Effects of thinning on growth and development of second poplar generations

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Abstract

Stands consisting of poplar stump sprouts and root suckers show high potential of successful establishment and pose a cheap management alternative to the currently planted poplar plantations. Due to the relatively small proportion of presently existing poplar plantations in Sweden, especially second generations, knowledge about production potential and silviculture treatments for poplar is scarce. Thus, this study focused on investigating production potential and response of poplar second generations to thinning treatments under the following 3 hypotheses, namely: (1) Stump sprouts are dominant in stands of poplar sprouts and root suckers, (2) Thinning increases volume production (3) Thinning improves stem growth, production, and stem stability of crop trees

The results showed that (1) the poplar clone "OP42" (*Populus maximowiczii* Henry x *Populus trichocarpa* Torr and Gray) produced significantly higher numbers of stump sprouts in comparison to root suckers seven years after harvest. Notably, the number of root suckers shared 42 % of the total number of stems in the stands; (2) Standing volume was significantly higher in the unthinned control treatment (6000 stems ha^{-1}) in comparison to all thinning schemes; (3) Thinning increased stem diameter, volume growth, and stability of crop trees.

In conclusion, it is important to include poplar root suckers in investigations regarding second generations of poplar stands. Thinning schemes of densities up to 1100 stems ha^{-1} are recommended to optimize growth, production and wind stability for pulp production. Heavy thinning schemes of 550 stems ha^{-1} are recommended for high quality timber production. For bioenergy-based production, no thinning (6000 stems ha^{-1}) is recommended. Row thinning (3000 stems ha^{-1}) might not be recommended.

Keywords; Poplar *Populus sp.*, stump-sprouts, root-suckers, thinning, volume-production, diameter growth, stability

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1. Introduction

1.1. Overview about needs and growth of poplar

The growing demand for energy is estimated to increase by 50% globally until 2025 (Pkeguezuelo *et al*., 2015). The aims of reducing usage of non-renewable resources and mitigating greenhouse gas emissions has addressed the need of new energy sources which can be produced at low cost and are at the same time environmentally sustainable (Sannigrahi *et al*., 2010).

Bioeconomy as a new scientific-based economic model uses green and sustainable biomass sources to help reducing dependency on fossil fuel energy and offers a great opportunity for a new innovative and sustainable economic development (EU, 2018). It poses promising solutions for a climate change adaptation and mitigation (EU, 2018).

Short-rotation forestry (SRF) is specially designed for biomass production, with rotation intervals of less than 30 years (Tullus *et al*., 2012) and its utilization of high yielding species possess a promising energy source (Pkeguezuelo *et al*., 2015).

In temperate regions, hybrid poplars range among the fastest growing species (Dickmann *et al*., 1983; Mitchell, 1992; Sannigrahi *et al.*, 2010) and are often planted as short-rotation energy crop on former agricultural lands (Sannigrahi *et al.*, 2010). Due to this fact as well as high cellulose content in conjunction with low ash and extractive contents, hybrid poplar could provide a good source for production of bioethanol, thermal energy and pulp. (Sannigrahi *et al*.,2010).

In Europe, native poplar species and exotic breeds from North American species were initially planted in Italy in the 20th century for industrial purposes (Johansson & Karačić, 2011). Depending on climatic conditions and production purposes spacing and rotation length varies (Johansson & Karačić, 2011). For instance, in Mediterranean countries, poplar is often planted in 4m x 4m spacings and rotations of 10 to 15 years, while in Central Europe 7m x 7m spacings with longer rotations of 20 to 40 years are practiced (Johansson & Karačić, 2011) with varying end products from mechanical pulp to plywood, veneer, and construction lumber (Schreiner, 1959, Mc Carthy, 2016).

1.2. Growing of Poplar in Sweden

In Sweden, hybrid poplar was introduced in the 1930s with clones mostly originating from Oregon and Washington (Christersson, 1996). Clones with promising adaption to Swedish conditions were obtained from the USA, Belgium, British Columbia, Fort Nelson, Canada and are currently tested in field trials (Christersson, 2010).

Cultivation of poplar in Sweden was subsidized by a Swedish governmental program in the 1990s as part of preventing future energy crisis (Christersson, 2010). Increasing share of broadleaf species including poplar is promoted by the Swedish government as mean of spreading the risk of stands solely consisting of coniferous tree to negative impacts of climate change and enhancement of biodiversity (Mc Carthy, 2016).

Presently, the area of poplar in Sweden extends itself over about 1300 ha (Dimitriou & Mola-Yudego, 2017). Until 2010, the hybrid poplar clone “OP42” (*Populus maximowiczii* Henry x *Populus trichocarpa* Torr and Gray) has been the most commonly planted variety among 12 other clones in Southern Sweden (Mc Carthy, 2016).

Planting of bare-root seedlings is the most popular method of establishment for poplar stands in Sweden (Böhlenius & Övergaard, 2014). Due to their sensitivity to competition, soil preparation and vegetation control play key roles in survival of poplar seedlings (Böhlenius & Övergaard, 2015). Silvicultural treatments like spacing, pre-commercial thinning, and rotation length depend on the desired final product (Mc Carthy, 2016).(e.g. biomass, pulp, timber). A rotation period of 15 to 25 years (Mc Carthy, 2016) with spacings of 3m x 3m (ca. 1100 stems ha^{-1}) or 2.5m x 2.5m (ca. 1600 stems ha^{-1}) (Tullus et al., 2013, Mc Carthy, 2016) are widely practiced in Sweden.

1.3. Production of poplar stands in Sweden

When planted on farmland, poplar and hybrid aspen can yield considerably higher biomass production than other common planted species in Sweden (e.g. Norway spruce, Scots pine) (Karačić *et al*., 2003; Mc Carthy, 2016). MAI (Mean Annual Increment) ranges from 10 to 31 m^3 ha^{-1} throughout the country (Karačić *et al*., 2003; Chistersson, 2010; Johansson & Karačić, 2011; Nielsen *et al*., 2014). The highest MAI has been recorded at 45 m^3 ha^{-1} in the southernmost parts of Sweden (Christersson, 2010). In term of biomass for biofuel, a poplar stand yielded an average of 8.81 ± 0.92 ton ha^{-1} year^{-1} which is equivalent to 75-105-ton ha^{-}1 in a 10-15 years plantation (Johansson & Karačić; 2011). This is considerably lower than for willow plantation (*Salix spp.)*, where average of MAI increment for biofuel ranges at 10-12 ton dry matter ha^{-1} year^{-1} (Christersson, 1986; Christersson et al., 1993; Mola-Yudego, 2010; Volk et al., 2011a; Stanturf & Oosten,2014).

Volume production of poplar stands is influenced by spacing and cutting cycles (Mitchell, 1995; Christersson, 2010). High density poplar plantation should reach a maximum of 7000 stems ha^{-1} (Wright, 1998), with optimal biomass production within a period of 6 to 15 years (Mitchell, 1995). However, in highly dense stands lengthening of rotation often leads to high mortality rates caused by self-thinning or infectious diseases (Mitchell, 1995). Gradually, stands planted at lower density would overtakes denser stands (Mitchell, 1995).

1.4. Browsing, wind damage and diseases of poplar in Sweden

Hybrid aspen stands are susceptible to browsing from moose, deer and other wildlife and thus depend on protection through fencing (Rytter et al., 2002; Zakrisson et al., 2007; Bergquist et al., 2009; Christersson, 2010; Edenius et al., 2011; Myking et al., 2011; Bergqvist et al., 2014; Edenius & Ericsson, 2015; Mc Carthy, 2016). For planted poplar stands, a threat by browsing was reported in many studies and thereby caused reduction in growth and survival (Schreiner, 1959; Stanturf et al., 2001, Charles et al., 2014; Mc Carthy; 2016). Fencing is required for successful establishment of poplar stands (Schreiner, 1959; Stanturf et al., 2001; Christersson, 2010; and Mc Carthy, 2016) for a period of 8 to 10 years after planting (Christersson, 2010). It has been reported that wildlife prefers certain clones for browsing (Netzer, 1984; Karacic et al., 2003). For example, 11 to 12 years old poplar stands in Sangletorp and Rydsgard neighboring wildlife protection areas did not show severe damages by browsing (Karaci*c et* al., 2003). However, during food shortages, shifting of browsing by wild animals to unfavored clones has been reported (Netzer 1984). For second poplar generations, browsing impact is negligible (Christersson, 2011; Johansson & Hjelm, 2012; Mc Carthy et al., 2014). Christersson (2011) reported that for 15 years old poplar absence of fencing and thus browsing by wildlife did not negatively influence stand yield, because losses were compensated by the enormous number and fast growth of sprouts and root suckers.

Wind damage often refers to tree falling or uprooting (Cremer et al., 1982). Several factors influence the susceptibility of trees to wind damage, namely: wind climate, landscape structure, stand structure, site conditions, tree characteristics and silviculture treatments (Cremer et al., 1982, Peltola et al., 2013, Hanewinkel et al., 2013). Poplar has been reported to be under great threat of wind damage and browsing in Sweden (Christersson, 2011). It is listed as vulnerable to wind damage as some species like Norway spruce (Hanwinkel et al., 2013; Peltola et al., 2013*)*, with damage already occurring at speeds of 10m s^{-1} (Gardiner et al., 2013). It is still unclear under which conditions wind causes severe damage to poplar plantations and if resistance regarding this matter depends on climate, site, or clonal properties. For example, when planted on shallow soils or sites with high water levels wind damage could be a serious issue due to shallow root systems (Stanturf et al., 2001). Due to loose soil texture and bare root systems, 20% of trees in a poplar stands planted on organic soil have been reported to have suffered from windthrow Christersson (2010). When planted on clay soil, the hybrid poplar clone "OP42" has been reported to show increased wind stability with only minor related damage (Christersson, 2010). Additionally, a plantation of hybrid poplar ("OP42" and a crossing of *Populus trichocarpa x Populus deltoides)* was reported to be damaged by wind due to the combination of wind, heavy rain and the big leaves causing top shoots and branches to be broken. Due to high wood density with the resulting stem strengthening, P. *deltoides* showed to be more resistant to wind damage than balsam poplar hybrids (Fortier et al., 2012). In contrast, Hanley (1984) and Stanturf et al., (2001) also noted that some poplar clones pose high wind resistance, thus being at no risk regarding this matter. For example, under suitable conditions and right clonal choice, poplar is planted as windbreaker in agroforestry systems worldwide (eg. United State, China, India, Canada, Russia, Netherland, France) with a long history (Fortier et al., 2012, Isebrands et al., 2014, Mc Carthy, 2016).

Diseases and pests of poplar plantations in Sweden like leaf rust, septoria leaf spot, leaf beetles and stem cankers have been reported to have occured through time (Schreiner, 1959; Christersson, 2008; Christersson, 2010; Christersson, 2011; Mc Carthy, 2016). For example, plantations planted for pulp production in the 1930s and 1940s in Sweden resulted to be unsuccessful due to pressure of various diseases (Christersson, 2008). However, the current effects of diseases on poplar are not severe in Sweden (Christersson, 2011). Only leaf rust, Melampsora and Massonia fungi have recently be reported to have caused a minor loss in volume production of polar (Christersson, 2011). Presently this disease pressure persist but is managed by growers through application of preventive silvicultural strategies like short-rotation, spacing, weeding, thinning and clone selection (Christersson, 2008; Christersson, 2010; Mc Carthy, 2016). Clone selection has been proven to have a positive impact regarding disease resistance and should be seriously considered (Stanturf et al., 2001; Christersson, 2011; Mc Carthy, 2016, Ostry et al., 2014).

1.5. Thinning of hardwood species

There is very little knowledge about thinning and silviculture practices for second poplar generations in Sweden and the world in general. Many studies reported thinning to be positively correlated to diameter growth (Cremer et al., 1982; Graham, 1998; Juodvalkis et al., 2005; Rytter & Stener, 2005; Rytter & Stener, 2014; McCarthy & Rytter, 2015; Rytter & Rytter, 2017) which is an important asset when it comes to log assortment and the possibility of compensating economic loss due to reduction in volume production (Rytter & Stener, 2005). Positive correlations between thinning intensity and diameter increment have also been found (Joudvalkis et al., 2005) to occur until certain thinning grades (Assmann, 1961). Height growth has been reported to be influenced by different thinning treatments in several studies (e.g. Steneker & Jarvis, 1996, Rytter, 2013; Rytter & Rytter, 2017). This condition has been claimed to only appear under extreme silviculture treatments Cremer (1982) and Niemistö (1995). Height is less sensitive to thinning than diameter (Rytter & Stener, 2005; Rytter & Stener, 2014; Mc Carthy & Rytter, 2015) and has also reported to be unaffected by thinning (e.g. Graham, 1998, Rytter, 2013). Total production often decreases due to clearance of stems and wider spacing in thinning practices (Niemistö, 1991, 2013; DeBell & Harrington, 1997; Simard et al., 2004, Nilsson et al.,2010) until re-occurrence of crown competition.

Many studies reported thinning to help reducing risk of wind damage (e.g. Cremer et al., 1982; Hanewinkel et al., 2013) and heavier thinned stands have been reported to be less damaged by wind (Cremer et al., 1982). However, wind damage risk has also been reported to increase right after performing thinning as the result of canopy opening which can also lead to increased occurrence of wind turbulence in stands (Cremer et al., 1982). More severe damage through wind is often caused by application of high thinning grades, thinning from above, or if remained trees are high and slender (Booth, 1974; Mayhead et al., 1975; Cremer et al., 1977; Cremer et al., 1982, Hanewinkel et al., 2013). The essential time duration for trees to regain stability after thinning often ranges from 2 to 8 years (Cremer et al., 1982; Hanewinkel et al., 2013) and depends on various factors like stand age, growth rate, status of the stand at the time of thinning (Cremer et al., 1982), species, thinning grade, thinning techniques (e.g. thinning from above, thinning from below). The Stem Height/Density ratio is a good indicator for risk of stem breakage due to wind (Petty & Worrell, 1981; Cremer et al., 1982; Hanewinkel et al., 2013; Peltola et al., 2013) and has been reported to be more valuable in assessing of wind risk than crown opening or canopy roughness indices (Cremer et al., 1982). Additionally, a positive correlation between tree height and vulnerability to wind damage exists (Hanewinkel et al., 2013). Dominant height can often be used as an indicator for assessing wind damage because it is often independent from silvicultural treatments (Hanewinkel et al., 2013).

Immediate responses to thinning have been reported to occur in deciduous tree species such as hybrid aspen (Juodvalkis et al., 2005; Rytter & Rytter, 2017) due to a fast-growing ability in response to competition release (Juodvalkis et al., 2005). However, thinning is likely to lose its effects at the point when canopy closure is reached (Juodvalkis et al., 2005; Mc Carthy & Rytter, 2015) and further thinning is suggested to maintain the effects of thinning (Mc Carthy & Rytter, 2015). Self-thinning strongly appears in stands without thinning posing the possibility of leading to reduction in growth of root suckers (Rytter & Stener, 2005). Thinning at younger ages results in better volume increment in low and moderate thinning grades in comparison to old aged stands (Juodvalkis et al., 2005).

1.6. Sprouts and Root Suckers

After harvest, new poplar stands can regenerate as second generations by growing either sprouts or root suckers from stumps of previously harvested stands (Johansson & Hjelm, 2012). Sprouts directly emerge from stumps, while suckers grow from the existing root system (Johansson & Hjelm, 2012). There is a number of factors influencing stump capacity of producing sprouts and root suckers including (1) tree species, (2) clonal differences, (3) stump age, (4) harvesting season, (5) stump size, (6) stump high, (7) site quality (Davidson & David, 1972; DeBell & Alford, 1972; Strong & Zavitkovski, 1983; Stanturf et al., 2001; Mc Carthy et al., 2014). Among these factors, stump age (< 10 years of age) and harvesting season are the most important (Johansson & Hjelm, 2012). For example, stumps harvested in summer resulted in fewer sprouts and reduction of sprout diameter by 50 % (Ford & Albert, 1954).

Average numbers of sprouts produced under various site conditions and for different clones range in between 9 to 13 sprouts per stump (Ford & Snow, 1954; Davidson & David, 1972, Laureysens et al., 2003). Dominant sprouts have been reported to emerge early and competition from other sprouts in the same stumps to be negligible (Davidson & Davis, 1972). Sprouts and root suckers have been reported to be strongly produced within the first year after harvest and to significantly drop in the following 10 years (Wendel, 1975). Often one to two dominant sprouts has been found to contribute as the main source of biomass of a stump (Laureysens et al., 2003). In order to reduce competition for ensuring sufficient log diameter and volume for pulp or timber, one or two sprouts per stump are recommended (Stanturf et al., 2001)

Beck (1977) found the numbe of sprouts as well as sprout diameter and height to not dependent on stump size (Beck, 1977), while Mc Carthy et al. (2014) reported a positive correlation of stump size and number of sprouts.

After thinning, an average of five sprouts has been reported to emerge from thinned sprouts of yellow poplar by Beck (1977). Re-sprouting of the removed sprouts and root suckers after thinning has been reported to pose no significant risk to survival of crop trees (Beck, 1977).

1.7. Crop trees

Crop tree management is a silvicultural treatment which selects and favours growth and development of the most desirable trees through freeing them from competition of neighboring trees (Lamson *et al*., 1990; Perky *et al*., 1994; Vodak, 2004). Criteria for selection of crop trees vary depending upon management practices and the expected end products (Vodak, 2004).

Selection of crop trees for thinning in second poplar generations is undertaken for single best stems among clumps in terms of size, shape, emergence from underground and absence of suppression from other sprouts (Beck, 1977; Rytter, 2013).

1.8. Problem statements and research hypothesis

With high potential of successful regeneration from selected clones producing straight sprouts (Johansson & Hjelm, 2012; Mc Carthey, 2016) as well as quick establishment and inexpensive management, poplar sprout stands managed for biomass production pose a good alternative compared to conventional planting (Johansson & Hjelm, 2012). The present knowledge regarding management of second poplar generations mostly refers to short coppicing stands under short rotation periods of 2 to 10 years (Johansson & Hjelm, 2012). Moreover, due to the relatively small proportion of poplar plantations in Sweden as of today, information regarding production potential of stump sprout and root sucker stands managed intensively for pulp and timber as final products is scarce. Thus, there is a need to investigate how these second generations could be managed for pulp or timber as final products in rotations of 15 to 20 years and how different treatments might influence production.

In this study we investigated the growth response and development of sprouts and root suckers of hybrid poplar to different thinning treatments. Three hypotheses were tested, namely: (1) Stump sprouts are dominant in stand of poplar sprouts and root suckers, (2) Thinning increases total volume production, (3) Thinning improves growth, development and stem stability of crop trees.

2. Material and methods

2.1. Site description

The experimental site is located in a former farmland in Sturup, Southern Sweden (Coord. N55° 3326.3” E13° 2859.7”). *Figure 1.* shows a map of Sweden with the trial position marked.

In Sturup, the length of the growing season is 220 days year^{-1}, with a mean temperature of 15.1°C. Annual precipitation, mean temperature and minimum temperature are 650 mm year^{-1} 8.5 °C year^{-1} and -28 °C year^{-1} (Christersson, 2010).

During 2011 to 2017, there were 365 days (1706 hours) on which wind speeds ≥ 10 m s^{-1} occurred, in average on 52 days year^{-1}. Wind speeds ≥15 ms^{-1} were recorded on 16 days. Strong wind was most frequently recorded from October to April during the observed treatment period. Data was obtained from Sturup weather station (Swedish Meteorological and Hydrological Institute, 2018)

2.2. Description of the parent stand (first generation stand)

The poplar plantation was established in 1991 by planting of bare rooted plants of the clone “OP42” (*Populus maximowiczii* Henry x *Populus trichocarpa* Torr and Gray) in square pattern at a planting density of 1100 plants ha^{-1} (3 m x 3m). The first stand was harvested in winter after 15 growing periods in 2004. Annual increment including branches was 27.6 m^{3} ha^{-1} year^{-1} with an average biomass production of 8.9 ton ha^{-1} year^{-1} (Böhlenius, pers.comm. 2018). After harvest, stumps were left for growing sprouts and root suckers for a period of 7 years before thinning treatments were applied.

2.3. Poplar sprout and root sucker stands before thinning (second generation stand)

After clearcut, new stems emerged as stump sprouts or root suckers. Across all plots, an average of three stems occurred as root suckers and four stems as stump sprouts at age seven (*Table 1.*). In total, the number of sprouts in our study stand accounted for 56 % of the total number of sprouts and root suckers. Mean diameters of stump sprouts and root suckers were 63.6 cm and 76.5 cm, respectively. In average, the total stem density ranged between 6250 and 6940 stems ha^{-1} for the treatment plots with a mean value of 6700 stems ha^{-1}. Mean standing volume was 187 m^3 ha^{-1} and varied between 193 m^3 ha^{-1} and 181 m^3 ha^{-1}. Basal area varied among treatments from 29 to 32 m^3 ha^{-1} and an average of 30 m^2 ha^{-1} for all experimental plots. During the first seven years after clearcut, the annual increment ranged at 26 to 28 m^3 ha^{-1}.

Table 1. *Mean values for the experimental plots of sprout and root sucker stands before thinning in 2011*

Mean number of stump sprouts or root suckers				**Mean diameter of stump sprouts or root suckers**			**Growth**		
Total no. of stems [ha^{-1}]	No. of Sprouts [stump^{-1}]	No. of Root suckers [stump^{-1}]	No. total [stump^{-1}]	Stump sprouts [mm stem^{1}]	Root suckers [mm stem^{-1}]	Sprouts and root suckers [mm stem^{-1}]	Standing volume [m^3 ha^{-1}]	Basal area [m^2 ha^{-1}]	Annual increment [m^3 ha^{-1}]
6727	4.3	3.1	7.5	76.5	63.6	72	187	30	27

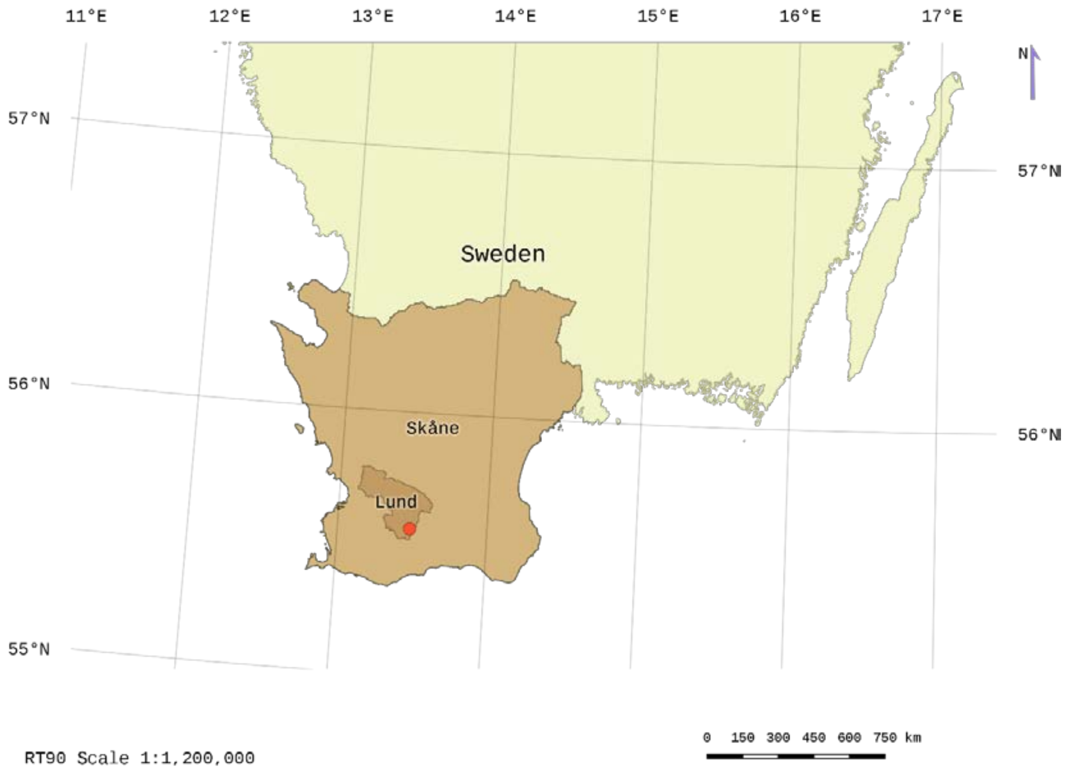

Figure 1. *Location of study area in Sturup, Southern Sweden.*

2.4. Software and packages used

Data was analyzed using Rstudio Version 1.1.423 (packages: agricolae, car, doBy, ggplot2, lattice, Lsmean, tidyr, plyr, readr, Rmisc, scales).

2.5. Thinning treatments and experimental design

The experiment is established as Latin square design (*Model 1.*). Treatments are assigned randomly and appear only once in each column and row (Gao, 2005; ILRI, 2011). Additionally, the number of replications is required to be equal to the number of treatments (ILRI, 2011) and all treatments appear equally within blocks and rows (Box et al., 2005; Gao, 2005; ILRI, 2011). This helps to reduce the effects of site quality and geographical differences more efficiently than a one-direction block design and minimizes experimental errors (Box et al., 2005; ILRI, 2011).

$$\mathbf{Y_{ijk} = \mu + a_i + b_j + c_k + \varepsilon_{ijk}} \quad (1)$$

Where each of *i, j, k* ranges from 1 to t

a_i = effect due to treatment *i*

b_j = effect due to row *j*

c_k = effect due to column k

ε_{ijk}: = general error terms.

(Gao; 2005; ILRI, 2011)

The experiment consists of four blocks and four treatments. One plot per treatment (n total = 4) was assigned to each block (*Fig. 2*). Thinning treatments were as follows; Control (6000 stems ha^{-1}) - no thinning performed; 1100 stems ha^{-1} –retention of biggest sprouts; 550 stems ha^{-1} – retention of biggest sprouts and removal of every second tree row; Row thinning (3000 stems ha^{-1}) – removal of every second tree row. Each plot had a dimension of 24m x 24m with a buffer zone of the same thinning treatment (2 tree rows; 6 m) between each plot. In most cases thinning selection of retaining trees favored sprouts growing against the main wind direction, with potential of reducing wind damage. At the last measurement, the second-generation plantation of hybrid poplar was 13 years old.

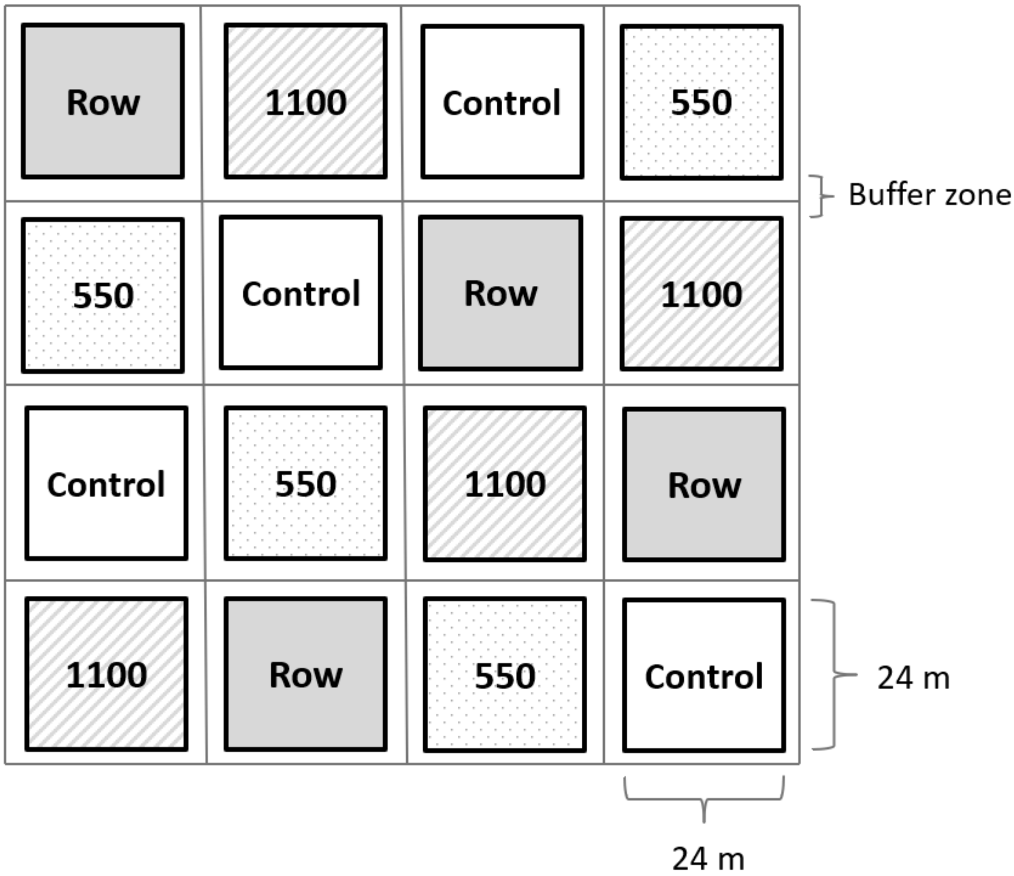

Figure 2. *Experimental design of thinning treatments in second generation of poplar. Treatments: Control (6000 stems ha-1)- no thinning (unthinned), 1100 stems ha-1 – retention of biggest sprouts, 550 stems ha-1 - retention of biggest sprouts and removal of every second tree row, Row thinning (3000 stems ha-1) - removal of every second row with retention of all original sprouts in remained stumps (source: modified from Böhlenius, 2017).*

2.6. Measurements

The data used in this study was collected in two main time periods: (1) before thinning and (2) after thinning.

Before thinning, initial stem density as well as stem diameter (1.3 m above ground) of all stump sprouts and root suckers were measured. Trees with a diameter < 4cm were excluded from the measurement.

After thinning treatments, the diameter of all remaining trees and height of sample trees (ca. 220 trees) was collected in year zero, year two, year four and year six post thinning at the end of the growing period (fall or winter). Sprouts which emerged after thinning were included in the caliper measurements when they became larger than 4 cm in diameter.

Height was measured from ground surface to tree top. Selection of sampled trees for height measurement (ca. 220 trees) was performed by ensuring equal numbers of sampled trees for every diameter class. In case sample trees were missing (e.g. due to self-thinning or wind damage), the next tree in the same diameter class was selected as replacement. The average top height of 100 dominant trees ha^{-1} (tree with biggest stem diameter) was calculated in order to assess site index of the experimental site (Stearns-Smith, 2002; Johansson, 2011). Top height of dominant trees is often used as indicator for site potential in terms of suitability and productivity for planted species (Hägglund, 1981; Johansson, 2011). This is due to the fact that this variable is often free from impact of management (Cremer et al., 1982; Stearns-Smith, 2002; Johansson, 2011, Hanewinkel *et al*., 2013).

For diameter measurement, the trees were permanently marked and numbered at 1.3 m height above ground. All trees were measured for diameter twice at a perpendicular angle. Diameter was then derived by taking the average of these measurements. Diameter distribution is an important attribute in providing information about stand properties and to support decision making in forest management (Kudus et al., 2000; Li et al., 2006; Zheng & Zhou, 2010). This is because diameter is correlated to many other variables such as volume, stand composition, age, site, density and economic value (Kudus et al., 2000).

2.7. Summary for mean experimental plot values after thinning applications

Thinning treatments were applied when the second rotation reached 7 years of age. Depending on the respective thinning treatment, stems were removed from the stand in different thinning grades ranging from 56 % for row thinning (3000 stems ha^{-1}) to 86 % for thinning 1100 stems ha^{-1}, and 92 % for thinning 550 stems ha^{-1}. Numbers of retained stems by treatments ranged from 447 to 6163 stems ha^{-1} (*Table 2*). The mean basal area before thinning among treatments was 30 m^2 ha^{-1} and varied from 4 to 29 m^2 ha^{-1} after thinning from heavy thinning to unthinned control (6000 stems ha^{-1}) experimental plots. Stem diameter was significantly smaller in unthinned (6000 stems ha^{-1}) and row thinning (3000 stems ha^{-1}) treatment stands (73 mm) than in 1100 and 550 stems ha^{-1} thinning treatments (102 to 107 mm). Standing volume significantly differed among all treatments and ranged from 29 to 174 m^3 ha^{-1} in the 550 stems ha^{-1} treatment and the unthinned treatment (6000 stems ha^{-1}), respectively. In the first growing season after thinning, MAI varied across treatment plots and ranged from 13 to 32 m^3 ha^{-1}, with highest values found in the unthinned treatment and lowest values found in 550 stems ha^{-1} treatment.

Table 2. *Summary of mean treatment values after thinning in 2011*

Treatment	**Age** [years]	**No. of Stems** [stems ha^{-1}]	**No. of Stems removed** [stems ha^{-1}]	**BA before thinning** [m^2 ha^{-1}]	**BA after thinning** [m^2 ha^{-1}]	**Diameter** [mm $stem^{-1}$]	**Standing volume** [m^3 ha^{-1}]	**Annual increment** [m^3 ha^{-1}]
Control (6000 stems ha^{-1})	7	6163		29	29	73	174	32
1100 stems ha^{-1}	7	968	5972	31.6	9	107	61	27
550 stems ha^{-1}	7	447	6306	30	4	102	29	13
Row (3000 stems ha^{-1})	7	3000	3915	30	14	73	82	25

2.8. Data analysis

2.8.1. Volume equation

Presently no volume equation specifically designed for estimating volume of second poplar generations for Sweden exists. Several volume equations were assessed in the past by Hjelm & Johansson (2012), either constructed specifically for poplar or applicable for both poplar and aspen for its applicability and predictive possibility under Swedish conditions. One of the most frequently used sampled tree clone for assessing the equation is "OP42" (*Populus maximowiczii* Henry x *Populus trichocarpa* Torr and Gray) (Hjelm & Johansson, 2012) which is the same clone as used in this study. The equation developed by Eriksson (1972) is currently ranked among the best level of performance in terms of low Absolute Bias and Root Mean Square Error (Hjelm & Johansson, 2012). This equation had been developed for aspen in Sweden since 1972 (Eriksson, 1972) and its wide diameter range covers this study's data range. In addition, it only requires values for diameter and height as independent variables which are available in the data of this study.

On the other hand, Johnsson's volume equation constructed for hybrid aspen has been used in the studies of Rytter & Stener (2005), Christersson (2010), Rytter & Stener (2014) but was reported to give 10 % lower volume estimation than Eriksson's equation due to exclusion of branches (Christersson, 2010). In addition, the function of Johnsson underestimates 25 % of volume production for energy (Christersson, 2010). Since our study focuses on growth responses of second poplar generation to thinning, inclusion of branches and leaf matter is important for growth assessment. Furthermore, the stems in our study treatments could serve various production purposes. Thus, we decided to use Erikssons equation for volume estimations *(Model 2.)*

Since the Eriksson equation was not specifically constructed for hybrid poplar and especially for second poplar generations, caution should be given regarding underestimation of volume productions (Hjelm & Johansson, 2012). A high multicollinearity level of Eriksson's volume equation has been reported (Hjelm & Johansson, 2012) which might cause coefficient values to be lower or create a high coefficient standard error (Burk et al., 1989; Kozak, 1997; Hjelm & Johansson, 2012). However, multicollinearity was reported to not affecting the predictive possibility of the equation (Kozak, 1997; Hjelm & Johansson, 2012).

In addition, estimation bias could be produced because stem diameter and density differed significantly among treatments (e.g. 6000 stems ha^{-1} for unthinned control and only 550 stems ha^{-1} for heavy thinning treatment) and only certain numbers of sampled trees were selected for volume estimation.

Volume of all sampled trees was computed using the equation of Eriksson(1972) as shown below:

$$V = 0{,}01548D^2 + 0{,}03255D^2H - 0{,}000047D^2H^2 - 0{,}01333DH + 0{,}004859DH^2 \quad (2)$$

where:

V = above ground over bark volume [dm^3]

D = diameter at breast height [cm]

H = height [m]

Top height was measured for only about 220 trees and stem volume estimation requires both DBH and top height. Thus, stem volume could only be calculated directly for 220 sampled trees (both height and DBH available) with the function of Eriksson(1972). In order to compute volume for trees for which only diameter was measured, a linear regression model *(Model 3.)* was derived between diameter and volume of sampled trees for each plot (plot-wise method) (16 plots x 3 years). In order to test the fitness of the regression coefficient, a regression line based on the trees sampled was used as a standard model and compared with the estimated volumes from the regression relationship. The regression coefficients were then used to compute the volume of all remaining trees in the plot. It should be noted that a general equation was used for the whole 550 stems ha^{-1} treatments (treatment-wise) instead of separate equation for every plot of this treatment due to big gap in diameter, height and its lower density.

$$\log V_i = \beta_1 + \beta_2 \log D_i + \varepsilon_i \quad (3)$$

Where:

$\log V_i$ = log transformation of bark stem volume from stump to top of the tree

$\log D_i$ = log transformation of diameter at breast height (1.3 m)

ε_i = general error term

2.9. Statistics

Treatment effects were analyzed for (1) crop trees and (2) all living trees in the treatments at each age after thinning.

For individual crop trees, approx. 20 of the biggest trees (approx. 340 to 360 trees ha^{-1}) in each treatment were selected to analyze effects of thinning on crop tree growth and development. The selection of these trees was based on tree diameter and for single best stems among clump.

The dominant stems should be the best in terms of size, shape, emergence from underground, and absence of suppression from other sprouts (Beck, 1977; Rytter, 2013).

A Shapiro and a Levene test were initially used in order to test for normality and homogenity of the data. When the conditions were met, an ANOVA (Analysis of Variance) was implemented for a one-factorial design with treatment effects on standing volume, stand density, stem volume, diameter, height, and volume increment as described by the model *(Model 4.)*. If one or both conditions for normality or homogenity were violated, a Kruskal-Wallis test for non-parametric data was applied. A significance level of 0.05 was selected as standard for all tests. When significant difference was found for treatment effects, a pair-wised Tukey post-hoc test for the ANOVA test or Wilcoxon test for the Kruskal Wallis test was used to perform pair-wise comparisons between groups. In addition, the "BH" p adjusted method (as abbreviation of Benjamini & Hochberg, 1995) was also included as a method of reducing incorrect rejections of the null-hypothesis (false discovery rate) (Benjamini & Hochberg, 1995).

$$Y_{ij} = \mu + treat_i + \varepsilon_{ij} \quad (4)$$

Where:

Y_{ij} = the desired observed stand characteristic (height/volume/diameter/increment),

μ = the overall mean, $treat_i$ the fixed effects of thinning treatments, and

ε_{ij} = the random term error of measurement ij.

3. Results after thinning

3.1. At stand level

3.1.1. Stand mortality

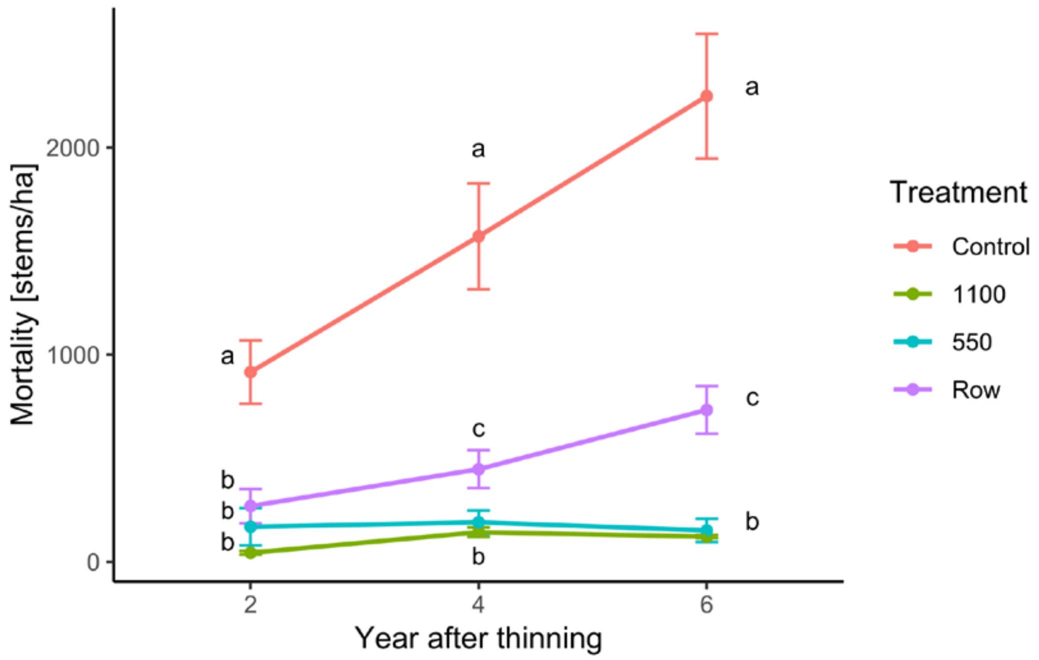

Figure 3. *Mortality of poplar sprout and root sucker stands after thinning sorted by treatments. Treatments: Control (6000 stems ha^{-1})- no thinning (unthinned); 1100 stems ha^{-1} - retention of biggest sprouts, 550 stems ha^{-1} - retention of biggest sprouts and removal of every second tree row, Row thinning (3000 stems ha^{-1})- removal of every second tree row. Bars indicate ± SE. Different letters (a, b, c and d) indicate significant differences within each year (p <0.05, Kruskal Wallis test, "BH" p adjusted method).*

Mortality of poplar sprout and root sucker stands significantly differed among all treatments (*Fig. 3*). Highest mortality rates occurred in unthinned (control) treatment stands (6000 stems ha^{-1}) with a self-thinning rate of 34 %, reducing mean values of treatments from 6100 to 4000 stems ha^{-1}. In the row-thinned treatment (3000 stems ha^{-1}) the mortality was about 16 % of total stand density during treatment period which was lower than for unthinned stands. Low or no mortality occurred in stands of the 1100 and 550 stems ha^{-1} treatments.

3.1.2. Standing volume

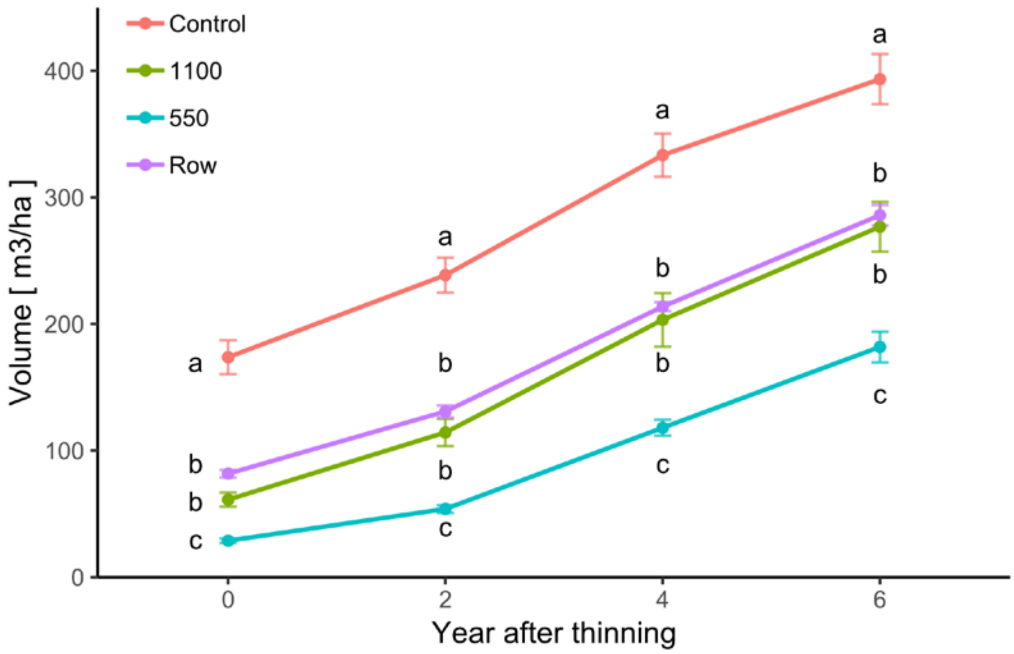

Figure 4. *Standing volume for each treatment after thinning [m^3 ha^{-1}].*

Standing volume increased through the observed years in all treatment plots (*Fig. 4*). Unthinned control treatments (6000 stems ha^{-1}) yielded significantly higher standing volume than all thinned treatments (393 m^3 ha^{-1} at year six). The 550 stems ha^{-1} thinning treatment yielded the lowest volume (181 m^3 ha^{-1}) among all treatments which is less than half of the unthinned treatment. No significant differences in standing volume were found between the row-thinning (3000 stems ha^{-1}) and 1100 stems ha^{-1} treatments with productions of 286 m^3 ha^{-1} and 277 m^3 ha^{-1}, respectively in year six.

3.1.3. Mean diameter growth of individual trees at stand level

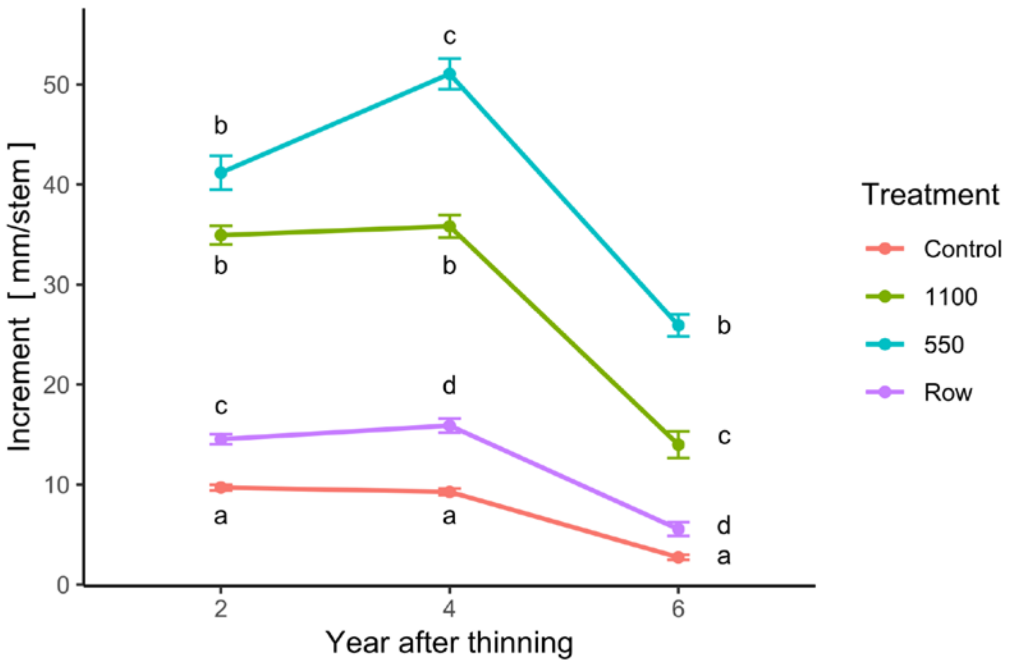

Figure 5*. Mean diameter growth of individual trees at stand level sorted by treatments from 2011 to 2017. Diameter was measured at 1.3 m height above ground.*

In the first two years, diameter growth of the 1100 and 550 stems ha^{-1} treatments did not significantly differ from each other, showing mean increment of 35 and 41 mm, respectively *(Fig. 5)*. In contrast, diameter increment was found differed between stems diameters of the unthinned control (6000 stems ha^{-1}) and row (3000 stems ha^{-1}) treatments with the mean value of 9.7 and 14.5 mm, respectively.

After four years, mean stem diameter growth differed significantly among all treatments. Higher thinning regimes (removal of more trees) resulted in larger stem diameter growth. For example, in year six after thinning, the trees in the unthinned treatment (6000 stems ha^{-1}) showed less than half of the diameter increment (27 mm) of the trees in the 550 stems ha^{-1} treatment (55 mm).

3.1.4. Diameter distribution at stand level

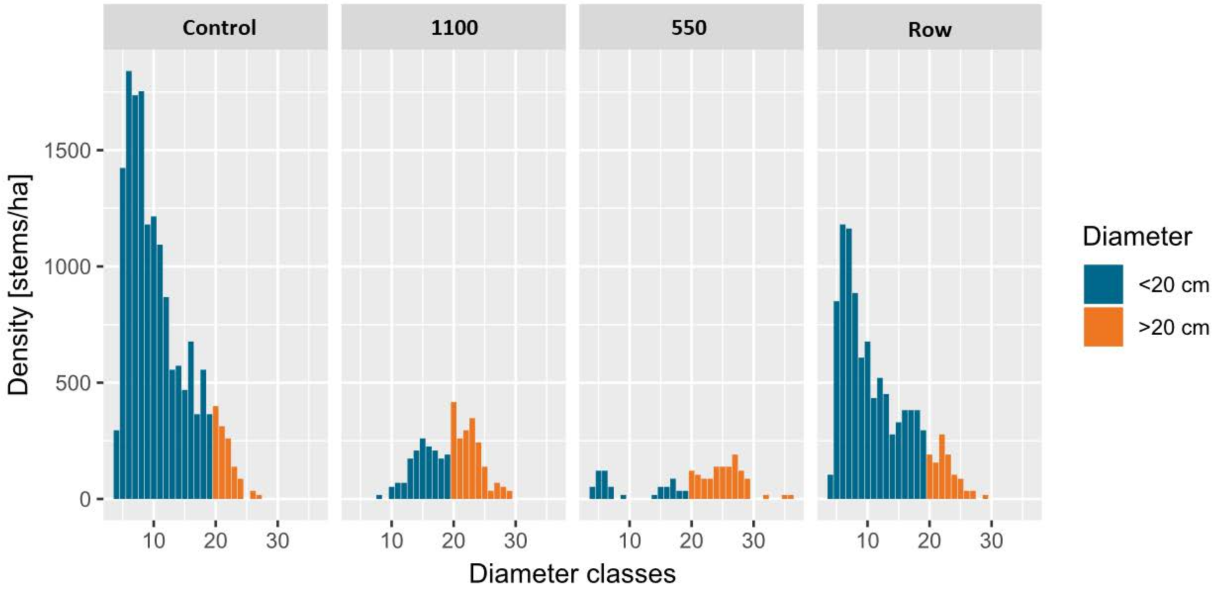

Figure 6: *Diameter distribution of 13 years old poplar sprouts and root sucker stand by treatments at the Sturup's experimental site*

The diameter distribution of the poplar sprout and root sucker stands varied depending on treatments *(Fig.6).* Unthinned control (6000 stems ha^{-1}) and row-thinned (3000 stems ha^{-1}) treatments showed similar diameter distributions with more than 90% of stems having a small diameter (< 20 cm). Less than 10% of stems were found to be big in the unthinned and row-thinned treatments with mean diameters ranging from 21.7 to 22.8 cm.

In the 1100 stems ha^{-1} treatment stands, the two diameter groups were found to occur quite balanced, stems with a diameter > 20 cm had a share of 42% and a mean value of 23 cm. Only very few stems showed diameters smaller than 10 cm.

The 550 stems ha^{-1} treatment was the only treatment showing a higher number of stems with diameters > 20 cm and mean value of 25.3 cm (which is 60 %). A number of smaller trees (< 10 cm) showed up due to re-sprouting of 2rd generation sprouts and root suckers after thinning application.

3.1.5. Mean periodic annual increment (PAI) of treatment plots at stand level

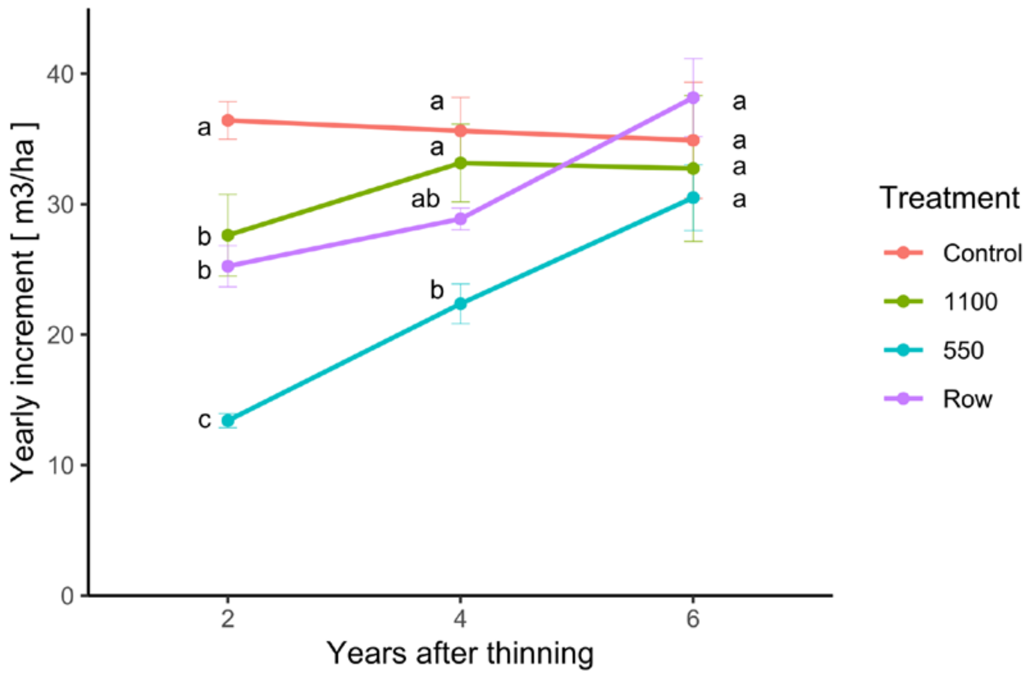

***Figure 7**. Mean Periodic Annual Increment (PAI) of stands sorted by treatments.*

Mean periodic annual increment at stand level differed among all treatments in the beginning (*Fig. 7*). In the first four years, the unthinned control treatment (6000 stems ha^{-1}) showed the highest increment among all treatments, showing its highest PAI of 36m^3 ha^{-1} yr^{-1} at year one while the 550 stems ha^{-1} treatment showed the lowest growth rate of 13 m^3 ha^{-1} yr^{-1}. However, the trees in the unthinned stands (6000 stems ha^{-1}) gradually decreased in annual growth through the observed period while the other thinning treatments gradually increased in growth. No significant difference in increment was observed between the row treatment (3000 stems ha^{-1}) and the 1100 stems ha^{-1} treatment. Finally, at year six the growth of all four treatments was no longer distinguishable, showing a mean value of 34 m^3 ha^{-1}.

3.1.6. Total gross volume production of poplar sprout and root sucker stands

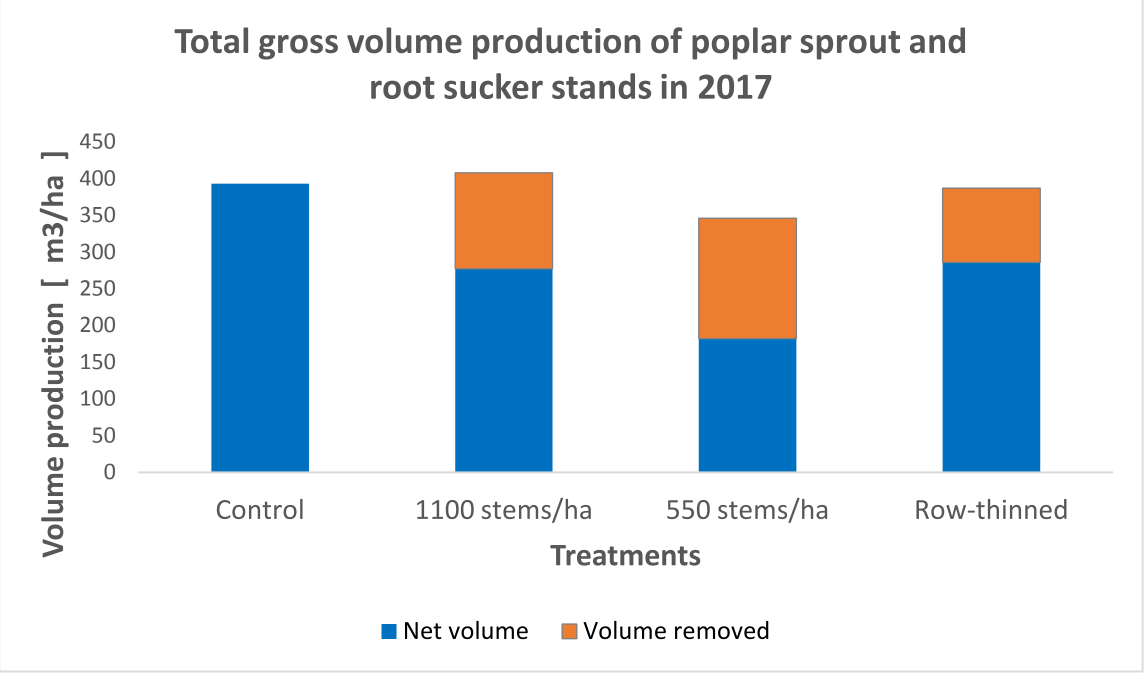

Figure 8. *Total gross volume production of poplar sprout and root sucker stands including volume removed by thinning in 2011.*

Volume production (standing volume) of second generations in the unthinned control treatment (6000 stems ha^{-1}) in 2017 was higher in comparison to all three other thinning treatments (*Fig. 8*). The amount of volume removal was highest in the 550 stems ha^{-1} and lowest in the row-thinned treatment (3000 stems ha^{-1}). Regarding inclusion of volume removal from thinning in the calculation of total gross volume production, differences among the unthinned control (6000 stems ha^{-1}), 1100 stems ha^{-1}, and the row-thinned stands (3000 stems ha^{-1}) were negligible, ranging from 387 to 408 m^3 ha^{-1}. The 550 stems ha^{-1} treatment showed the lowest total gross volume production among all treatment with a mean value of 346 m^3 ha^{-1}.

3.2. Crop trees

3.2.1. Mean diameter increment of crop trees

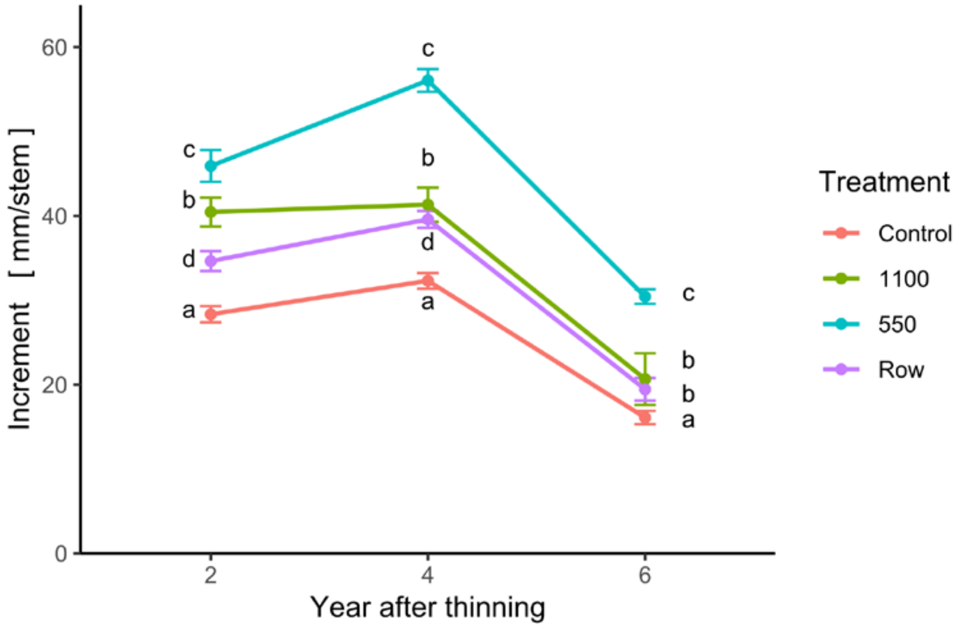

Figure 9. *Mean diameter growth of crop trees sorted by treatments (selection of approximately 350 of the biggest trees ha^{-1}).*

In the first four years, stem diameter growth of crop trees significantly differed among all treatments *(Fig.9)*. Year four showed the highest diameter growths over the observed period with mean increment ranging from 32 to 56 mm recorded for unthinned control (6000 stems ha^{-1}) and 550 stems ha^{-1}, respectively. Afterwards, the increment curves leveled off and at year six, no significant different in diameter increment was found between row (3000 stems ha^{-1}) and 1100 stems ha^{-1} treatments with the mean value ranging from 19.4 to 20.6 mm. Higher thinning grade (removal of more trees) resulted in bigger stem diameter growth which is also true to stems diameter at stand level *(section 3.1.3).*

3.2.2. Mean height growth of crop trees

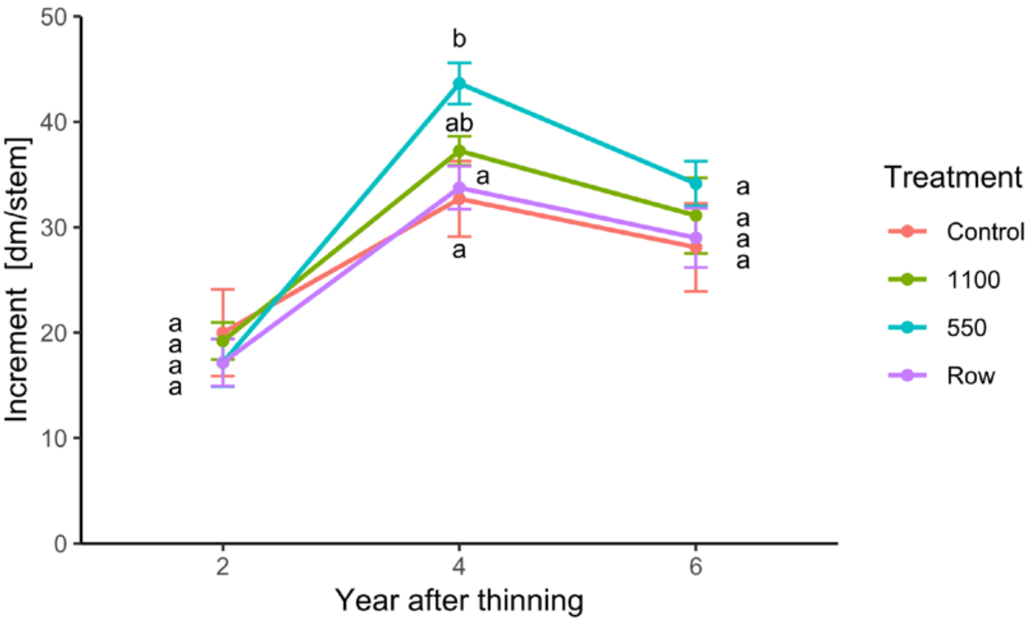

Figure 10. *Mean increment of top height of crop trees sorted by treatments (approx. 350 trees ha^{-1}). Height was measured from ground surface to tree top.*

Mean growth of top height only significantly differed at year four after thinning with the highest increment of 43.6 dm in the 550 stems ha^{-1} treatment *(Fig. 10)*. These differences in top height increment could not be found anymore in both year two and six, where crop trees showed similar height growth. The trees in the 550 stems ha^{-1} treatment showed the quickest height increment, because initially during the first two years the trees in this treatment showed the lowest mean value of about 150 dm.

3.2.3. Top height for site index assessment

The mean top height of the 100 thickest trees ha^{-1} over the experimental site regardless of treatments was 24m at year six. The mean height of the 100 dominant trees ha^{-1} for each treatment was also calculated with the mean value varies among treatments. The unthinned control (6000 stems ha^{-1}) treatment showed the lowest mean stem height of 17.5 m which is 10.5 m lower than in the 550 stems ha^{-1} treatment. The 1100 stems ha^{-1} stand yielded an average height of 24.3 m which is very similar to the overall mean top height of the whole experimental site. The row treatment (3000 stems ha^{-1}) showed a slightly higher mean value of top height than the unthinned control treatment (6000 stems ha^{-1}) which is 18.8 m.

***Table 3**: Mean height of the 100 thickest trees calculated by treatments over the experimental site at 13 years of age (2017).*

	Control (6000 stems ha^{-1})	**1100 stems ha^{-1}**	**550 stems ha^{-1}**	**Row (3000 stems ha^{-1})**
Mean height of 100 trees ha^{-1}	17.5	24.3	28	18.8
Site index equivalents in Johansson (2011)	24	30	33	27

3.2.4. Height/Diameter ratio of crop trees

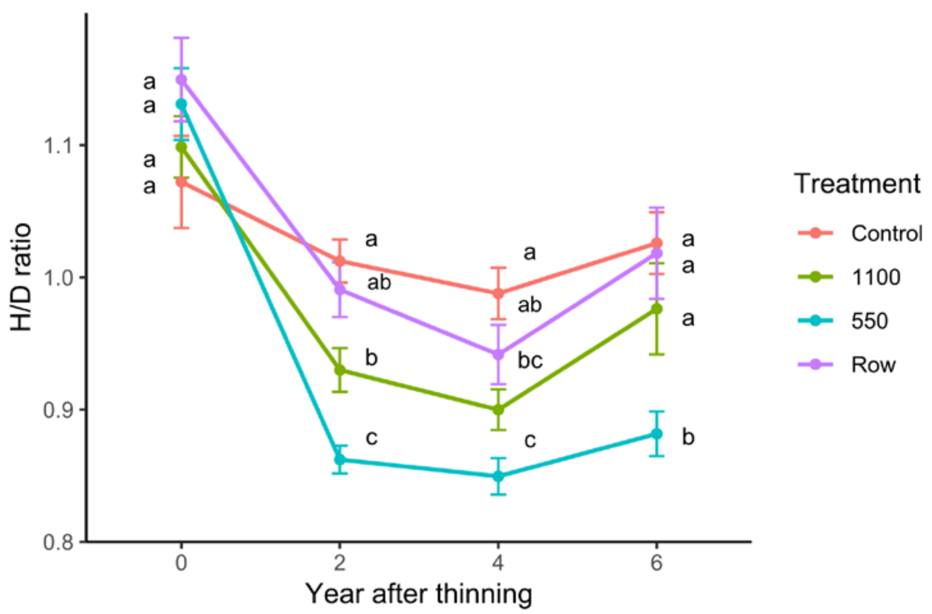

***Figure 11.** H/D (Height/Diameter) ratio of crop trees sorted by treatment indicating tree stability against wind damage.*

Initially, height-diameter ratios among all treatments were similar *(Fig.11)*. During the following years, thinning treatment influenced the height diameter ratio, trees in the unthinned control stands (6000 stems ha^{-1}) showed a higher H/D ratio in comparison to 550 stems ha^{-1} thinning treatments. At year six, the 550 stems ha^{-1} treatment showed a lower H/D ratio in comparison to the other thinning treatments. All other treatments did no longer significantly differ from each other.

3.2.5. Mean annual increment of individual crop tree

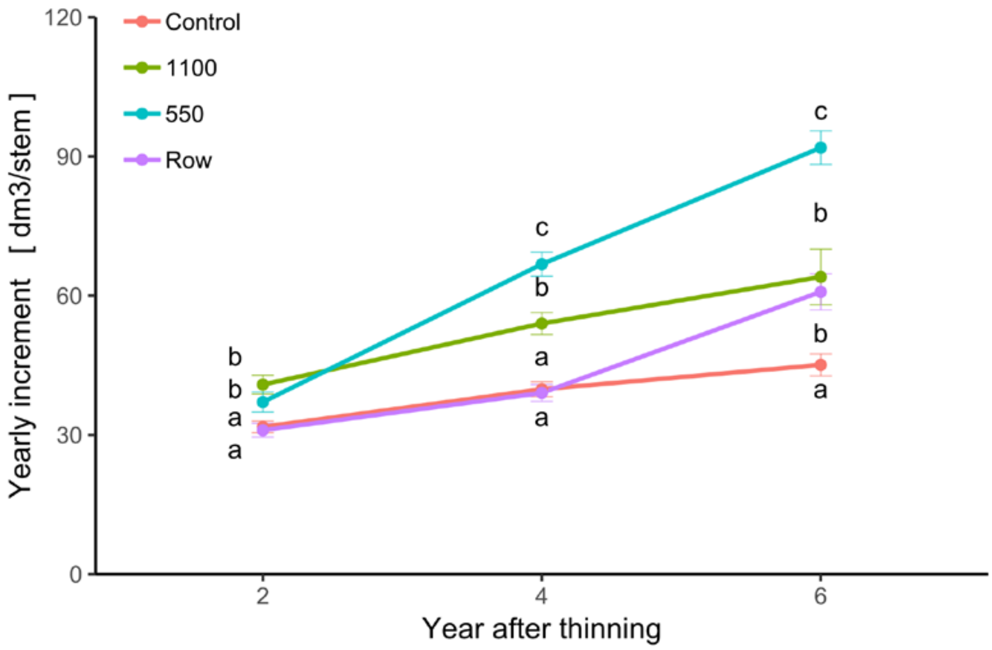

Figure 12. *Yearly increment of crop trees sorted by treatment from 2012 to 2017.*

Thinning showed positive effects on yearly volume increment in comparison to absence of thinning. For individual crop trees in general, trees in the unthinned control treatment (6000 stems ha^{-1}) showed the lowest increment among all four treatments six years after thinning *(Fig. 12)* and the 550 stems ha^{-1} treatment showed the highest volume increment. Trees in the 1100 stems ha^{-1} treatment initially showed similar growth to the 550 stems ha^{-1} treatment, with growth changing to become significantly lower during the following periods. The row treatment (3000 stems ha^{-1}) initially showed similar increment in comparison to the unthinned treatment after year four. At year six, the yearly crop tree increments in the row treatment (3000 stems ha^{-1}) was higher and comparable to the 1100 stems ha^{-1} treatment.

4. Discussion

Before thinning, sprout and root sucker stands at age seven showed (1) in average 7.5 shoots per stump (sprouts and root suckers). Numbers and stem diameter of sprouts were significantly higher than for root suckers; (2) the annual increment was 27 m^3 ha^{-1} yr^{-1} and therefore similar to many poplar stands planted in Sweden (Christersson2010).

After thinning it was found that: (1) no thinning led to occurrence of the strongest self-thinning in stands; (2) total gross production was reduced under heavy thinning of 550 stems ha^{-1}; (3) thinning reduced volume production (standing volume); (4) thinning enhanced diameter growth and stem volume as well as stem stability of crop trees.

In our experimental stands, the hybrid poplar clone OP42 (*Populus maximowiczii* Henry x *Populus trichocarpa* Torr and Gray) produced an average of 3 out of 7 shoots per stump as root suckers *(Table 1)*. In total, the number of root suckers was high and accounted for 42 % of the total number of sprouts and root suckers. This is in contrast to previous knowledge, where root suckers were considered to only occur in balsam poplar (*Populus balsamifera* Linnaeus) (Zasada *et al*., 2001, Johansson & Hjelm, 2012) and often excluded from investigation due to low appearance (Mc Carthy *et al*., 2014). Thus, it is important to include root suckers in studies about second poplar generations. Our findings are also in accordance with findings in six years old yellow-poplar stands reported by Beck (1977). Number and diameter of stump sprouts in the seven years old stands in our experiment are in line with the previous study of Johansson & Hjelm (2012) as the mean number of sprouts was four $stump^{-1}$ with a diameter of 76 mm.

A major difference between hybrid aspen and poplar is that the total number of stump shoots (sprouts and root suckers) in poplar *(Table 1)* is much lower than for hybrid aspen, which is known for its ability to produce massive numbers of root suckers (50-124000 stems ha^{-1}) (Mc Carthy & Rytter, 2015). However, in our experiment root suckers were removed unselectively during thinning treatments due to practical reasons like the inability of the thinning machine to avoid removal.

Dominant sprouts have been reported to emerge early (Davidson & David, 1972), with often two sprouts occurring in a co-dominant way (Ford & Albert, 1954; Davidson & David, 1972). Because of strong internal competition (Mc Carthy *et al., 2014)*, there is a negative correlation between the number of sprouts and sprout age due to self-thinning (Johansson & Hjelm, 2012). This means that for ensuring sufficient log diameter and volume for pulp or timber production only one to two sprouts per stump are recommend until the end of rotation (Beck, 1977; Stanturf *et al.* 2001). These results are also supported by our finding of only a few dominant crop trees growing on each stump.

Similar to Mc Carthy & Rytter (2015) we observed a high mortality rate of 34 % in unthinned control plots (6000 stems ha^{-1}) due to self-thinning *(Fig. 3)*. Thinning still maintained its effects on density in the poplar stands of our study six years after thinning. In contrast, effects of thinning on stand density in aspen root sucker stands have been reported to diminish in time (Mc Carthy & Rytter, 2015). This altogether suggests that competition is less present in second generations of poplar than in hybrid aspen root suckers. However, these differences might have occurred due to site specific differences site since thinning response and self-thinning are highly site dependent (pers. comm. Holmström, 2018). At current growth rates, it would take years for the poplar stands to show the same densities in all treatments as in aspen stands since currently there are way too many more stems in the unthinned control (6000 stems ha^{-1}) and row-thinned (3000 stems ha^{-1}) treatments than in 1100 and 550 stems ha^{-1} *(Fig. 6)*.

Standing volume was highest in unthinned control stands (6000 stems ha^{-1}) *(Fig. 4)* and thinning significantly reduced volume production due to removal of stems and wider spacing. This is in accordance with the previous studies by Niemistö (1991, 2013), DeBell & Harrington (1997) and Simard et al. (2004). In contrast, Telenius (1999) reported no differences in volume production of unthinned to thinned stands of a planted hybrid poplar clone (*Populus tremula* x *tremuloides*, spacing of 1m x 2m with 50 % stems removed equivalent to 38 % biomass removal) after 6 growing seasons. The possible explanation might be that because in comparison to planted systems, stands of sprouts and root suckers have; (1) higher densities due to enormous numbers of sprouts and root suckers (DeBell et al., 1993; Mitchell, 1995; Johansson & Karačić, 2011); (2) quicker establishment and higher survival rates of sprouts and root suckers growing from stumps (Johansson & Hjelm, 2012; Mc Cathy, 2016) due to water and nutrient intake through the existing root system (Johansson & Hjelm, 2012).

Diameter increment was significantly higher in all thinned than unthinned control stands at both stand and crop tree levels (*Fig 5 & 9*). These results support previous studies where thinning was also positively correlated to diameter growth (Cremer et al., 1982; Graham, 1998; Juodvalkis et al., 2005; Rytter & Stener, 2005; Rytter & Stener, 2014; McCarthy & Rytter, 2015; Rytter & Rytter, 2017). Higher thinning regimes (removal of more trees) resulted in larger stem diameter growth and bigger stem dimension *(appendix 1)*. Thus, if the higher price of selling pulp and timber could compensate the production loss due to thinning, thinning is recommended. A thinning scheme of 1100 stems ha^{-1} is highly recommended since it showed the highest number of stems > 20 cm *(Fig. 6)*, similar volume to row-thinning (3000 stems ha^{-1}) and higher production than in the 550 stems ha^{-1} thinning treatment *(Fig 4)*. However, in the previous study of Davidson (1983) dominant hybrid poplar sprouts showed no effects on diameter growth three years after thinning. Similar results were reported for yellow poplar *(Liriodendron tulipifera)* stands in which thinning showed no effects upon both diameter and height gain of dominant sprouts 18 years after thinning (Beck, 1977).

Our results suggest that row thinning might not be recommended as a thinning practice. The treatment of 1100 stems ha^{-1} yielded similar standing volume and total gross volume production to the row-thinned system (*Fig. 3 & 8*). The 1100 stems ha^{-1} treatment resulted in significantly bigger trees in comparison to the row-thinned treatment (3000 stems ha^{-1}) *(Appendix 1)* which is often preferred by the pulp and timber industry with higher merchantability (Nilsson *et al*., 2010). This could be explained by the fact that the removal of every second row did not sufficiently free retained trees from competition (*Fig.3*) causing the mean diameter of crop trees to not significantly differ from the unthinned treatment (*Appendix 2*). These results indicate that the main source of competition was situated within stumps as competition still persisted in row-thinned stands and the techniques applied in row thinning did not sufficiently free the retained trees from competition. In contrast, almost no mortality occurred in the 1100 and 550 stems ha^{-1} treatments as only dominant stems were retained. This suggests that thinning schemes of 1100 and 550 stems ha^{-1} are sufficient in order to prevent occurrence of self-thinning within the stand. Even though it might be costlier to perform a selection of dominant trees in a 1100 stems ha^{-1} treatment than removing every second tree row. Longer rotation (> 15 years) could be expected in row-thinned (3000 stems ha^{-1}) stands to reach maturity and the density of 1100 stems ha^{-1} while 550 and 1100 stems ha^{-1} could be harvested earlier. Hence, it might be more beneficial to keep the rotation shorter and start a new plantation. Additionally, higher risk of wind damage and diease pressure should be carefully considered. This is because closer distance between trees and canopy intersection will increase the branch swing force and touching of canopy leading to more severe wind damage. Same applies for diseases as these could then spread quicker in denser stands, especially fungal root pathogens. Christersson (2008) also reported stem cancer risk to be high in stands with 15-20 years of age.

During the first two years after thinning, the PAI levels of all thinned stands were significantly lower than for unthinned stands (*Fig. 7*) (it should be noted that the increment level mentioned here is Periodic Annual Increment calculated for the poplar stand of sprouts and root suckers during observation period). This result for poplar sprout and root sucker stands also follows the thinning response rule (Skovsgaard & Vanclay, 2008) as volume growth of stands would be reduced if the basal area removal > 50% (BA removal ranging from 53% in row-thinned (3000 stems ha^{-1}) to 82% in 550 stems ha^{-1} treatments). At year six, thinning lost its effect on stand volume growth as the PAI was the same among all treatments even BA removal was > 50% as mentioned previously.

The overall mean PAI of 13-year-old poplar sprouts and root suckers across all treatments in our experimental setup was 34 m^3 ha^{-1} which is considerably higher than for commonly planted species in Sweden (Karačić *et al.*, 2003; Mc Carthy & Rytter, 2015). It is also higher than thinned stands of planted hybrid aspen which range at a MAI level of 19.5 m^3 ha^{-1} for stands in between 17 to 26 years of age (Rytter & Stener, 2014) or in between 18 to 20 m^3 ha^{-1} in 12 years old aspen root sucker stands (Mc Carthy & Rytter, 2015). It is also comparable to planted stands as reported by Christersson (2010).

For unthinned control (6000 stems ha^{-1}) treatment stands, annual increment of second poplar generations reached a growth rate of 36.4 m^3 ha^{-1} yr^{-1} at eight to nine years of age and maintained this PAI level in the following years. Production loss in the current experimental setup is expected to increase during the following years as many trees were observed to be dying. Regarding biomass production for energy purposes, harvesting is recommended in unthinned control (6000 stems ha^{-1}) stands in accordance with Laureysens *et al.*, (2003) and Johansson & Karačić (2011) at an age before counterbalance occurs by self-thinning to achieve high economic returns and avoid density dependent mortality (Karačić *et al., 2003).* Thus, thinning might not be necessary if energy production is considered (Johansson & Karačić, 2011).

The PAI of 32.5 m^3 ha^{-1} in the 1100 stems ha^{-1} treatment in our study (885 stems ha^{-1} in 2017) *(Fig. 7)* was considerably higher than the MAI of 23 m^3ha^{-1} of a 16 years old same poplar clone with an initial spacing of 1100 stems ha^{-1} reported by Christersson (2010). The possible explanations are: (1) the poplar plantation of Christersson situated in Näsbyholm was planted on a less favourable soil type (organic soil), together with wind damaging 20% of the trees (due to loose texture of the organic soil and shallow root system) (Christersson, 2010); (2) slower growing of planted poplar stands during the establishment phase during which the necessary preliminary root system development has been reported to cause lower growth (Christersson, 2011; Böhlenius.*per.com, 2018)*; (3) the improved effects of poplar sprout and root sucker stands on productivity and production as previously mentioned.

In our study stand, total gross volume production was slightly lower under heavy thinning of 550 stems ha^{-1}, while other thinning grades did not differ. This result is in line with the study of Nilsson et al., (2010). This could be explained that the heavy thinning grade in the 550 stems ha^{-1} treatment reduced its volume increment because it had lowest volume growth during the first four years *(Fig. 7).*

The possibility of poplar stands with lower spacing to catch up and overgrow denser stands in terms of volume production after a period of 6 to 15 years as stated by Mitchell (1995) is unlikely to manifest in the extend of our study (*Fig.4*). The unthinned control (6000 stems ha^{-1}) treatment still posed the highest volume production, although self-thinning was observed *(Fig. 3 & 4)*. Because stem loss due to self-thinning was quite small, the negative impact upon volume was very low. In addition, even during excessive occurrence of self-thinning in the unthinned treatment, total volume was still higher than in other treatments due to the following reasons: (1) self-thinning removed low volume stems with the process stopping at certain higher densities, (2) presence of numerous high volume stems in the unthinned treatment, (3) 55 %-85 % of biomass was removed by thinning in the row-thinned treatment and the 550 stems ha^{-1} treatment, respectively *(data not shown)*, (4) wider spacing (e.g. 550 stems ha^{-1}, spacing of 6m x 3m) with higher individual increment was not able to compensate for only few stems being present in the stands. For example, in 2017 after seven growing seasons post thinning, the 550 stems ha^{-1} treatment yielded only less than half of the volume production of the unthinned treatment, 180 m^3 ha^{-1} and 390 m^3 ha^{-1}, respectively.

Treatment effects of thinning upon height of crop trees were observed only four years after crown opening, when the height increment in the 550 stems ha^{-1} treatment was significantly higher than in other treatments *(Fig. 10).* It is clear that the significant difference in height growth only appeared under extreme thinning treatment (92% stem removal or 85% biomass removal); this result is also supported by Cremer (1982) and Niemistö (1995). At year two and six, thinning showed no effects since height growth no longer differed between all treatments. These results are in line with previous studies which reported height to show less sensitive responses to thinning treatments than diameter (Rytter & Stener, 2005; Rytter & Stener, 2014; Mc Carthy & Rytter, 2015); but in contrast with studies which reported height to be unaffected by thinning (Graham, 1998, Rytter, 2013). The absence of differences in height growth in all treatments after year four could be explained by the re-occurrence of crown competition and the sensitivity of poplar regarding this matter.

According to the first site index curve constructed for poplar in Sweden by Johansson (2011) and based on the mean top height over the whole experiment site (24m), the site index of Sturup's experiment site is 30. This is considered as good site and suitable for growth and development of the planted hybrid poplar.

On the other hand, the equivalent site index of the Sturup's experimental site by treatment is 24 for the unthinned control (6000 stems ha^{-1}), 27 for the row-thinning treatment (3000 stems ha^{-1}), 30 for the 1100 stems ha^{-1} treatment, and 33 for 550 stems ha^{-1}, respectively (*Table 3.*). We could see that thinning treatments had impacts on mean top height of dominant trees among treatments. Lower density stands yielded higher height of dominant trees. This is in contradiction to the findings of Cremer et al., (1982), Stearns-Smith (2002)**,** Skovsgaard & Vanclay (2008); and Hanewinkel et al., (2013) as height of dominant trees is often free from silviculture management. This could be explained by the fact that in comparison to the studies of Cremer et al (1982) and Niemistö (1995) the thinning applications in our studies were more extreme.

In addition, the 1100 stems ha^{-1} treatment also represents the common spacing of planted poplar stands in Sweden with a very similar mean top height to the overall mean top height across all stands. Thus, 30 might be closer to the predicted site index presented in the study of Johansson (2011). However, attention should be given regarding the reliability of the results as most of the stands in the referenced curve were first generation planted poplar stands (rooted seedlings) and the author also adviced that thinning treatments should not be applied in the stand.

The H/D ratio was calculated solely for dominant crop trees since these play a key role in determining stand stability (Cremer et al., 1982). This especially accounts for when thinning programs are designed to retain dominant trees since this ratio could be misinterpreted when small stems are removed (Cremer et al., 1982). In our study location, over seven years on 365 days wind speeds ≥ 10 m s^{-1} occurred (*Sturup weather station*, SMHI, 2018) thus showing potential to damage trees (Gardiner et al., 2013). However, the wind damage observed in our experimental stand was negligible during the treatment period. The possible explanations for this are: (1) strong wind events often occurred from October to April the year after, (2) higher wind stability as the trees remained leafless in the winter leading to lower wind dragging (Hanewinkel et al., 2013); (3) frozen ground in the winter time provided better stability for trees.

The higher H/D ratio in unthinned control stands (6000 stems ha^{-1}) in comparison to the 1100 and 550 stems ha^{-1} treatments which occurred due to competition in our study stand has also been also reported by Cremer et al., (1982) *(Fig. 11)*. This result suggests higher stability of crop trees within stands. Thus, our study findings suggest that thinning favoring dominant trees is recommended. The unselective thinning mechanism of row thinning (3000 stems ha^{-1}) in our study should be avoided because it resulted in a similar H/D ratio to the unthinned treatment stands. This is also in accordance with (Cremer et al., 1982). Further thinning is needed four years after thinning to maintain tree stability in the 1100 stems ha^{-1} treatment and the row thinning (3000 stems ha^{-1}) treatments since its H/D ratio did not significantly differ from the unthinned treatment stands.

The stability of stands or trees against wind damage is related to various factors as mentioned previously in Cremer et al. (1982), Peltola et al. (2013) and Hanwinkel et al. (2013) (wind damage, pp.5). Thus, the H/D ratio is only sufficient for determining individual tree stability (Hanewinkel et al., 2013). Furthermore, height of dominant trees should also be considered together with the H/D ratio (Hanewinkel et al., 2013), because when trees reach maturity stage, the H/D ratio seems to lose its predictive possibility as height growth at that time occurs slower than diameter growth causing smaller a H/D ratio (Harris, 1981; Cremer et al., 1982).

Practitioners and forest owners should be aware of the possibility that the productivity observed in the experiment might be higher than in practice because the data was obtained from small experimental plots with very homogeneous conditions. In contrast, big plantations often pose a lower average site index, clone site matching, vulnerability to diseases and weed competition (Mitchell, 1995).

5. Conclusions

Due to the high number of sprouts and root suckers as well as the fast growth and development second poplar generations of the clone "OP42" (*Populus maximowiczii* Henry x *Populus trichocarpa* Torr and Gray) pose a good alternative to planted poplar stands in Sweden. They provide same or even higher volume increment, a high rate of successful regeneration, mitigation of wildlife browsing risk and a wide selection possibility for later silviculture treatments.

Thinning reduced standing volume in all thinned treatments. Slight losses in total gross production only occurred in heavy thinning of 550 stems ha^{-1}. Thinning schemes of 1100 and 550 stems ha^{-1} enhance diameter, volume and stability of individual trees. Retention of dominant trees is important in order to reduce internal competition and enhance growth development of crop trees.

For energy production, stands of sprouts and root suckers should not be thinned. Harvest should be done at 8 or 9 years of age or before counterbalance (increment = production loss) occurs.

For pulp production, a thinning scheme of 1100 stems ha^{-1} is recommended.

For timber production, a thinning scheme of 550 stems ha^{-1} is suggested.

Row thinning (3000 stems ha^{-1}) might not be recommended.

6. Outlook

It is important to include root suckers in studies about hybrid poplar second generations because their share of total stump numbers shoots is high.

Presently, no volume equation constructed for second poplar generation exists. Often, volume estimation is based upon equations designed for aspen or hybrid aspen in Sweden from the past which could potentially lead to underestimations of actual volume production.

Thus, more research is needed in order to construct new volume equations for stands of poplar sprouts and root suckers.

Stem quality is an important factor for timber value. The current study has just considered the effect of thinning on growth and volume production of stem/log/trees regardless of quality assessments like straightness, taper, and stem defects (knot, decay, twisted, etc.). Further studies about quality assessment for 2^{nd} poplar generations are essential as the impact regarding this matter on log prices is high.

A conjunction with future studies on economic potential of 2^{nd} poplar generations is crucial to provide better understanding and information for supporting decision making in forest management since this study mainly focused on the silviculture aspect.

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Appendix

Appendix 1: Mean diameter of individual trees at stand level

No.	Treatment	Year	N	DBH	Significant letter
1	Control (6000 stems ha^{-1})	2	1223	8.608013	A
2	1100 stems ha^{-1}	2	219	14.18219	B
3	550 stems ha^{-1}	2	100	14.773	B
4	Row (3000 stems ha^{-1})	2	661	8.844629	A
5	Control (6000 stems ha^{-1})	4	1072	9.903825	A
6	1100 stems ha^{-1}	4	199	17.8206	B
7	550 stems ha^{-1}	4	89	20.54326	C
8	Row (3000 stems ha^{-1})	4	616	10.59951	D
9	Control (6000 stems ha^{-1})	6	923	10.78852	A
10	1100 stems ha^{-1}	6	202	19.26881	B
11	550 stems ha^{-1}	6	89	23.32472	C
12	Row (3000 stems ha^{-1})	6	546	11.79634	D

Appendix 2: Mean diameter of crop trees

No.	Treat	Year	N	DBH	Significant letter
1	Control (6000 stems ha^{-1})	2	78	15.87051	A
2	1100 stems ha^{-1}	2	78	16.98974	B
3	550 stems ha^{-1}	2	77	16.09286	A
4	Row (3000 stems ha^{-1})	2	80	15.1825	C
5	Control (6000 stems ha^{-1})	4	76	19.06579	A
6	1100 stems ha^{-1}	4	68	21.29706	B
7	550 stems ha^{-1}	4	70	22.09143	B
8	Row (3000 stems ha^{-1})	4	78	19.14615	A
9	Control (6000 stems ha^{-1})	6	76	20.67566	A
10	1100 stems ha^{-1}	6	70	23.24929	B
11	550 stems ha^{-1}	6	70	25.09071	C
12	Row (3000 stems ha^{-1})	6	78	21.08526	A

Appendix 3: Mean top height of crop trees

No.	Treat	Year	N	Height	Significant letter
1	Control (6000 stems ha^{-1})	2	13	17.23077	A
2	1100 stems ha^{-1}	2	24	16.25833	AB
3	550 stems ha^{-1}	2	39	14.81282	C
4	Row (3000 stems ha^{-1})	2	14	16.06429	B
5	Control (6000 stems ha^{-1})	4	11	20.47273	A
6	1100 stems ha^{-1}	4	21	20.06667	A
7	550 stems ha^{-1}	4	39	19.37692	A
8	Row (3000 stems ha^{-1})	4	12	19.53333	A
9	Control (6000 stems ha^{-1})	6	11	22.99091	A
10	1100 stems ha^{-1}	6	21	23.2381	A
11	550 stems ha^{-1}	6	39	22.6641	A
12	Row (3000 stems ha^{-1})	6	13	22.43846	A