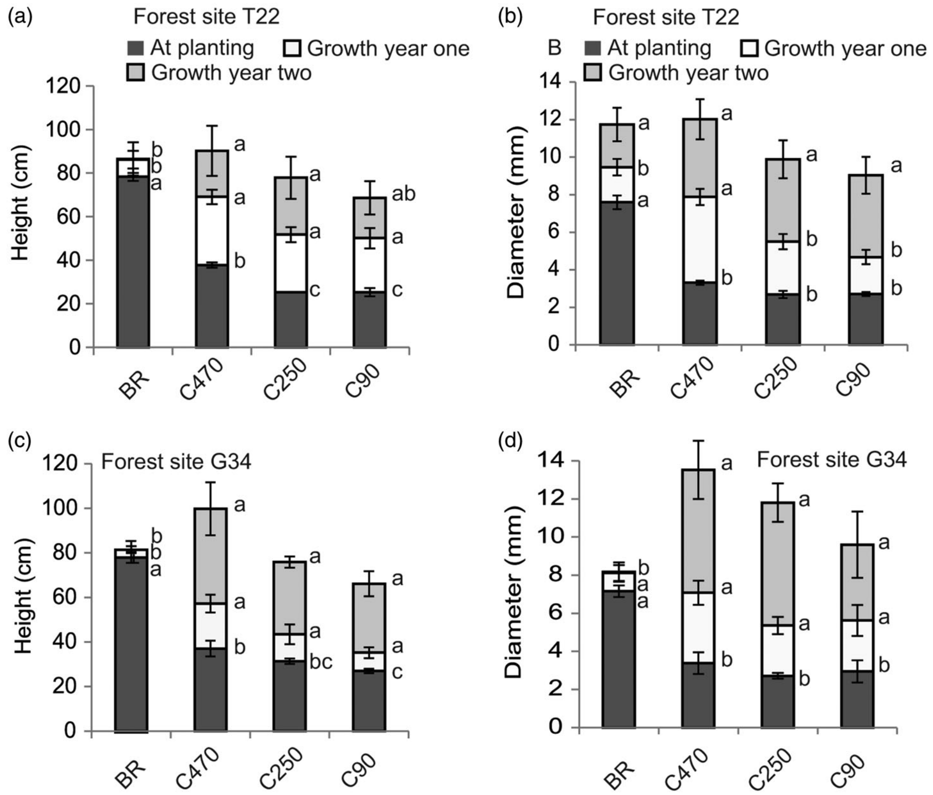


Figure 3. Plant height and diameter growth. Height (a) and (c) and diameter (b) and (d) were recorded at the end of the first and second growth period for the different plant types: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants and C90 – 90 ml container-grown plants. Values with the same letters are not significantly different at the $p = .05$ level: means ($n = 4$), error bars indicate standard error.

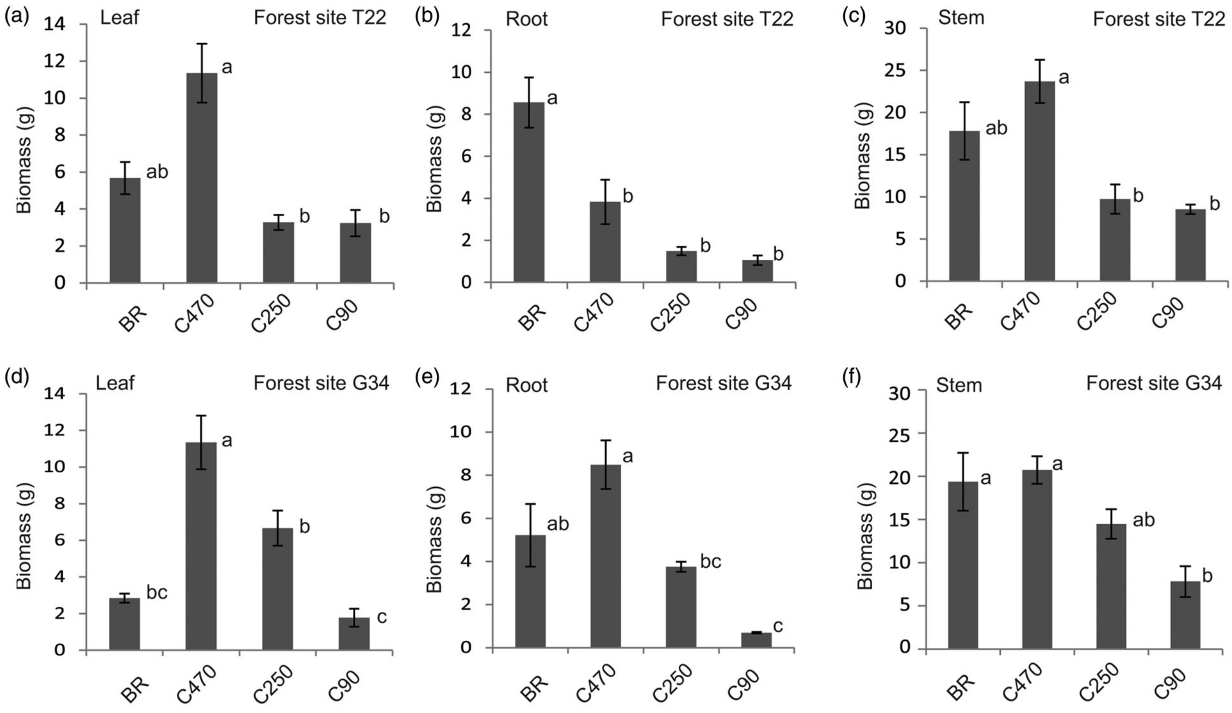


Figure 4. Biomass production of poplars grown at forest sites. Biomasses after the first growth period at the two forest sites are shown in (a and d) Leaf, (b and e) root and (c and f) stem. The different plant types were: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants and C90 – 90 ml container-grown plants. Values with the same letters are not significantly different at the $p = .05$ level: means ($n = 4$), error bars indicate standard error.

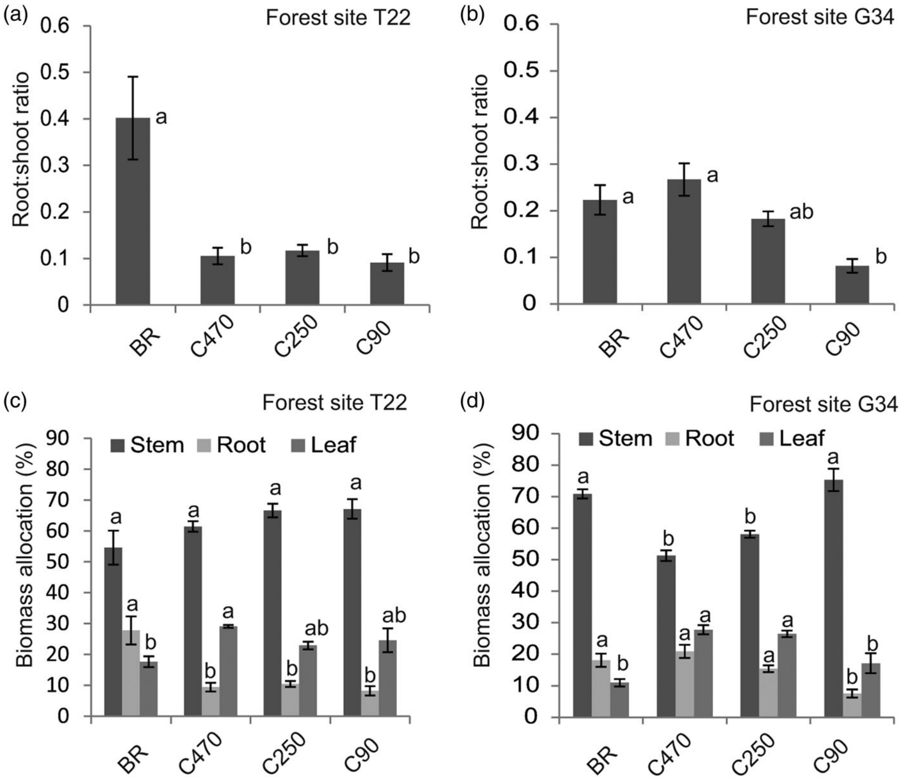


Figure 5. Biomass allocation and root-to-shoot ratio. Shoot-to-root ratio and biomass allocation were determined after the first growth season. Root-to-shoot ratio for forest sites T22 (a) and G34 (b). Biomass allocation in percentage (%) to different tissues – stem, root and leaf – is shown in (c) T22 and (d) G34. The different plant types were: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants and C90 – 90 ml container-grown plants. Values with the same letters are not significantly different at the $p = .05$ level: means ($n = 4$), error bars indicate standard error.

difference in N concentrations was found between container sizes (Figure 6(e)). Compared to BR planted at G34, all containerized plants displayed higher N concentrations, but at T22 only C470 grown plants had higher N concentrations. Among the containerized plants grown at T22 and G34, C470 grown plants reached the highest P concentration, but for plants from the other container sizes (C250 and C90) P concentrations were similar (Figure 6(b) and 6(f)). P concentration in BR plants at T22 and G34 was lower compared to C470 plants but contained a similar level to the C90 plants (Figure 6(b) and 6(f)). In contrast to N and P, the concentration of K was similar between all plant types at both sites (Figure 6 (c) and 6(g)). At both sites, total N content was highest in C470 plants (Figure 6(d) and 6(h)), and there were no differences between BR and C90 plants. At T22, total N content in C250 and C90 plants was similar (Figure 6(d)), but at G34, there was a gradual decrease in total N content with decreasing container size, with the highest amounts in C470 and the lowest in C90 plants (Figure 6(h)). The ratio of macronutrients K to N was above 0.35 for all plant types at both sites (Figure 6 (i) and 6(k)). The highest P to N ratio was found in C470 plants (Figure 6(j) and 6(l)), but the ratio was below 0.1 for C470 and the other plant types. This was observed at both forest sites, T22 and G34 (Figure 6(j) and 6(l)).

Discussion

We investigated effects on the establishment of five types of poplar planting material – un-rooted cuttings, bare-rooted plants and plants grown in containers of different sizes – on former agricultural and forest land. Our two main findings are that on agricultural land un-rooted and rooted plants attained equal height and biomass growth (Figure 2), but on forest land, containerized plants were superior to bare-rooted plants and un-rooted cuttings (Figure 3).

Our results agree with earlier publications, which report that cuttings can be successfully used as transplants on agricultural land (Hartmann & Kester 1975; DeBell & Harrington 1997; Hofmann-Schielle et al. 1999), and confirm that growth of un-rooted cuttings is equal to bare-rooted plants when planted on an agricultural site (Böhlenius & Övergaard 2015). In our experiment on agricultural land, plants reached a height growth between 281 and 328 cm after two years, with no differences in height growth between plant types (Figure 2). Could it be that poplars should be planted as un-rooted cuttings instead of rooted plants? There are several advantages associated with this approach. Un-rooted cuttings are less expensive planting material, easier to store and the procedure for planting them is simpler and easy to mechanize. As the transplanted cuttings have no above-ground parts that need to be supplied by the root system, drought stress could be less severe after planting, although there has to be soil moisture present at the time of planting, otherwise roots cannot develop. Rooted plants have a large above-ground biomass that requires significant amounts of water and rapid root development is necessary for successful establishment and growth.

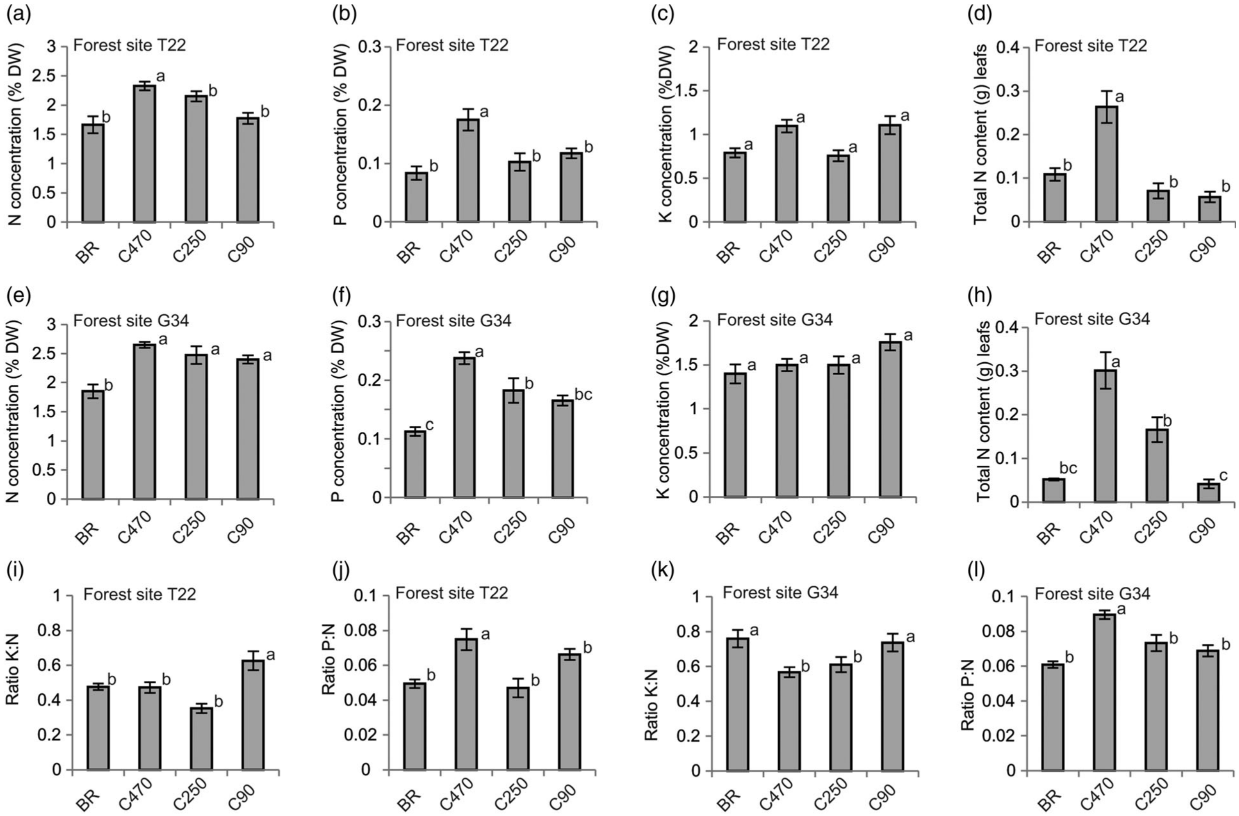


Figure 6. Macronutrient content in poplar plants grown at forest sites. Macronutrient concentration, Nitrogen (N), Phosphorus (P) and Potassium (K) and total N content were determined in leaf samples from plants grown at forest site T22 (a–d) and forest site G34 (f–h). Potassium to Nitrogen ratio (K:N) for T22 is shown in (i) and in (j) for G34. Phosphorus to nitrogen ratio (P:N) for T22 is shown in (k) and in (l) for G34. The different plant types were: BR – bare-rooted plants, C470 – 470 ml container-grown plants, C250 – 250 ml container-grown plants and C90 – 90 ml container-grown plants. Values with the same letters are not significantly different at the $p = .05$ level: means ($n = 4$), error bars indicate standard error.

There are, however, negative sides to planting un-rooted cuttings. A developing shoot from a cutting has a smaller diameter and is more easily damaged by rodents or other browsers. In extremely dry conditions, the transplanted cutting and its developing root could suffer from dehydration and then either mortality or poor root development and slow establishment could occur.

Populus spp. are sensitive to competition (Coll et al. 2007; Otto et al. 2010; Tullus et al. 2011), and at our experimental site, vegetation were under strict control. Therefore, our results suggest that on agricultural land, establishment of poplar could be achieved by transplanting un-rooted cuttings instead of rooted plants if competing vegetation is controlled. At other sites with less effective vegetation control, dryer soils or years with low precipitation, survival and early growth of the different plant types may be different. However, growth of transplanted un-rooted cuttings was similar to that of bare-rooted plants planted at a site with sandy soil in the south of Sweden (Böhlenius & Övergaard 2015) and high survival of un-rooted cuttings was also found when planted in another year with similar and different soil conditions (Böhlenius & Övergaard 2014). However, in this experiment, only one clone (OP42) was used. This should be considered before establishing poplar plantations with other poplar clones using cuttings as rooting capacity could differ between clones. Establishment of other poplar genotypes and/or at other sites with the same plant types (un-rooted cuttings and rooted plants) could reveal different effects on plant growth and mortality. If poplar plantations are established over large areas, planting cuttings instead of more expensive rooted plants could have an impact on the economy. Our results do indicate that high survival of transplants is obtained independent of plant type used (Table 2). However, in these experiment, eight plants of each plant type were used and therefore mortality/survival or high/low growth of one individual plant could influence our result as each plant represents 12.5% of the total percentage.

On agricultural land, there is always a possibility of repeating planting, as the site can be chemically treated, plowed, harrowed and re-planted if establishment fails completely. On forest land, this is not possible. In the first and second years after a clear-cut competing vegetation is limited, but over time, by year two or three, vegetation cover increases (Nilsson & Örlander 1995), and there is no available method to control the increasing competing vegetation at this stage. As *Populus* spp. are sensitive to competing vegetation (Coll et al. 2007; Otto et al. 2010; Tullus et al. 2011), this suggests that there is a two-year window when poplars can be established on forest land. In this case, the plant type used has to establish rapidly, where survival and early growth of the plants are important. In contrast to agricultural land, we found that survival and height growth of the plant types differed at the forest site (Table 2 and Figure 3).

Our results agree with earlier reports, which found that containerized plants were superior to bare-rooted plants (McDonald 1991; Nilsson & Örlander 1995; Thiffault et al.

2003) and suggest that un-rooted cuttings should not be used as transplants on forest land. Our biomass analysis suggests that the roots of the bare-rooted plants had not increased in size after the first year (Figure 4 and Table 1), but we found that the roots of containerized plants did grow after planting (Figure 4 and Table 1). This indicates that bare-rooted plants have problems in making contact with the surrounding soil to access water and nutrients, but that containerized plants do not suffer in the same way. Our nutrient analysis gives support to this as bare-rooted plants have lower N and P concentrations and total N content (Figure 6) than containerized plants from the largest containers. Nevertheless, the ratio of macronutrient K to N concentration in poplar leaves (Figure 6(k)–(l)) was above the optimal level (K:N 0.35, P:N 0.1) (Ingestad 1979; Aronsson & Elowson 1980; Linder 1995) but the P to N ratio was below 0.1. While K concentrations were similar between the largest and smallest container plants (C470 and C90) and N concentrations at G34, P concentrations were higher when the largest containers were used at both sites. Thus, the P to N ratio was highest in the plants grown in the largest containers, indicating that container size may have a positive effect on P uptake. It could be that the containers are functioning as nutrient source after the first year (larger containers add more nutrients), but it is more likely that plant grown in the larger containers have a better capacity to get in contact with the surrounding soils to access nutrients and thereby increase N and P concentrations (Figure 6). It has been shown that poplars can develop a good root system that can reach a depth of more than 1 m after the first year (Friend et al. 1991). A reduction in root functioning and increased shoot-to-root ratio are common reasons for the poorer performance of large seedlings in comparison to small ones (Jobidon et al. 1998; Lamhamedi et al. 1998). However, in our case, shoot-to-root ratio of the largest (C470) and the smallest (C90) container-grown plants were similar (Table 1). In contrast, root biomass before planting was 0.27 g for the largest containers (P470) and 0.18–0.16 g for C250 and C90, respectively (Table 1). It is possible that this difference may explain the plants ability to increase their P content (Figure 6).

We could not detect any height growth differences (Figure 3) between plants grown in the different container sizes, but stem and leaf biomasses were higher in C470 compared to C90 plants (Figure 4(a), 4(c), and 4(d)). The number of surviving bare-rooted plants was high, 97% to 94% the first year and 81% to 75% after the second year at G34 and T22, respectively. However, these plants exhibited only marginal height growth after two years (Figure 3). In contrast, containerized plants grew taller in the first and second years after planting. This suggests that bare-rooted plants suffered from growth check or planting check, while containerized plants did not. In conifers, growth check can last up to three years (Grossnickle 2005) and has long-term implications for plantation performance. Burdett et al. (1984) proposed that there are two phases to growth check: the first phase is altered growth of the newly planted seedling because of water stress and the second phase occurs when restricted access to nutrients limits seedling growth. Once the plants have achieved sufficient root growth to allow high plant water status and nutrient uptake, growth check is overcome. Possibly, during this period, bare-rooted plants can develop roots that can supply the above-ground part with sufficient water and nutrients. However, after the first year, we could not detect any increase in root biomass for the bare-rooted plants (Figure 4 and Table 1). This could be a consequence of large variation in root biomass at the time of planting and therefore differences could not be found, or that there was no root growth at our experimental sites. If this growth arrest continues (for several years), competing vegetation will increase (Nilsson & Örlander 1995) and then inhibit poplar growth due to reduction to available water and nutrient resources in the soil. Containerized plants, however, increased their root biomass and grew taller after planting (Figure 3, Table 2 and Figure 4). This suggests that the growth check found for bare-rooted poplar plants does not occur if containerized poplar plants are used instead.

At a typical forest site, competing vegetation is limited after clear cutting and increases with time (Nilsson & Örlander 1995). This suggests that during the first years after planting, plants will be exposed to limited interference and competition for resources, the two major mechanisms for plant competition (Tilman 1990). In our study, it is more likely that competition for resources is more important at the beginning of establishment and that interference and/or competition are important later in the establishment phase. Even though the height growth of containerized plants was similar, plants with the smallest containers were shorter than plants grown in the largest containers, and if competing vegetation is of a similar height, a small transplant size could be a competitive disadvantage.

In conclusion, we demonstrate that using any of the plant types (un-rooted cuttings, bare-rooted or containerized plants) resulted in the establishment of poplar plants with high growth on agricultural land. The use of cuttings as transplants when establishing poplar plantations on agricultural land could reduce the initial cost and make poplar plantations easier to create. This could be an important step to increasing the extent of poplar plantations on agricultural land. On forest land, however, containerized plants performed better than bare-rooted and un-rooted cuttings. Using container-grown plants at such sites would facilitate the rapid establishment of poplar plantations on forest land and thereby increase the potential available area of such plantations. However, a clear understanding of the actual potential for growing poplars on forest land will require a long-term assessment of growth trends at forest sites with different characteristics.

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