



Biomass Production of the Poplar Clone OP42 During the Second Rotation Plantation—The Effects of Four Thinning Treatments

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Abstract

Poplar (*Populus* species and their hybrids) plantations can produce large amounts of biomass on agricultural land during the first rotation. However, there is limited knowledge regarding plantation re-establishment through re-sprouting (second rotation) after harvest, stand management options for such plantations, and biomass production during rotation length up to 20 years. In this study, we analysed biomass production responses to thinning treatments in an 18-year-old second rotation poplar plantation in Southern Sweden. The first rotation plantation was established with clone OP42 (*Populus maximowiczii* A. Henry × *P. trichocarpa* Torr. and Gray). The thinning experiment was conducted seven years after the first rotation harvest, comprising four treatments: unthinned – 6000 stems ha⁻¹, light thinning – 3000 stems ha⁻¹, medium thinning – 1100 stems ha⁻¹, and heavy thinning – 550 stems ha⁻¹. Eleven years after thinning, standing volume/biomass reached 484 m³ ha⁻¹ (162 Mg DM ha⁻¹) in the unthinned and medium thinning plots, 443 m³ ha⁻¹ (148 Mg DM ha⁻¹) in lightly and 338 m³ ha⁻¹ (113 Mg DM ha⁻¹) in heavily thinned plots. The mean annual increment was not different among the unthinned, light, and medium thinnings, 26 m³ ha⁻¹ yr⁻¹ (9 Mg DM ha⁻¹ yr⁻¹). The total production, including living, dead and removed trees, was highest following the medium thinning, 695 m³ ha⁻¹ (233 Mg DM ha⁻¹). Gradual self-thinning in the unthinned and lightly thinned plots was increased by a drought period. Overall, this study suggests that the second rotation of poplar plantations has high biomass production and provides an alternative to planting after harvest.

Keywords Poplar plantation · Second rotation · Thinning treatment · Self-thinning · Drought effect · Biomass production

Introduction

The future challenges posed by climate change and increased energy demand necessitate a transition to alternative fossil free and carbon neutral energy supply strategies to replace fossil-based energy systems [1]. In this context, woody biomass can serve as an alternative feedstock for energy and carbon neutral steel production [2], replace cotton fibre, and provide biofuels [3]. However, this transition requires a steady biomass supply from agriculture and forestry. Increased demand for woody biomass to support both new processes and current industries may lead to future shortages.

One option for increasing the production of woody biomass per unit area is to plant fast-growing trees of the genus

Populus. Plantation forestry in many parts of the world has adopted this approach [4–9]. Most of these plantations have been established on abandoned agricultural land [4, 10–15], although they are occasionally found on forest land [16–18]. On agricultural land these plantations can produce 3.3 to 9.2 Mg dry mass (DM) ha⁻¹ yr⁻¹ [10, 19], corresponding to 1.1 to 3.1 m³ ha⁻¹ yr⁻¹ during a first rotation period of approximately 20 years from planting to final harvest.

After final harvest, poplars have the capacity to regenerate by producing a large number of stump sprouts and root sprouts, although the latter are less common [20]. Sprouting differs between species: species such as black cottonwood (*Populus trichocarpa* Torr. and Gray), grey poplar (*Populus × canescens* (Aiton) Sm.), and silver poplar (*Populus alba* L.) usually produce stump sprouts, while balsam poplar (*Populus balsamifera* L.) produces both stump and root sprouts [21]. These sprouts are able to draw on the existing root system of the parent tree, helping them to establish and start growing rapidly [22]. The sprouting ability of the stump is influenced by several factors including the specific clone,

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the season in which it was harvested, and the stump height [23]. Sprouting is most successful where harvesting is carried out during the dormant season [24, 25]. It has been shown that 8- to 21-year-old poplars can produce between 18 and 37 stump sprouts per living stump 1 year after harvest [26].

As a post-harvest establishment method, sprouting of poplars has both advantages and disadvantages compared with planting. Establishing a poplar plantation is usually expensive due to the high cost of plant material (bare rooted plants) and the need for effective vegetation management [17, 27, 28]. In contrast, stump and root sprouts emerge at no cost during the second rotation. In addition, the large number of sprouts makes it possible to select future crop trees. Their rapid growth enables the trees to reach browsing-safe heights 2 or 3 years after harvest, making it possible to leave plantations unfenced [29]. If fencing were to be performed, and if large areas of poplar plantations were established, fencing would not only have an impact on the economy but also constrain the public recreation possibilities in the landscape. Management of these coppiced systems can be challenging, giving the high number of stems. However, using vigorous sprouting as a re-establishment method proves to be both cost- and resource efficient.

Internationally, sprouting of poplars after harvest is commonly used in forestry where rotations are 4 to 5 years long [30]. However, in Nordic countries with longer rotations of up to 20 years, there is limited practical experience or knowledge about the management of poplar plantations that have been established through stump and root sprouts [26]. Re-establishment through sprouting has the potential to offer flexibility in how a plantation is managed, as it can be oriented towards dense plantations for biomass production or more widely-spaced stands of larger diameter trees for conventional forestry. Early thinning is likely to be needed to meet future demand for biomass, both to reduce competition between young trees and harvest biomass. It is therefore important to better understand biomass production and management options in second rotation poplar plantations.

The aim of this study was to assess the sprouting potential and biomass production during the second rotation of poplar plantation in southern Sweden established with the clone OP42 (*Populus maximowiczii* A. Henry \times *P. trichocarpa* Torr. and Gray), and their response to different thinning treatments. We analysed survival and growth data from a thinning experiment which was performed 7 years after harvest of the first rotation, and which used four different treatments: (1) unthinned – tree density of 6000 stems ha^{-1} , (2) light thinning – tree density of 3000 stems ha^{-1} , (3) medium thinning – tree density of 1100 stems ha^{-1} , and (4) heavy thinning – tree density of 550 stems ha^{-1} . Height, diameter, and tree survival were recorded to gain insight into the effects of thinning treatments 11 years after thinning.

Material and Method

Study Site

The study site, Sångletorp, is located on agricultural soils near Skurup in southern Sweden (latitude 55° 33' 26.3"N, longitude 13° 28' 59.7"E) (Fig. 1). The first rotation of commercial poplar plantation was established in 1991 using clone OP42 (*Populus maximowiczii* A. Henry \times *P. trichocarpa* Torr. and Gray). Bare rooted plants were planted in a square pattern with a spacing of 3 \times 3 m, corresponding to a density of 1100 stems ha^{-1} . The stand was harvested in September 2004 at the age of 14 years. Following the harvest, stumps were left to allow for regeneration through stump and root sprouts.

Climate Data

To assess the climate conditions of the study site, daily temperature and precipitation data were obtained from the closest observational station run by the Swedish Meteorological and Hydrological Institute (SMHI) at Lund (25 km from Sångletorp). Normal daily temperature and monthly precipitation were calculated as averages for the reference period of 1991–2020. To address an apparent decline in tree survival 8 growing seasons after thinning, temperature and precipitation anomalies were calculated as the difference between normal and actual temperature and precipitation in 2018.

Experimental Design

The thinning experiment was conducted in 2011, 7 years into the second rotation of the poplar plantation. Four treatments were applied, defined by thinning intensity, i.e. the



Fig. 1 Location of the studied poplar stand in southern Sweden

number of stems retained after thinning: (1) unthinned, with an average stand density of 6000 stems ha⁻¹, (2) light thinning to 3000 stems ha⁻¹, achieved by removing every second tree row, (3) medium thinning to 1100 stems ha⁻¹, achieved through retention of the biggest shoot, and (4) heavy thinning to 550 stems ha⁻¹, retaining the biggest shoot and removing every second tree row. In all treatments, stump sprouts were retained, while root sprouts were removed non-selectively. The experiment was conducted on 16 plots grouped into four blocks, each block having one plot for each of the treatments. The plot size was 24 × 24 m with a buffer zone of 6 m between the treatments, comprising two rows of trees subject to the same treatment as the adjacent plot.

Measurements

Stem diameter, tree height, and number of stems were measured at the time of thinning and 0, 2, 3, 4, 6, 8, and 11 growing seasons after thinning, hereafter referred to as years after thinning. The diameter of all living trees was measured at breast height (130 cm above ground) in two perpendicular directions using an electronic caliper, the mean value of these being used as the diameter. Trees with a diameter smaller than 4 cm were excluded from the study.

For height measurements, 10 to 15 sample trees representing the different diameter classes were selected within each plot. The trees were divided into five diameter classes: 0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm, > 40 cm. The same sample trees were retained throughout all years of observation, except where a sample tree died, in which case it was replaced by the next tree of the same diameter class.

Estimations of Stem Volume and Biomass Production

The volume of all sampled trees was calculated using the equation from Eriksson [31] (Eq. 1):

$$V = 0.01548D^2 + 0.03255D^2H + 0.000047D^2H^2 + 0.01333DH + 0.004859DH^2 \quad (1)$$

where V is the stem volume (over bark from the stump to the tip of the tree, dm³), D is the tree diameter at breast height (cm), and H is the height of the tree (m). This equation was developed for European aspen, and has been shown to perform well for predicting the volume of poplar trees growing on farmland in Sweden [32]. The volume of those trees only measured for diameter was estimated by relating the volume of sample trees to the diameter using the following regression model (Eq. 2):

$$\log V_i = a + b \log D_i + \varepsilon_i \quad (2)$$

where $\log V_i$ is the logarithmic transformation of stem volume, $\log D_i$ is the logarithmic transformation of tree diameter, ε_i is the general error term, and a and b are the parameters. A separate volume equation was obtained for each treatment.

To convert the stem volume to biomass of dry matter (DM), 335 kg m⁻³ was used [33].

Analysis of Thinning Effect on Biomass Production

The effect of treatments on stand characteristics was analysed with ANOVA, using the following statistical model (Eq. 3):

$$y_{ij} = \mu + treat_i + b_j + \varepsilon_{ij} \quad (3)$$

where y_{ij} is the observation ij (observed stand characteristic for treatment i), μ is the overall mean, $treat_i$ is the fixed effect of the thinning treatment, b_j is the random effect of the block, and ε_{ij} is the random error term for observation ij . The normality of the data was examined using the Shapiro-Wilk test and the homoscedasticity was checked using the Levene test. Where either of these assumptions was violated, the Kruskal-Wallis test for non-parametric data was used to analyse the data. The significance level for all tests was set to 0.05. Where significant differences between the treatments were found, pair-wise comparisons among treatments were performed using the Tukey test for ANOVA analyses and the Wilcoxon test for Kruskal-Wallis analyses.

Results

Number of Sprouts and Biomass/Volume Production 7 Years After Final Harvest

After final harvest of the first rotation of the poplar plantation, the second rotation regenerated through stump and root sprouts (Table 1). Seven years after harvest (at the time of thinning), each stump had on average 4.3 stump sprouts and 3.1 root sprouts with a mean diameter of 6.9 cm. The basal area was 30 m² ha⁻¹ and the standing volume of living trees was 192 m³ ha⁻¹ (62 Mg DM ha⁻¹), resulting in a mean annual biomass production of about 27 m³ ha⁻¹ year⁻¹ (9 Mg DM ha⁻¹ year⁻¹) for the initial 7 years.

Effect of Thinning Treatments on Remaining Trees' Diameter and Harvested Volume/Biomass

The thinning treatment influenced the diameter of the remaining living trees and the harvested volume/biomass. After thinning treatments, the mean diameter was 7.3 cm in the unthinned and heavily thinned plots, while trees in the lightly and medium thinned plots had a larger mean diameter of 10.2 and 10.7 cm, respectively (Table 1). The percentage

Table 1 Mean estimates of variables from retained trees before (2011) and after (2012) thinning treatments in the second rotation poplar stand (clone OP42)

Variable	Before thinning	After thinning				P-value	
		Treatment					
		Unthinned	Light thinning	Medium thinning	Heavy thinning		
No. stump sprouts per stump	4.3	n/a	n/a	n/a	n/a	n/a	
No. root sprouts per stump	3.1	n/a	n/a	n/a	n/a	n/a	
Mean diameter (cm)	6.9	7.3 ^b	10.2 ^a	10.7 ^a	7.3 ^b	2.2e-16	
BA (m ² ha ⁻¹)	30	29 ^a	4.4 ^d (86%)	9 ^c (70%)	14 ^b (54%)	1.915e-10	
Production	Standing volume (m ³ ha ⁻¹)	192	172 ^a	28 ^d (86%)	59 ^c (69%)	81 ^b (58%)	6.186e-09
	Standing biomass (Mg DM ha ⁻¹)	64	58 ^a	9 ^d	20 ^c	27 ^b	6.186e-09
	Removed volume (m ³ ha ⁻¹)	n/a	n/a	99	187	185	n/a
	Removed biomass (Mg DM ha ⁻¹)	n/a	n/a	33	63	62	n/a

Different letters indicate significant differences ($p < 0.05$) among thinning treatments within a year. Values in brackets represent the percentage of basal area and volume/biomass removed during the thinning treatments; n/a stands for not applicable

of basal area and volume/biomass production removed by thinning varied from 54 to 86% for basal area and from 58 to 86% for volume/biomass production. This corresponds to the following basal area and production values of retained trees: 4.4 m² ha⁻¹ and 28 m³ ha⁻¹ (9 Mg DM ha⁻¹) with light thinning, 9 m² ha⁻¹ and 59 m³ ha⁻¹ (20 Mg DM ha⁻¹) with medium thinning, and 14 m² and 81 m³ ha⁻¹ (27 Mg DM ha⁻¹) with heavy thinning, respectively. Accordingly, the amount of volume/biomass removed during thinning was as follows: 99 m³ ha⁻¹ (33 Mg DM ha⁻¹) with light thinning, 187 m³ ha⁻¹ (63 Mg DM ha⁻¹) with medium thinning, and 185 m³ ha⁻¹ (62 Mg DM ha⁻¹) with heavy thinning.

Effect of Thinning Treatments on Tree Survival

In the plots subjected to the unthinned and light thinning treatments, the number of living stems decreased gradually over the first 6 years, through self-thinning, from 6000 to 4000 stems ha⁻¹ and from 3000 to 2370 stems ha⁻¹, respectively (Fig. 2a). Between years 6 and 8, stand density reduced more strongly than in the earlier years, to 2340 stems ha⁻¹ in the unthinned plots and 1720 stems ha⁻¹ in the lightly thinned plots. However, the survival rate returned to the previous level during years 9 to 11. At the end of the study period, the number of living stems did not differ significantly between the unthinned and lightly thinned plots, with 1540 stems ha⁻¹ and 1380 stems ha⁻¹, respectively. By contrast, little self-thinning occurred in the medium and heavily thinned plots over the observation period.

Decreased stem survival following the unthinned and light thinning treatments coincided with the extremely warm summer of 2018 (Fig. 2b). The temperature anomalies at the study site showed that the summer of 2018 was prolonged, from May to mid-August, with temperatures well above normal levels on most days. During the May-August period, about a third of days exceeded the 30-year climatological 95th percentile. The summer of 2018 was also characterised by an extended drought during May, June, and July, with monthly precipitation anomalies of 95%, 75%, and 96% below the normal precipitation level, respectively (Fig. 2c).

Effect of Thinning Treatments on Diameter Growth and Distribution

The distribution of stems per diameter class at the beginning of the study (2 years after thinning) was similar for the unthinned and light thinning treatments, with the trees fitting into two diameter classes: 0 to 10 cm and 10 to 20 cm (Fig. 3). Around the middle of the study (6 years after thinning), all trees increased in diameter, moving into the next diameter class, but a decline in the number of trees in the first diameter class was observed in the unthinned and lightly thinned plots. At the end of the study period (11 years after thinning), the unthinned and lightly thinned plots experienced a substantial reduction in the number of small trees (diameter 0 to 10 cm), leading to a relatively equal distribution of stems among the two classes: 10 to 20 cm and 20 to 30 cm. In the plots subjected to medium and heavy thinning, most of the stems were in the second diameter class 10 to 20 cm at the start of the experiment (2 years after thinning).

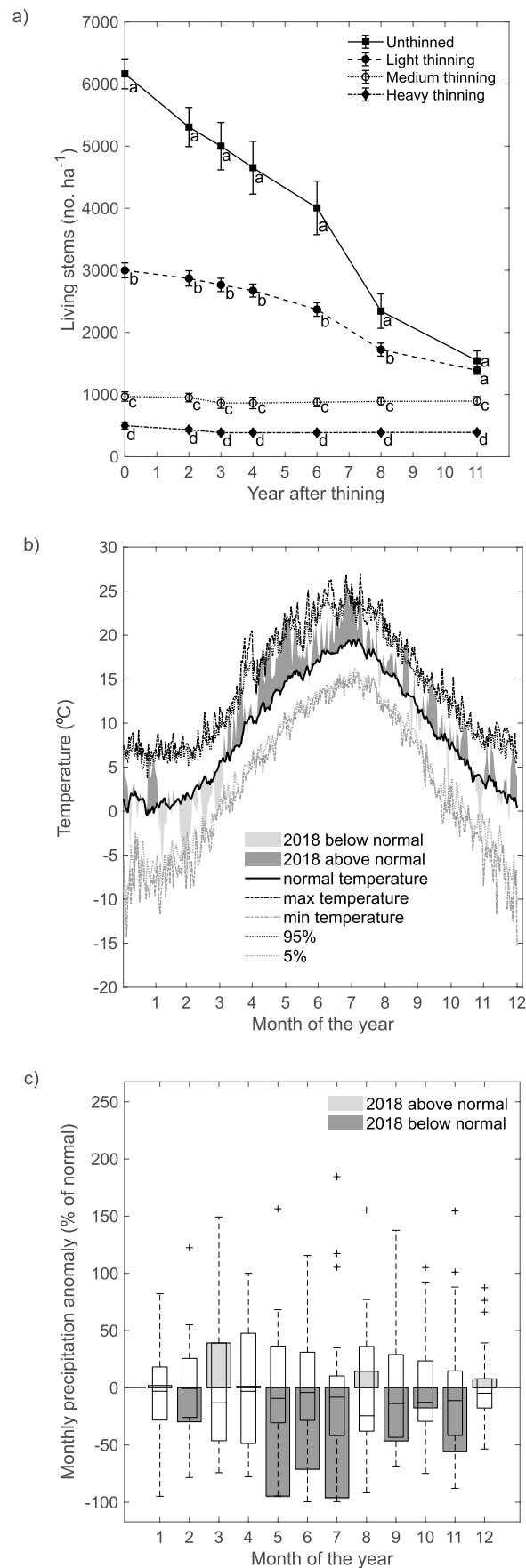
Fig. 2 Tree survival, temperature, and precipitation at the study site. **a** Survival of trees in the second rotation poplar stand (clone OP42) in years after thinning treatment. Symbols represent mean value for each treatment, error bars denote the standard deviation of the mean, and letters indicate significant differences ($p < 0.05$) among the treatments within a year. **b** Daily mean temperatures at the study site in 2018. For each day, anomalies with respect to the 30-year mean for the period 1991–2020 are displayed in light grey (cold) or dark grey (warm). The diagram also shows the warmest and coldest diurnal mean temperature and the corresponding 5th and 95th percentiles for 1991–2020. **c** Monthly mean precipitation anomalies (% of normal) at the study site in 2018 with respect to the 30-year mean for the period 1991–2020. Positive (wet) and negative (dry) anomalies are shown in light grey and dark grey, respectively. For each month, the distribution of anomalies for 1991–2020 is displayed as a boxplot

Subsequent tree diameter growth resulted in a higher number of stems in the 20 to 30 cm diameter class for the medium thinning treatment, while most stems in heavily thinned plots were in the 20 to 30 cm and 30 to 40 cm diameter classes.

Stand Development After Thinning Treatments

Basal area, stem wood volume/biomass, and mean annual increment (MAI) showed a steady increase for all treatments over the first 6 years (Fig. 4a-c). However, for basal area and MAI a minor reduction was observed in the unthinned treatment after year 6 (Fig. 4a, c). Thinning treatments had a significant effect on basal area growth during the first 6 years, with basal area increasing as thinning intensity decreased. After year 6, the basal area increment was similar in the light and medium thinning treatments (Fig. 4a). However, after 11 years, no significant differences in basal area could be identified among unthinned, light, and medium thinning treatments, with an average value of $41 \text{ m}^2 \text{ ha}^{-1}$, while heavy thinning resulted in a lower basal area of $27.6 \text{ m}^2 \text{ ha}^{-1}$. Eight years after thinning, an average volume/biomass production was highest in unthinned plots, reaching $440 \text{ m}^3 \text{ ha}^{-1}$ ($147 \text{ Mg DM ha}^{-1}$), and lower in heavily thinned plots, at $238 \text{ m}^3 \text{ ha}^{-1}$ (80 Mg DM ha^{-1}), while light and medium thinning had an intermediate response of $350 \text{ m}^3 \text{ ha}^{-1}$ ($117 \text{ Mg DM ha}^{-1}$) (Fig. 4b). However, 3 years later (11 years after thinning), average production in the unthinned and medium thinned plots reached the same level of $484 \text{ m}^3 \text{ ha}^{-1}$ ($162 \text{ Mg DM ha}^{-1}$), while lightly and heavily thinned plots reached volume/biomass production levels of $443 \text{ m}^3 \text{ ha}^{-1}$ ($148 \text{ Mg DM ha}^{-1}$) and $338 \text{ m}^3 \text{ ha}^{-1}$ ($113 \text{ Mg DM ha}^{-1}$), respectively.

MAI for unthinned plots reached its peak of $30 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($10 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) 4 years after thinning. Thereafter MAI declined (Fig. 4c). The effect of thinning on MAI development across the treatments followed a similar pattern to volume/biomass production (Fig. 4b). MAI in the lightly and medium thinned plots were similar over the first 8 years, although it was lower than that in unthinned plots. However, 11 years after thinning, there were no differences



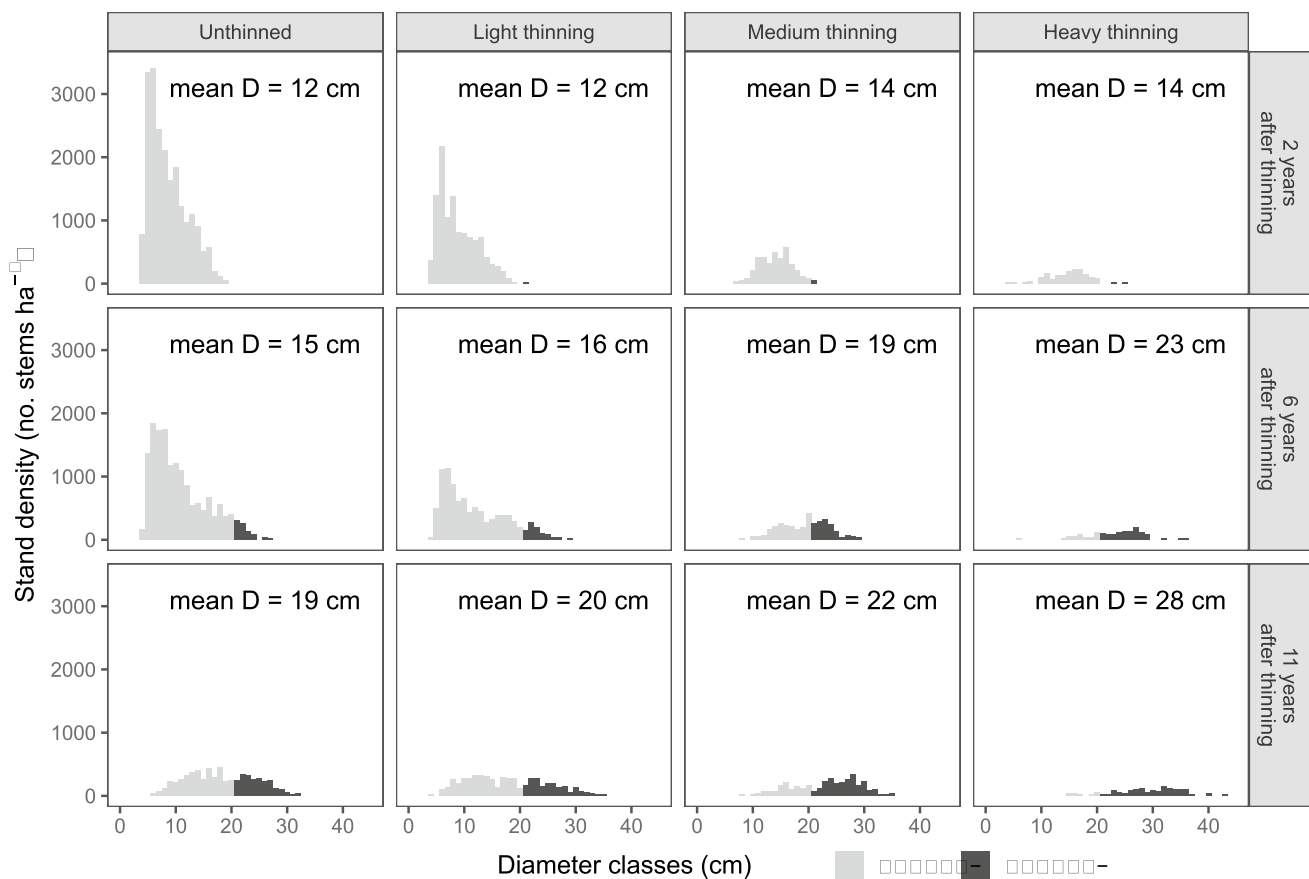


Fig. 3 Mean stem diameter and diameter distribution per diameter classes 2, 6 and 11 years after thinning treatment during the second rotation of a poplar stand (clone OP42)

in MAI among the unthinned, light, and medium thinning treatments, with MAI reaching $26 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($9 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$). Heavy thinning resulted in lower MAI than the other treatments, at $19 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($6.4 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$).

The stem wood volume/biomass of dead trees slowly accumulated over the first 6 years after thinning, reaching $31 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($10.4 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) in the unthinned plots, $10.4 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($3.5 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) in the lightly thinning and $12 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($4 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) in the medium thinned plots (Fig. 4d). Between years 6 and 8, the amount of dead biomass increased in unthinned and lightly thinned plots. This trend was also observed between years 8 and 11 after thinning, resulting in $138 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($46 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) and $58 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($19.4 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) of cumulative dead volume/biomass in the unthinned and light thinning treatments, respectively. Medium thinned plots experienced a slight increase in dead volume/biomass during years 6 to 11, while in heavily thinned plots the level was constant over the period from 3 to 11 years after thinning, resulting in a cumulative dead volume/biomass of $22 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ($7.4 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$) and $6 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ (2

$\text{Mg DM ha}^{-1} \text{ yr}^{-1}$) in the medium and heavy thinning treatments, respectively.

Total Volume/Biomass Production

At the end of the observation period (18 years after harvest of the first rotation), the total stem wood volume/biomass production, including living trees, dead trees, and trees removed by thinning, was highest for the medium thinning treatment, $695 \text{ m}^3 \text{ ha}^{-1}$ ($233 \text{ Mg DM ha}^{-1}$), followed by the unthinned treatment at $620 \text{ m}^3 \text{ ha}^{-1}$ ($208 \text{ Mg DM ha}^{-1}$), and light thinning treatment at $599 \text{ m}^3 \text{ ha}^{-1}$ ($201 \text{ Mg DM ha}^{-1}$) which were not different from one another (Fig. 5). Heavy thinning resulted in the lowest total volume/biomass, at $529 \text{ m}^3 \text{ ha}^{-1}$ ($177 \text{ Mg DM ha}^{-1}$). The total volume/biomass production of the unthinned and light thinning treatments included 22.2% and 9.7% of dead trees, respectively. The volume/biomass of dead wood was lower for the other thinning treatments, accounting for 3.1% in the medium plots and 1.1% in the heavily thinned plots. During thinning, 16.4% of the total volume/biomass was harvested in

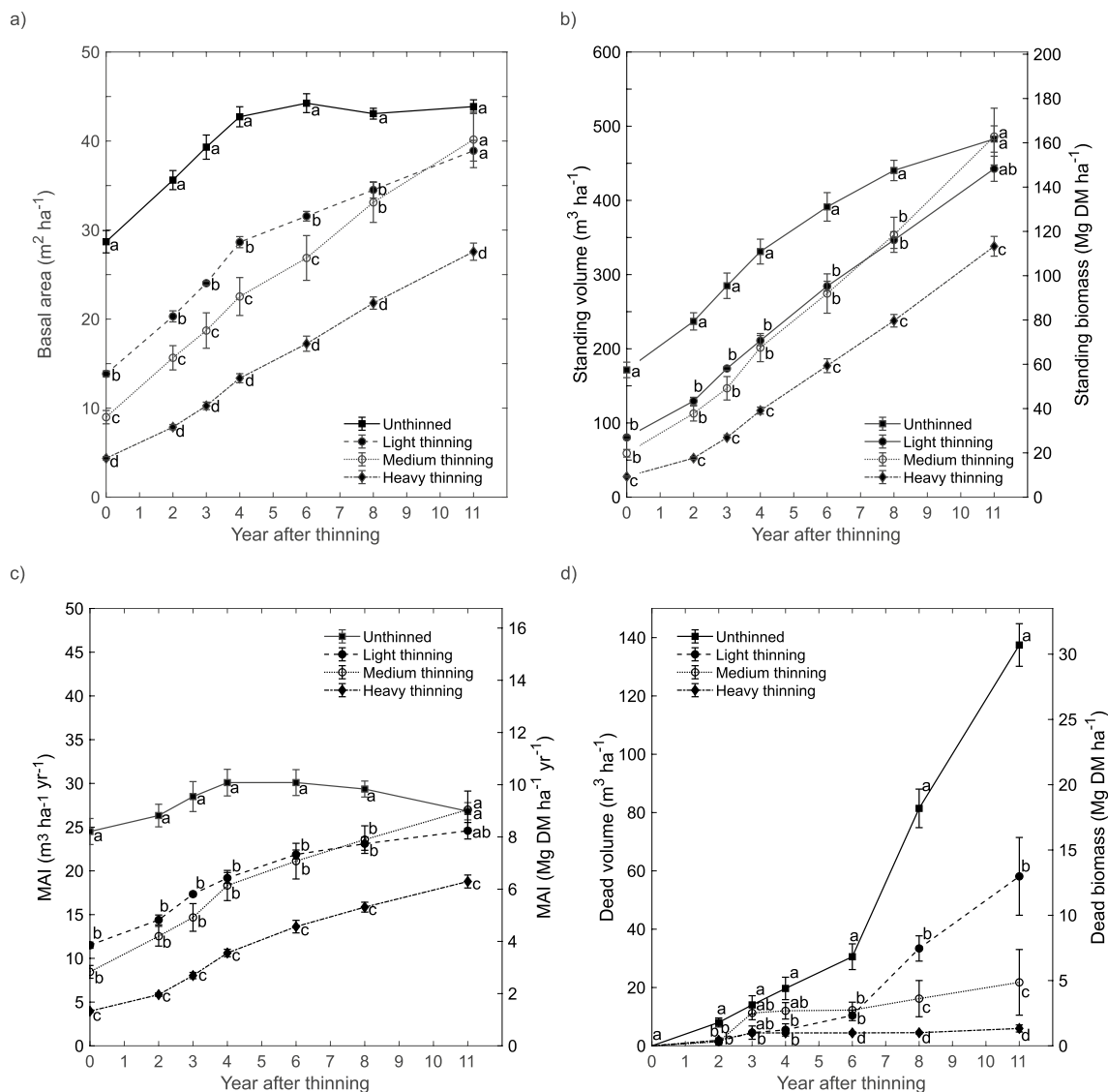


Fig. 4 Effect of thinning treatments on stand development of a second rotation poplar stand (clone OP42). Symbols represent mean value for each treatment, error bars denote the standard deviation of the mean, and letters indicate significant differences ($p < 0.05$) among

the treatments within a year. **a** Basal area of living trees. **b** Standing stem wood volume/biomass of living trees. **c** Mean annual increment (MAI) of standing stem wood volume/biomass of living trees. **d** Cumulative stem wood volume/biomass of dead trees

the lightly thinned plots, 26.9% in the medium plots, and 35% in the heavily thinned plots.

Discussion

Initial Poplar Sprouting Capacity During the Second Rotation

This study demonstrated that poplar has significant biomass production potential during the second rotation and that sprouting can be used as a method for regeneration. In line with other studies which have focused on younger

poplar plantations (2- to 6-years-old) [34], our results suggest that older poplar stumps can sprout vigorously after they are harvested. However, several factors influence resprouting after harvest. Earlier studies have shown that stump age, time of harvesting, and plant material (i.e. clone) can influence a stump's ability to sprout [24, 29, 35, 36]. Older stumps tend to have fewer dormant buds and to produce fewer root sprouts, as the buds are usually lost and root systems begin to decay as the tree matures [37–39]. In contrast, other studies have found that the abundance of bud clusters increases with stump age [38] and that root decay has also been observed in young stands [40] where sprouting is high. Straight after harvest, clone OP42 (the clone

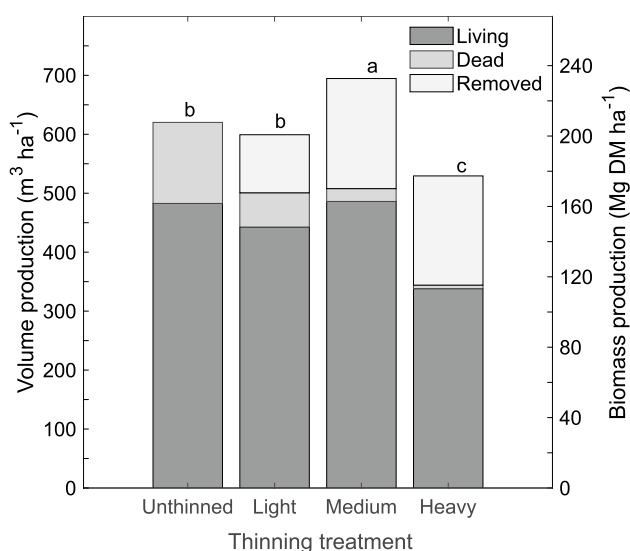


Fig. 5 Total stem wood volume/biomass production (including living, dead, and removed trees) 11 years after thinning treatment during the second rotation of a poplar stand (clone OP42). Letters indicate significant differences in the total stem wood volume/biomass production ($p < 0.05$) among the treatments

tested in this study) has been reported to produce between 27 and 37 sprouts per living stump in 19- to 20-year-old stands [26], and Jonsson [41] recorded 16 000 sprouts 3 years after harvest at Sångletorp, the stand investigated in the present study, corresponding to 16 sprouts per stump. By comparison, black cottonwood (*Populus trichocarpa* Torr. and Gray) produced 18 sprouts per stump in a 21-year-old stand [26], while 6 to 137 sprouts were recorded for 23 different clones (with an overall mean of 62 sprouts) in a 19-year-old poplar stand [29]. Thus, more or less re-sprouting would be expected where other clones are present. The timing of harvest also affects re-sprouting, with harvesting performed in the winter and early spring (January–March) resulting in much higher numbers of sprouts than harvesting performed between April and August [24, 36]. As our study site was harvested in the autumn (September), sprouting may have been higher if harvesting had taken place during the winter. However, winter harvesting may cause a great deal of damage where soil is not frozen and conditions are wet, making it a less desirable option [42].

Stand Survival Influenced by Self-Thinning, Thinning, and Drought

In our study, clone OP42 produced an average of seven sprouts (root and stump sprouts) per stump 7 years after harvest (Table 1). Although regeneration via stump sprout is considered the primary source of re-establishment in poplar plantations [20, 30], our results indicate that the

number of stump sprouts and root sprouts was approximately the same, at 4.3 and 3.1 stems per stump, respectively. Thus, it is evident that for this clone (OP42) both root and stump sprouts can be used as sources for re-establishment in second rotation plantations. Our results are in line with Johansson and Hjelm [26], who found three stump sprouts per stump 7 years after final harvest.

Eleven years after thinning, the unthinned plots reached almost the same level of stand density as the light and medium thinned plots, through a gradual reduction in tree numbers with increasing stand age (Fig. 2a). This finding aligns with other studies of shoot dynamics in different coppice systems, including poplar, aspen, and willow [35, 43, 44]. Early in the second rotation, when the initial shoot density is high, there is a great deal of intraspecific competition among sprouts for available resources such as light, water, and nutrients, leading to shoot mortality, a process often referred to as self-thinning [44]. The shoots with the highest growth rate become dominant and, as their height, diameter, and leaf area increase, they subsequently suppress the growth of all other shoots, leading to one or a few large sprouts on each stump [45]. However, this suppression is clone specific, as indicated by Laureysens et al. [35] who found that stool mortality, shoot dynamics, and shoot diameter distribution varied among clones in a 6-year-old coppice culture [35]. The occurrence of self-thinning in dense poplar plantations during the second rotation is supported by our results, given that the shoot mortality observed occurred mainly among smaller trees in the unthinned and light thinning treatments. In these plots, living trees displayed a gradual decline for the first 6 years, at a fairly constant rate. However, between years 6 and 8, tree mortality accelerated (Fig. 2a), and this increase coincided with an extreme drought during the summer of 2018 (Fig. 2b, c). In contrast, the medium and heavy thinning treatments released trees from such competition, as indicated by the constant stand density throughout the study period. A two-phase model for intraspecific competition has previously been established as follows: firstly, competition for soil resources leads to thinning of relatively high-density patches in the population, and secondly, competition for light leads to regular patterns of dominant and surviving trees [46]. The increased tree mortality due to drought following unthinned and light thinning treatments implies that these plots were in the first competition phase, during which competition for soil resources is the main factor driving tree mortality, rather than competition for light. In line with this, our results suggest that increased temperature and decreased rainfall during extreme drought events has a greater impact on the over-mortality of suppressed trees than of dominant trees, a finding which correlates with other studies [47].

Effect of Thinning Treatments on Diameter Growth and Biomass Production

At the end of the study (11 years post-thinning), there was a difference of 3 cm in mean diameter between trees in the unthinned and medium thinned plots, while the difference with heavy thinning was larger (9 cm) (Fig. 3), indicating that a reduction in competition transfers the biomass growth to fewer and larger trees. This aligns with earlier studies of *Populus* species and other hardwood trees [8, 43, 48–53]. However, the differences in mean diameters among unthinned, light, and medium thinning treatments are rather small, and the diameter distributions are similar, suggesting that the biomass produced by these stands may have similar characteristics (bark/wood ratio) for downstream applications.

Seven years after harvest, it was possible to perform a biomass harvest of 192 m³ (64 Mg DM ha⁻¹). Were a thinning operation to occur later in the rotation period, it may be expected that a larger amount of biomass could be harvested, although there is a risk of some biomass being lost due to self-thinning, intensified by drought periods. Eleven years after thinning (18 years after harvest), the standing volume/biomass of living trees was broadly the same for all treatments except the heavy thinning treatment (Fig. 4b). These findings suggest several management options, including either harvesting part of the growing biomass through light or medium thinning, or letting stem reduction take place through self-thinning.

If strong thinning (such as the heavy thinning treatment in our study) is applied, an MAI of 19 m³ ha⁻¹ yr⁻¹ (6.4 Mg DM ha⁻¹ yr⁻¹) of stem volume/biomass can be produced after 11 years, while for a lighter thinning (corresponding to the light or medium thinning treatments in this study) a higher MAI of 25–27 m³ ha⁻¹ yr⁻¹ (8–9 Mg DM ha⁻¹ yr⁻¹) can be expected. In contrast to the thinning treatments, which all displayed a gradual increase in MAI over the study period, MAI for the unthinned plots did not change dramatically over the second rotation, reaching 27 m³ ha⁻¹ yr⁻¹ (9 Mg DM ha⁻¹ yr⁻¹) at the end of the experiment compared to the 25 m³ ha⁻¹ yr⁻¹ (9 Mg DM ha⁻¹ yr⁻¹) observed at the start. This can be explained by the level of self-thinning, which was probably similar to that of tree growth (Fig. 3c). However, the observed volume/biomass production is comparable to that of other *Populus* plantations in Sweden and internationally [10, 19, 43, 54–56].

It should be noted that, including both harvested and dead wood in the measures of volume/biomass production, the resulting total volume/biomass production at year 11 (18 years after final felling of the first rotation) was highest following the medium thinning treatment, reaching almost 700 m³ ha⁻¹ (234 Mg DM ha⁻¹) (Fig. 5). This corresponds to the total MAI of 39 m³ ha⁻¹ year⁻¹ (13 Mg DM ha⁻¹ year⁻¹),

which is higher than that of first rotation plantations [10, 55]. The total production for the medium thinning was about 25% higher than if no thinning had been performed (Fig. 5). It is likely that this related to the increased volume/biomass growth during years 8 to 11 (Fig. 4b) and the fact that the amount of volume/biomass harvested in medium thinning was lost as dead wood in the unthinned treatment (Figs. 4d and 5). The observed biomass production does not include branches and tops, meaning that, if the end product is conversion to energy, even higher production can be expected. It is worth mentioning that this experiment was conducted at one site, and that biomass production may be higher or lower in plantations located at more or less fertile sites.

In summary, all parts of this study support the view that root and/or stump sprouts can be used as a regeneration method, resulting in rapid establishment of stands that can be managed using different thinning options to generate high biomass production.

Practical Implications

The high biomass production of 192 m³ ha⁻¹ (62 Mg DM ha⁻¹) (Table 1) 7 years after harvest may result in an early income or at least cover the cost for thinning operations. The economic return depends on several parameters, including the price of biomass, which in this case will be used for energy purposes as tree diameters are small, and the possibilities for using suitable machinery for total harvest and thinning. Our results do suggest that it is possible to use normal harvesting machinery, as there are commercially available harvesting heads which can handle multiple stems simultaneously, one of which was used to perform the thinning treatments in this experiment. This contrasts with the second rotation of hybrid aspen, which requires machinery development to manage the dense stands [43, 57]. If the aim is to recover as much biomass as possible, thinning operations need to be performed before heavy self-thinning occurs. Prolonging the time before thinning would result in greater biomass growth, but also a higher level of self-thinning. In the future, Northern Europe is expected to experience more frequent and severe drought due to climate change, resulting in reduced precipitation and increased evaporation rates regionally [58]. In this context, it is all the more important to harvest biomass while trees are thriving, and avoid the potential loss of available biomass through self-thinning.

Following the light and medium thinning treatments, similar values for MAI and volume/biomass production were observed (Fig. 4b, c), implying that either of these treatments can be used. However, there was a higher proportion of trees with smaller diameters in lightly thinned plots (Fig. 3). Thus, the advantage of light thinning is that the thinning operator does not have to distinguish between small and large trees, but instead can harvest all trees from the

same stump. However, this would impact the third rotation as the relevant stumps will not be present when the second rotation trees are harvested. It should be noted that medium thinning resulted in the highest total biomass production, followed by unthinned and light thinning treatments. Therefore, depending on the type and timing of thinning treatment, biomass quality (diameters) and quantity can be influenced.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

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