Influence of Drought on Tree Growth in Different Thinning Treatments in Second Rotation of Poplar Plantations

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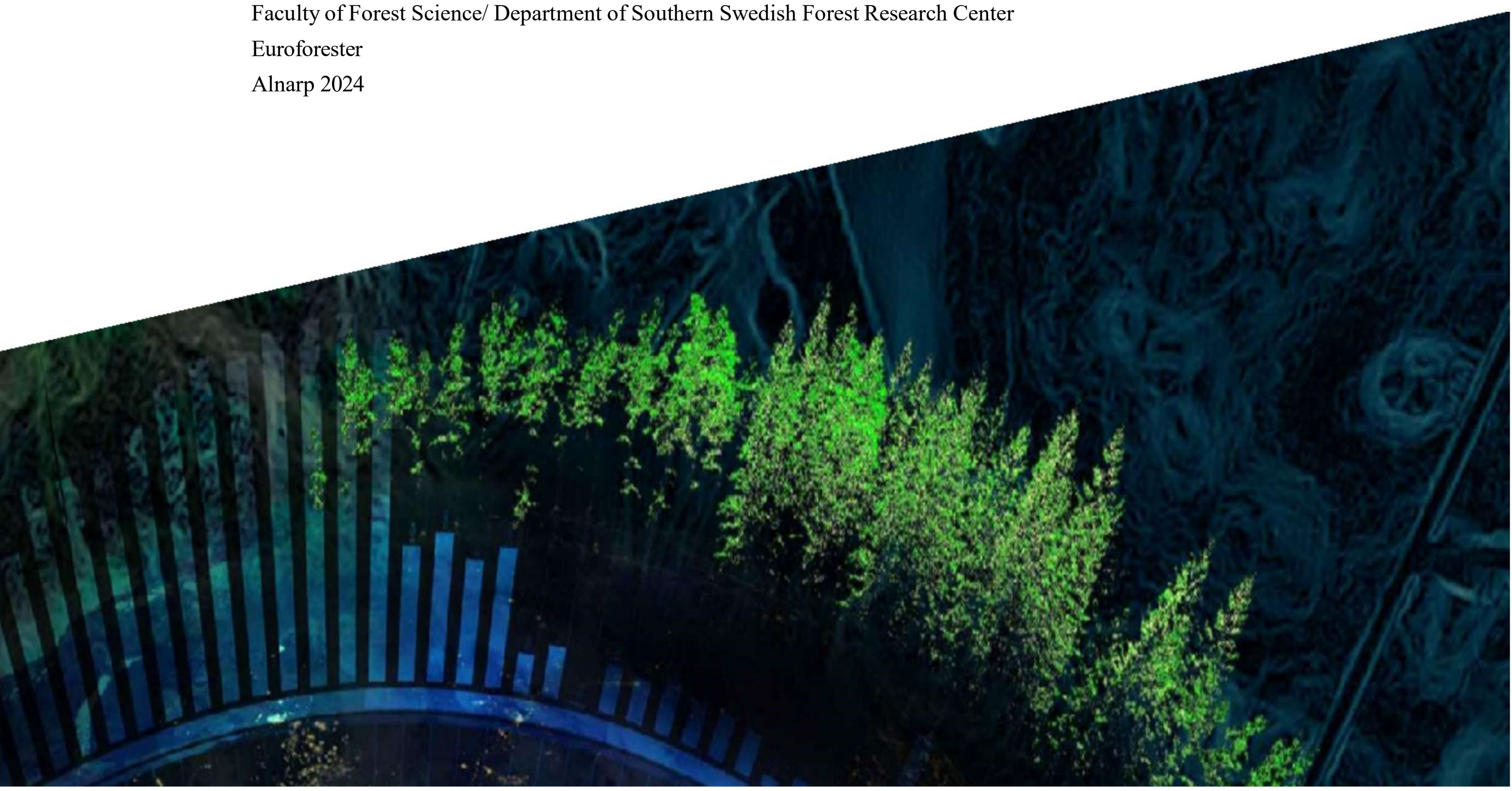

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Abstract

This study examines the dynamic interplay between tree growth and drought stress in a second rotation poplar plantation in southern Sweden. It evaluates the responses of trees, focusing on growth metrics (volume, basal area increments) and recovery patterns after water stress, across various thinning treatments and tree sizes by analysing tree ring width. Significant variations in growth metrics were observed, particularly during the drought of 2018.

To analyse the resistance (ability to remain largely unchanged) of trees during the drought, deltaDiv was calculated, where deltaDiv = (projected growth - observed growth) / observed growth. This calculated result highlighted that smaller diameter trees (dbh 9-11 cm) showed higher resistance to drought compared to larger diameter trees (dbh 25-35 cm).

The analysis of Volume Increment (VI) and Basal Area Increment (BAI) aimed to reveal the resilience (capacity to recover) of trees across different tree sizes (dbh 9-11 cm, 15-18 cm, 20-22 cm, and 25-35 cm) and thinning treatments (control/unthinned, light thinning, medium thinning, and heavy thinning). The study found that tree density influences drought resilience, with heavy thinning treatment (550 trees/ha) demonstrating higher resilience compared to unthinned plots (6000 trees/ha) and light thinning (3000 trees/ha) treatments, which showed limited growth responses.

Keywords: Poplar plantation, Tree ring width, Drought stress, Resistance, Resilience, Mixed effect model, Thinning treatments, Size-dependent responses, sustainability.

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Abbreviations

FAO	Food and Agriculture Organization of the UN
IPC	International Poplar Commission
SRC	Short Rotation Crops
BAI	Basal Area Increment
VI	Volume Increment
TRW	Tree Ring Width
dplR	dendrochronology program library in R
dbh	Diameter at Breast Height

1. Introduction

1.1 Distribution of Poplar

The genus populous exhibits extensive geographic distribution with its different species and clones. For instance, quaking aspen (*P. tremuloides*) spans from Alaska to central Mexico, while common aspen (*P. tremula*) extends from Europe to southeastern China. White poplar (*P. alba*) is found from Spain to China, Black cottonwood (*P. trichocrpa*) along the Alaskan coast to Mexico, and Japanese poplar (*P. maximowiczii*) throughout eastern Asia (Brian J. Stanton, 2010). These species cover significant longitudinal ranges, offering extensive possibilities to conquer as a prevalent fast-growing species throughout the world.

According to FAO report (2021), the total area occupied by poplars, willows and other fast-growing species across 22 countries from IPC (International Poplar Commission) is estimated at 88,744,976 hectares. Poplar formations dominate the landscape, encompassing 59,149,433 hectares, which accounts for 66% of the total area. Other fast-growing species plantations cover 27,355,874 hectares, representing 31% of the total. Willow stands occupy 1,559,954 hectares, while mixed poplar and willow formations cover 691,485 hectares.

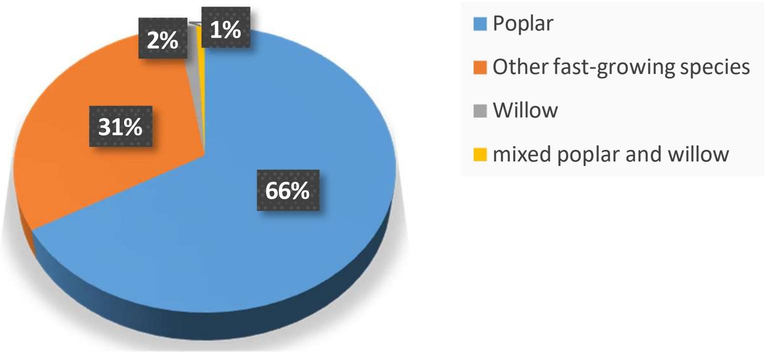

Figure 1. Total land occupied by poplar, willow and other fast-growing species across 22countries of IPC. Source of data: (FAO, 2021)

The biggest expansion of fast-growing species is observed in China, India, Sweden, Canada, Turkey and the USA. Poplar cultivation is notably prominent in China, Canada, Turkey and the USA. China, Portugal and the USA lead in mixed cultivation stands. Other fast-growing species are prevalent in Argentina, Canada, China, India, Turkey, Portugal and Sweden.

It is possible to cultivate many woody species in order to produce biomass, mainly broadleaf and fast-growing species are in main focus in this purpose. In Europe, the Salicaceae family, which contains species of Poplar and Salix, has benefited from the greatest industrial technological breakthroughs. There are well established plantations based on Populus species and hybrids in both central and southern Europe (Oliveira, 2020).

In Sweden, the area of naturally regenerated poplars can be found in total 240,000 ha, which is mainly used for industrial roundwood (30%), fuelwood biomass (10%) and for natural protection (60%). For plantation poplars the area is counted as 2,430 ha in total, where 70% is used for industrial roundwood and 30% for fuelwood biomass. It is also reported that from 2016- 2019 the newly planted area is 355 ha only with poplar in Sweden (FAO, 2021).

1.2 Significance of Poplar Plantations

In contemporary forestry management, the sustainable cultivation of fast-growing species such as Poplar, Hybrid Aspen has garnered significant attention due to its economic and ecological benefits (L. Christersson, 1993). In an economic analysis, *Riccardo Testa (2014)* demonstrated the economic feasibility of poplar plantations for biomass production as an alternative to traditional fossil sources, proving it to be a profitable business compared to traditional crops.

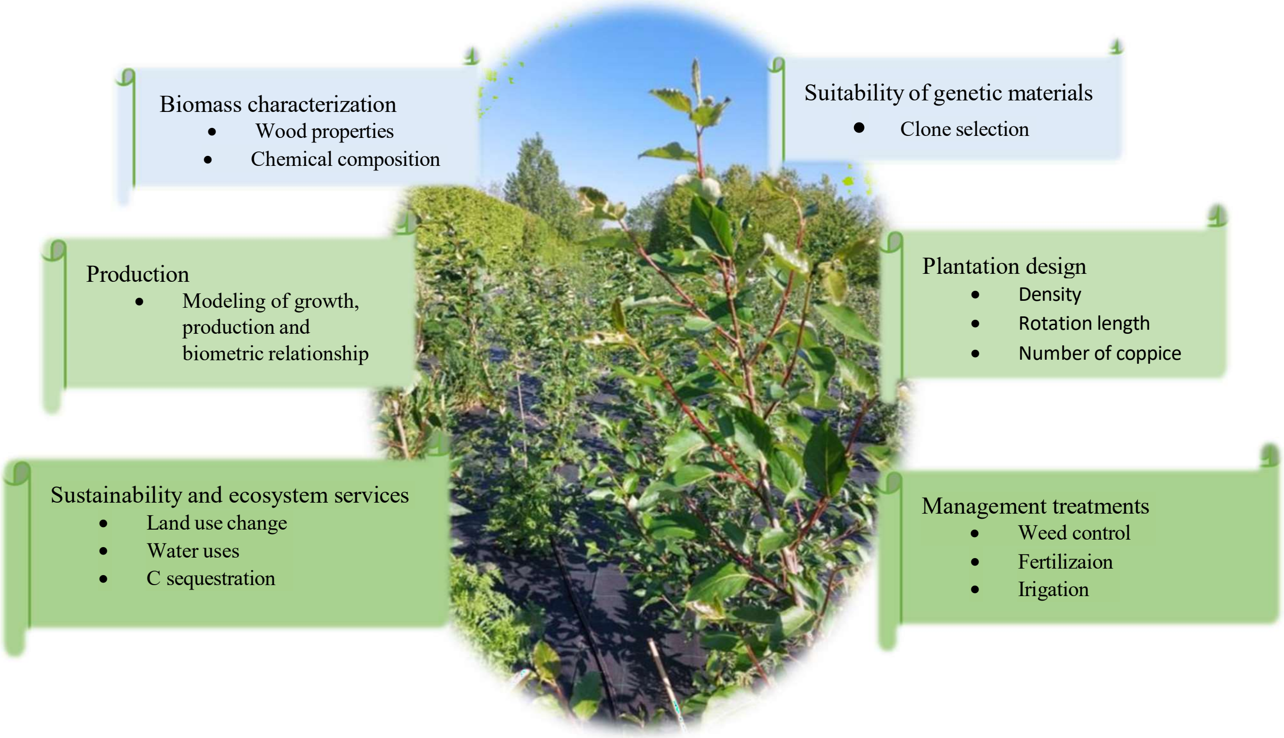

Figure 2.Proposed action for improving short rotation coppice-managed woody crops. (Oliveira, 2020)

Some management strategies can be undertaken in order to sustainably increase the biomass production from poplar and other Short Rotation Crops (SRC), such as selecting good genetic materials, better plantation design or different thinning treatments along with the production goals as well as site conditions (Figure 2). These development actions can be helpful for achieving a sustainable biomass production of SRC crops. The purpose of this study is also finding some evidences to set a proper development strategy to cope up with the drought stresses.

Moreover, the increasing global demand for biomass production has led to recommendations for expanding poplar plantations as Short Rotation Coppice (SRC) crops, thereby reducing pressure on natural forests (C. N. Pandey, 2012). Wood-based industries are also turning to this method of biomass production as a sustainable pathway (Christersson, 2008). Along with the economic benefits, poplar plantation is also ecologically viable because of its apparent environmental advantages, such as soil stabilization, nutrient and carbon sequestration has gathered a lot of interests (Riccardo Testa, 2014). However, the sustainable management of these plantations faces multifaceted challenges, with climate variability and associated disturbances, such as drought events, emerging as key concerns (Christersson, 2008) (C. N. Pandey, 2012).

1.3 Poplar Plantations and Climate change

It has been observed that precipitation levels are decreasing while temperatures are rising compared to the past few decades (A. J. Dittus, 2024). For example, around the experimental site average annual rainfall was 864mm in 2007, which dropped in approximately 693mm in next 10 years and during 2018 it was 507mm. On the other hand mean annual temperature was noted 9.7 °C in 2007 which recorded 10.2°C in 2018 at the same site. In future, warmer climate with drier summers, will affect in different forest tree species and not exceptional with populous species. Understanding a species' capacity to adapt to a changing climate requires knowledge of its resistance and resilience (Marc Hanewinkel, 2012).

The reactions of various species, particularly plant growth and development, have been greatly influenced by changes in the global surface temperature and precipitation regime (Archana Gauli, 2022). Environmental stresses have varying effects on different organs and tissues within a plant, and as such, molecular, cellular and morphological responses to stress vary among tissues, and throughout the developmental lifetime of a plant (Daniela Lovarelli b, 2018). In the next 100 years, climate change might pose a serious danger to biodiversity worldwide with a higher prediction of species loss as well as a major possibility in lowering wood or biomass productivity (Sharon B. Gray, 2016; URBAN, 2015; John A. Stanturf, 2001; Sarah R. Weiskopf, 2020). Prolonged periods of water deficits during a drought constitute a major environmental stressor that can have substantial effect on the growth of trees and the general functioning of ecosystems. Until the end of the twenty-first century, it is predicted that, central Europe will have rather rapid temperature increases along with a general decline in summer precipitation (Pimm, 2009).

Moreover, forest trees are particularly vulnerable to the effects of drought stress because of two weakness: their large size, which requires a sophisticated vascular water-transport system from soil to canopy, and their long generation time, which causes slow genetic response (Change, 2007; Laura Rosso, 2023). The way that different poplar genotypes weigh the trade-off between growth and drought resilience varies greatly. The genotypes that are most productive when water is not limited show the largest decline in biomass production during droughts (Paulo Eduardo Menezes-Silva, 2019; Romain Monclus, 2006). Drought also triggers in morphological and physiological characteristics in trees, like in leaves, roots and stems as showed in Figure 3.

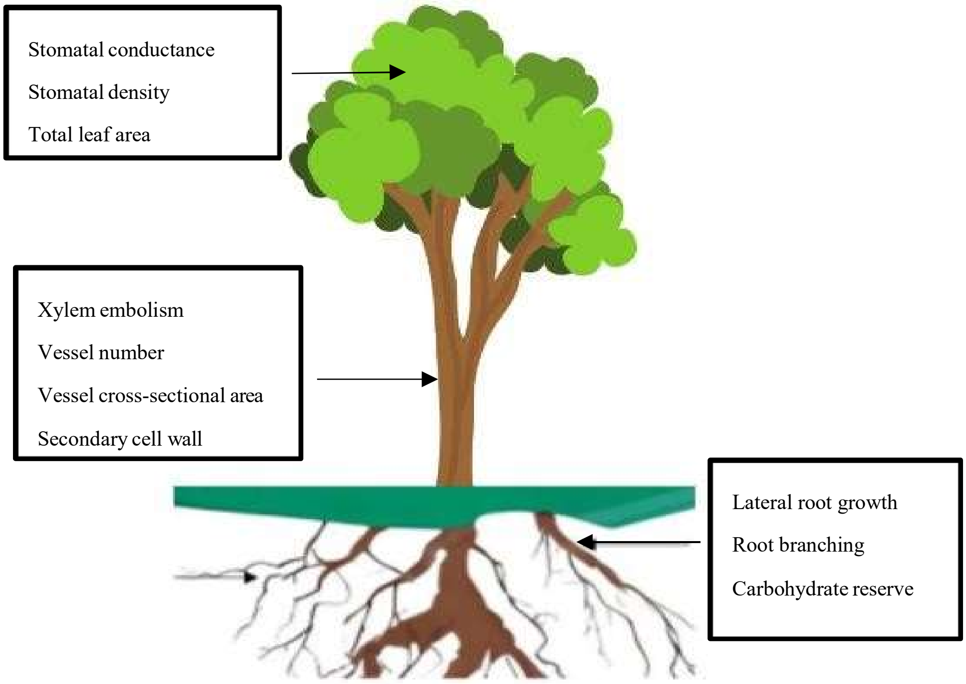

Figure 3. Responses of poplar to drought stress: signalling pathways and genes responsive to drought trigger physiological and morphological changes in the leaves, stem, and roots. (Laura Rosso, 2023)

Poplar is regarded as one of the temperate woody plant species which is most susceptible to drought-induced Embolism (William R. L. Anderegg anderegg, 2016). ‘Embolism’ is a tree physiological phenomenon formation influenced by the chemical compositions of water, surface tension in the xylem sap, the degree of tension in the water column and the anatomical and physiological characteristics of wood, including pit characteristics, diameter, length, and the connectivity of conduits (R. Monclus, 2009). Embolism vulnerability varies depending on the species and tissue (Steven Jansen, 2009). However, there have also been reported of varying stress susceptibilities in poplar species within individual trees and the hydraulic functionalities of poplar can be impacted by different environmental conditions (Stettler, 1996; William R. L., 2016; J. S. SPERRY, 1991).

1.4 Thinning and drought effects on poplar plantation

Thinning has a positive impact on tree growth and vigour in seasonal drought events by reducing stand density and leaf area. By decreasing inter-competition for water, better recovery characteristics can be achieved than in more competitive stands (Tetiana Svystun, 2024). In deciduous tree species like hybrid aspen a moderate thinning response to volume increment have been reported (Cabon, 2018) because they can grow rapidly in response to the emergence of competition. For extreme drought events thinning treatments are absolutely impactful for tree growth as well as survival of trees. In lower density plantation where the competition is lower for tree growth, trees show lower mortality and lower growth reduction than the highly dense plantation areas (Nguyen, 2018). A forest's canopy density and other microclimate factors might also change as a result of thinning, which have an impact on understory biodiversity as well (A. Juodvalkis, 2005).

1.5 Dendrochronological Analysis

Tree rings analysis is certainly crucial in finding several effects on growth like climatic or thinning on any kind of tree species. However, there are some factors not like climatic factors such as pests, sunlight exposure, soil nutrient characteristics, tree species, age, management, etc. effects are complicated to analyse in dendrochronological way. The impact of slow changes in climatic variables on tree growth can be seen with the help of this kind of analysis (Archana Gauli, 2022). Using dendrochronological analysis, it is possible to get detailed information about the long-term impacts of climatic influence on tree growth by retrospective of tree ring parameters (Ye Li, 2023). Tree-ring width (TRW) is the most often used parameter for these types of studies, while radial increment is at a certain point in the growing period and may be influenced by multiple factors (Šēnhofa S., 2015). The usual method for achieving this to create a tree-ring chronology from each unique tree ring series that is available. This enables for the identification of climate signals that influence the growth pattern of trees (Speer, 2010). Stronger and long-lasting reconstructions of important indices like temperature and precipitation are produced by compilation of tree core data and improvements in the statistical analysis of the tree rings data (Helama, 2004).

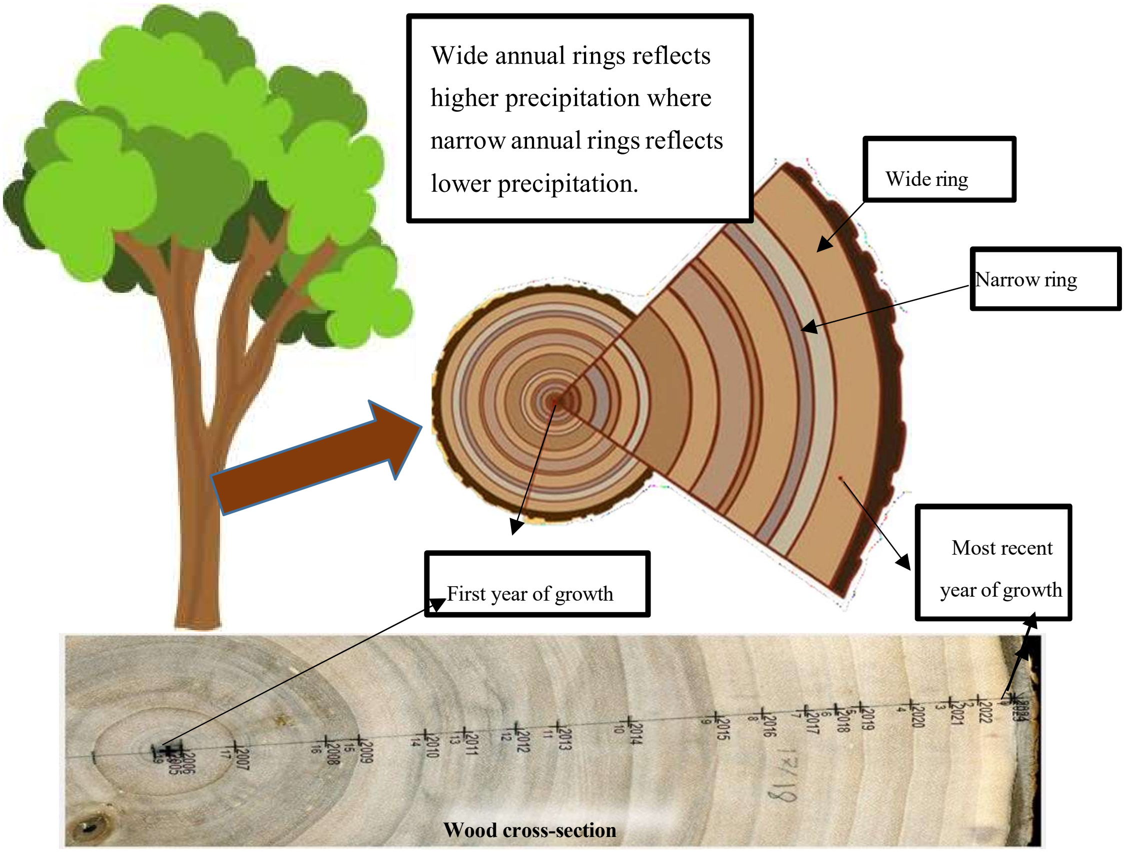

Figure 4. Dendrochronological analysis from wood sections.

Tree ring width varies among species and site conditions, providing means of evaluating how different tree species grow in response to climate change (Schweingruber, 1996). In Figure 4, we can see that, tree rings react with the higher and lower precipitation. *D. Eckstein, 1989* also mentioned that, the tree rings tell a story about the life of the tree and its growing environment. Tree rings act as organic repositories of historical climatic data, enabling the reconstruction of past climates. Since early 20th century, tree rings have been specifically used for temperature and precipitation variability reconstructions, tree-ring-based drought reconstructions and several other purposes (Chris Forman, 2021).

In response to periodic variation in climatic drivers of tree development phenology, temperate and boreal tree species have a yearly growth cycle that alternates between stages of summer growth and winter dormancy. Annual rings are formed as a result of the seasonal periodicity of climate effects on stem growth processes (Sten Gillner, 2014). Dendrochronology, the study of tree rings, sheds light on the seasonal timing of growth interactions (Chhin, 2010). Nonetheless, species-specific knowledge regarding different climatic conditions is quite limited or lacking in some important cases. Poplar in central Europe, where poplar is treated as a valuable tree species for biomass and pulp production. To maintain sustainable management of poplar plantations, there is an increasing need to identify critical climatic and eco-physiological mechanisms, along with the recovery and resistance levels of the species (K. R. Briffa, 1983).

1.6 Study objectives

In 2018, Sweden experienced an unusual dry spell, uncommon in its typical weather patterns, marked by significantly reduced precipitation and higher temperatures, leading to what was deemed as severe drought. This dry period had noticeably impact on the natural environment, including tree growth. This study aims to investigate the effects of drought on the inter-annual growth rates of fast-growing poplar species previously planted in a research plot in southern Sweden at Sångletorp, Skurup.

1.6.1 Research Questions

Research questions are as below:

1. How did the drought affect the annual growth rates (in volume increment (VI) and Basal Area Increment (BAI)) of fast-growing poplar plantation?
2. How did the thinning treatments affect the tree growth during drought?
3. How different trees sizes respond to overcome the growth loss due to the drought period?

2. Methodology

2.1 Study Area

The study was carried out at Sångletorp, which is an agricultural site close to Skurup in southern Sweden, with latitudes 55° 33' 26.3"N and longitude 13° 28' 59.7"E. In 1992, the first rotation of the commercial Poplar plantation was developed with poplar clone OP42 (*Populus maximowiczii Henry × P. trichocarpa Torr. and Gray*). Then, in a square pattern of 3 × 3 m was used to plant bare-rooted plants and the density of the plantation was 1100 stems per hectare. In September 2004, the 14 years old stand was harvested. Stump remnants were left after harvest to promote root and stump sprouts and subsequent regeneration. After 7 years, in 2011, the first thinning practice was done in four categories. Depending on the stem numbers per hectare thinning treatments were named after; (1) Unthinned control: average stand density 6000 stems/ha, (2) light thinning: average stand density 3000 stems/ha, (3) medium thinning: average stand density 1100 stems/ha and (4) heavy thinning: average stand density 550 stems/ha. In the experiment, total 16 plots were divided into four blocks, one for each of the treatments. Each of the plots was 24 by 24 meters including a buffer zone of 6 meters between treatments, had two rows of trees that received the same treatments as plot next to them.

Figure 5. Plantation Site, Sångletorp, Skane Lan, Sweden.

2.2 Climate Data

Annual precipitation and temperature data were collected from the closest observational station operated by the Swedish Meteorological and Hydrological Institute (SMHI) at Lund (25 km from Sångletorp) in order to evaluate the research site climatic condition at research site (2007-2023)

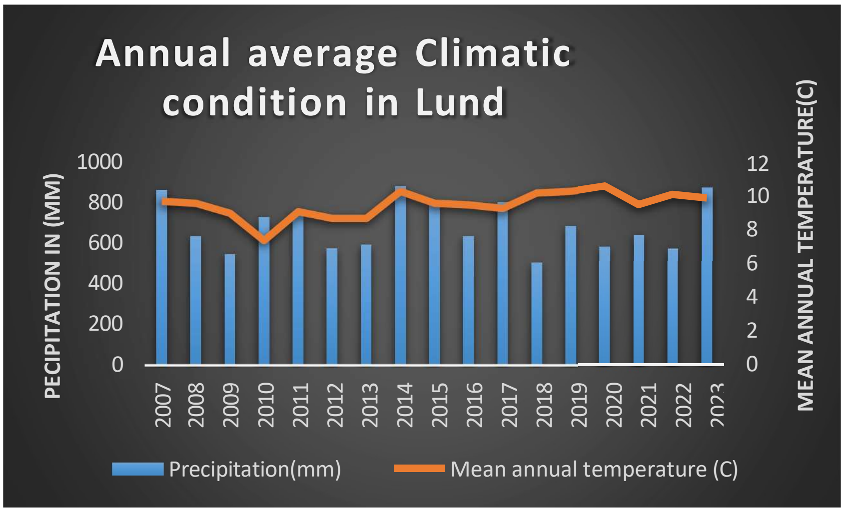

Figure 6. Inter-annual precipitation and temperature of SMHI weather station Lund (25 km from the experimental site)

2.3 Sampling and developing chronology

In June 2023, samples were collected from the stands, with trees categorized into four different diameter classes within each of the four thinning treatment blocks: unthinned control, light thinning, medium thinning, and heavy thinning. The diameter classes were defined as follows: tree 1 (dbh 9-11 cm), tree 2 (dbh 15-18 cm), tree 3 (dbh 20-22 cm), and tree 4 (dbh 25-35 cm). A total of 36 trees were sampled for analysis. From each tree, 5 to 10 discs were taken in every 2-3 meters of the total tree height, depending on the tree sizes. For smaller diameter trees, the distance between two discs were 2 meters and for bigger diameter trees it was 3 meters. Additionally, the diameter at breast height and the total height of the sample trees were measured.

Discs were air-dried and polished in the sanding machine to make the rings visible. After that the discs were examined under a stereo microscope for a clear identification of every tree rings. Then discs were scanned (model of the scanner: Epson Perfection V300 Photo) to take the image format of the rings for gathering tree rings chronologies. During the scanning the resolution was 2400 dpi. Each disc was scanned in two radii (A and B). The Coorecorder software was used for cross-dating and annual tree ring width (TRW) analysis with the precision of 0.001mm. During a particular TRW measurement there were some uncertain situations due to the tree ring structure (narrow rings and/or false rings), so the wood discs were also additionally checked under light microscope. Using Cdendro the cross-dated files were accumulated in each different files for different trees which data used in R for further statistical analysis. Tree ring width series from Cdendro were carefully checked and then statistically verified for cross-dating using the dendrochronology program library in R (dplR) (Dendrochronology, 2023).

2.4 Calculation of Drought Response to Tree Growth

The resistance power (deltaDiv) of trees was calculated using the ‘treeglia-1.0.1’ package (Huili Wu, 2023). Here, the tree ring data were formatted in a single tree basis. Then a hypothetical function ‘fun.dating.recovery’ was used to identify the specific year when tree growth returns to its projected trajectory following a disturbance event. Here, the single tree data was used to calculate yearly projected and observed growth values. The function iterated through the data, calculating the relative difference deltaDiv= (projected growth –observed growth)/observed growth). If the deltaDiv falls below the threshold (0.05) recovery considered complete and for no recovery the function commanded to returned to 0. Then a generalized mixed effect model was used to find the growth loss due to the drought period using the deltaDiv values. Here, tree size and thinning treatments both were used as a random effect. To estimate the marginal means for the interaction effects between ‘Tree Size’ and ‘Treatment’, emmeans is used (Lenth, 2021), ggplot2 is used for plotting and for model fitting lme4 R package is used. All statistical analysis is conducted in R version 4.3.3 (Team, 2021).

3. Result

3.1 Volume Increment

The analysis of volume increments was aimed on understanding the effects of drought on tree resilience (the capacity to recover). The volume increments of all trees across various thinning treatments (unthinned control, medium thinning, light thinning, and heavy thinning) showed a significant overall effect. However, the response varied by thinning treatment: heavy thinning had a significant effect on volume increment, while the other treatments did not provide sufficient evidence to reject the null hypothesis for the response variable.

Table 1. ANOVA table of volume increment.

Thinning Treatments	P-value		Tree Sizes	P-value
Overall	***		Overall	***
Unthinned control(6000trees/ha)	n.s		dbh 9-11 cm	*
Light thinning(3000trees/ha)	n.s		dbh 15-18 cm	n.s
Medium thinning(1100trees/ha)	n.s		dbh 20-22 cm	n.s
Heavy thinning(550trees/ha)	*		dbh 25-35 cm.	*

Across all thinning treatments (Unthinned control, Medium, Light and heavy thinning) and in all different tree sizes (dbh 9-11 cm; dbh 15-18 cm; dbh 20-22 cm and dbh 25-35 cm).

Note: (*** = p<0.001, ** = p<0.01, * = p<0.05, n.s. = p>0.05)

3.1.1 Volume increment of different diameter groups

Trees with diameter 9-11 cm subjected to various thinning treatments (unthinned control and light thinning), displayed a decline in volume increments during the drought in 2018 (Figure 7.A). This reduction persisted in the subsequent years, indicating a continuous decrease in volume increment. Similarly, the trees belonging to dbh group 15-18 cm, showed a reduction in volume increment as the effect of the drought. In contrast, this diameter group showed a gradual increase in volume growth the years following the drought.

Trees of group dbh 20-22 cm (Figure 7.C) exhibited the growth decline for the drought period and a recovery during the post-drought period. Largest trees (dbh 25-35cm) exhibited a decline in volume increment during the drought period. However, their increased VI after the drought in the following years can mean that they are resilient to drought (Figure 7.D).

In a summary, trees with dbh 9-11 cm experienced a decline in volume increments, which persisted subsequent, indicating continuous decrease in volume growth. For trees in 15-18 cm dbh group, a reduction in volume growth due to the drought was also observed, but here trees exhibited a gradual recovery in the post-drought period. This was further observed for trees with dbh 20-22 cm and the largest trees (dbh 25-35cm) displaying a decline in volume during the drought, followed by a recovery after drought.

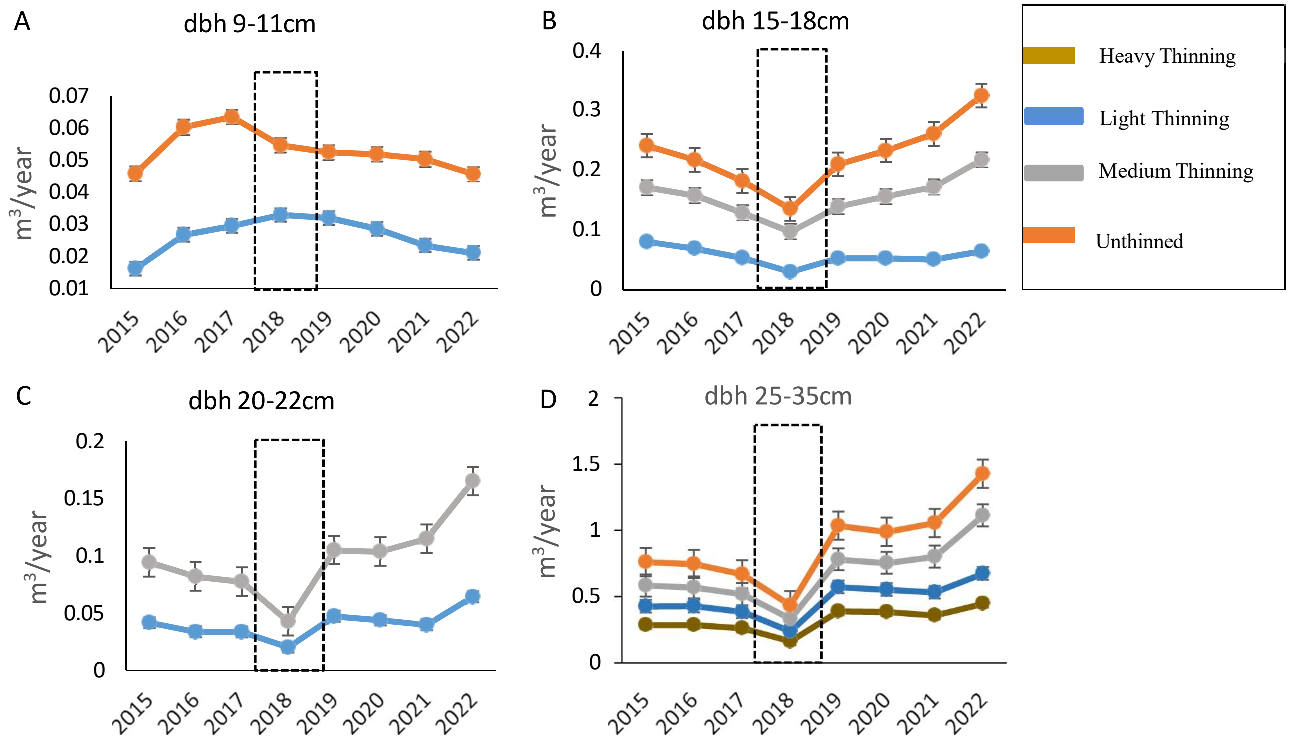

Figure 7. Volume increment across different tree sizes; (A) tree (dbh 9-11 cm), (B) tree (dbh 15-18 cm), (C) tree (dbh 20-22 cm) and (D) trees (dbh 25-35 cm); dotted box represent VI at drought period.

3.1.2 Volume increment in different thinning treatments

In the unthinned control thinning treatment, trees with a 25-35 cm diameter exhibited a reaction to the drought effect, while trees with a dbh 9-11 cm and dbh 15-18 cm were not as responsive to the drought period. After the stress period, the larger trees with a 25-35 cm diameter showed a recovery, while the smaller trees followed their normal growth increment (Figure 8.A).

In light thinning treatment all four tree sizes were present. Here, the largest trees (dbh 25-35 cm), trees with dbh 20-22 cm and dbh 15-18cm dbh showed growth decline to the drought period. The diameter group (dbh 9-11 cm) following their normal growth curve before drought, thus no response to drought was found (Figure 8.B).

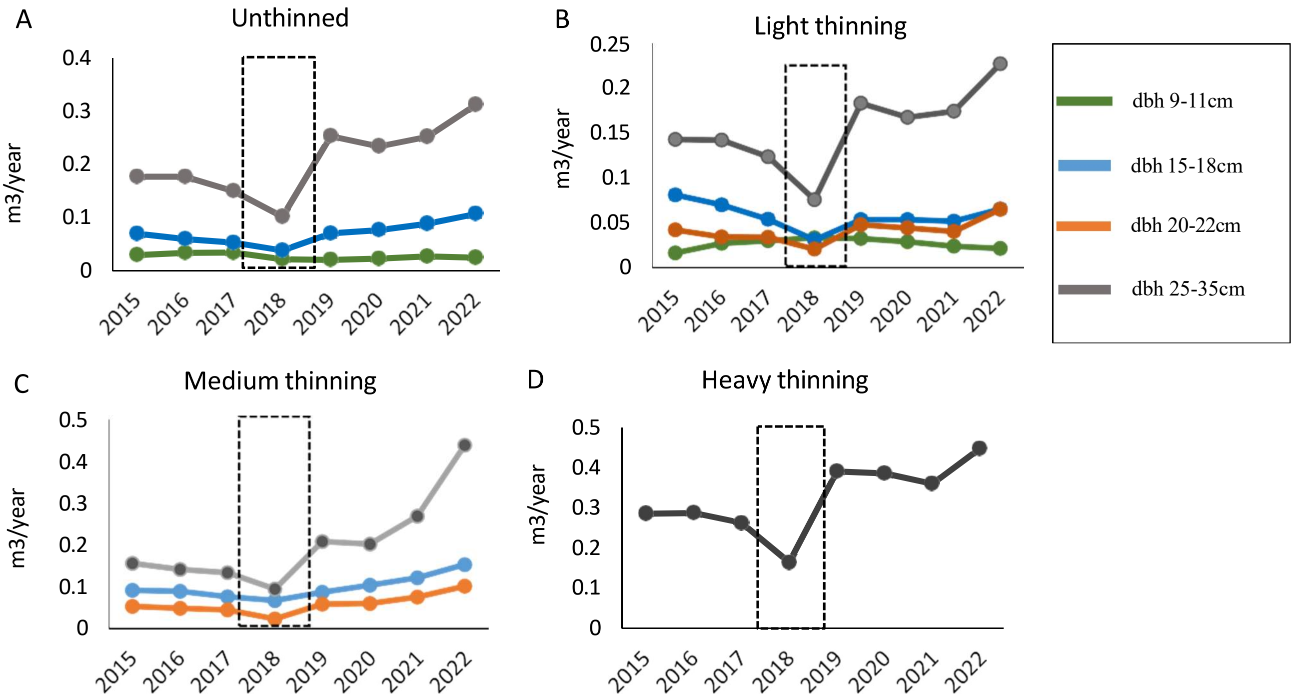

Figure 8.Volume increment across different thinning treatments; (A) Unthinned control (6000trees/ha.), (B) Light thinning (3000trees/ha.), (C) Medium thinning (1100trees/ha.) and (D) Heavy thinning (550trees/ha.); dotted box represents drought period.

In the medium thinning (Figure 8.C) trees with dbh 15-18 cm, 20-22cm and 25-35cm showed the similar result, while trees with dbh 25-35 cm showed a reduction to drought followed by a recovery and the trees of other diameter groups were less responsive to drought and the following recovery. In the heavy thinning treatment, trees with dbh 25-30 cm showed clear response to the drought effect followed by a increased growth in the post-drought period as well (Figure 8.D).

To summarize the overall volume increment across different thinning treatments and in unthinned control, only trees with dbh 25-35 cm trees showed significant drought response and recovery, while smaller trees (9-11cm) were less affected. In medium thinning treatment similar trend was visible, trees with dbh 25-35 cm showed a growth reduction during drought with an increasing pattern after drought, and smaller trees being mostly unaffected. Light thinning affected mainly 25-35 cm trees, with minor impact on 15-22 cm trees, while 9-11 cm trees maintained normal growth. In heavy thinning, the largest trees (dbh 25-35 cm) showed clear drought response and quick recovery.

3.2 Basal Area Increments

Statistically, the basal area increments (BAI) in this study revealed significant effects in response to various thinning treatments. The BAI results have been interpreted with an emphasis on the trees' resilience, specifically their capacity to recover from the drought experienced in 2018.

Table 2. ANOVA table of Basal Area Increment.

Thinning Treatments	**P- value**		**Tree Sizes**	**P- value**
Overall	***		Overall	*
Unthinned control(6000trees/ha)	*		dbh 9-11 cm	n.s
Light thinning(3000trees/ha)	n.s		dbh 15-18 cm	n.s
Medium thinning(1100trees/ha)	n.s		dbh 20-22 cm	n.s
Heavy thinning(550trees/ha)	**		dbh 25-35 cm	n.s

Across all thinning treatments (Unthinned control, Medium, Light and heavy thinning) and in all different tree sizes (dbh 9-11 cm, dbh 15-18 cm, dbh 20-22 cm and dbh 25-35 cm).

Note: *** = $p<0.001$, ** = $p<0.01$, * = $p<0.05$, n.s. = $p>0.05$

3.2.1 Basal Area Increment of different diameter groups

Trees with dbh 9-11 cm did not show any change in the basal area increment (BAI) during the drought period and followed a normal characteristic in BAI in control and light thinning treatments (Figure 9.A). In trees with (dbh 15-18 cm), graph showed a reduction in BAI during the drought (2018) in all thinning treatments following a post-drought recovery. BAI at medium thinning treatment showed higher value in this dbh group (15-18 cm) than unthinned and light thinning treatments (Figure 9.B).

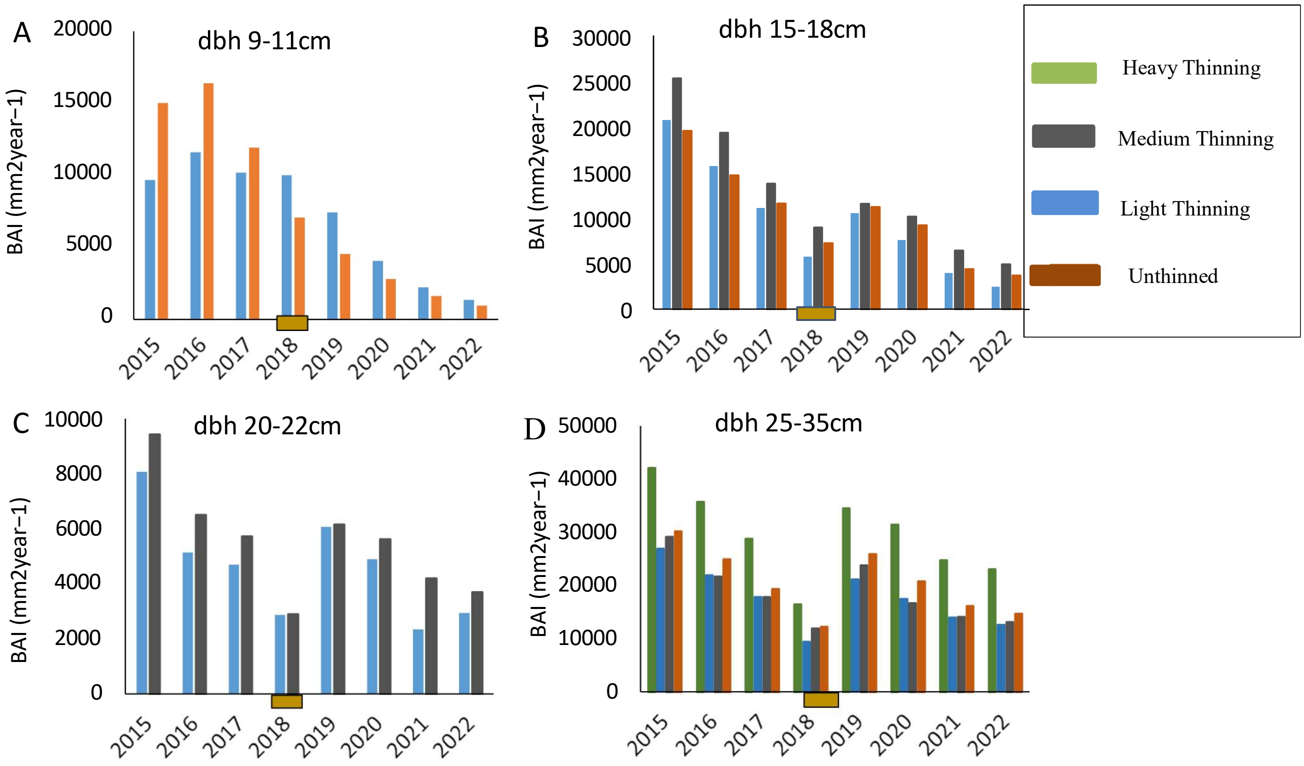

Figure 9.Basal Area Increment (BAI) across different tree sizes; (A) tree 1(Diameter 9-11 cm), (B) trees 2 (Diameter 15-18 cm), (C) tree 3(Diameter 20-22 cm) and (D) trees 4 (Diameter 25-35 cm).

Trees with dbh 20-22 cm showed a reduction in the drought period followed by a recovery after the disturbance in a similar way to both light thinning and medium thinning treatments (Figure 9.C).

In biggest trees (dbh 25-35 cm), in all treatments (unthinned control, light thinning, medium thinning and heavy thinning) trees showed a reduction in basal area increment during the drought with an increasing BAI after the drought (Figure 9.D). Here, trees in heavy thinning treatments represented higher proportion in BAI, than the medium, light and control thinning treatments.

To sum up, trees with smaller diameters (dbh 9-11 cm) showed no effects in BAI during the drought period, while trees with dbh 15-18 cm, 20-22 cm and 25-35 cm exhibited a reduction in BAI followed by a post-drought recovery. BAI at heavy thinning treatments with the largest trees demonstrated a higher increment in basal area after the drought among all.

3.2.2 Basal area increment in different thinning treatments

In unthinned control plot, trees with dbh group 9-11 cm, 15-18 cm and 25-35 cm, showed a reduction in BAI due to the drought. However, trees with dbh 25-35 cm showed a higher recovery at the post-drought period than the trees with dbh group 9-11 cm and 15-18 cm (Figure 10.A).

All trees with dbh groups (9-11 cm, 15-18 cm, 20-22 cm and 25-35 cm) in light thinning treatment, showed a reduction during the drought period followed by a recovery after the drought. Largest trees (dbh 25-35 cm) showed higher BAI compared to the other diameter groups in this thinning treatment (Figure 10.B).

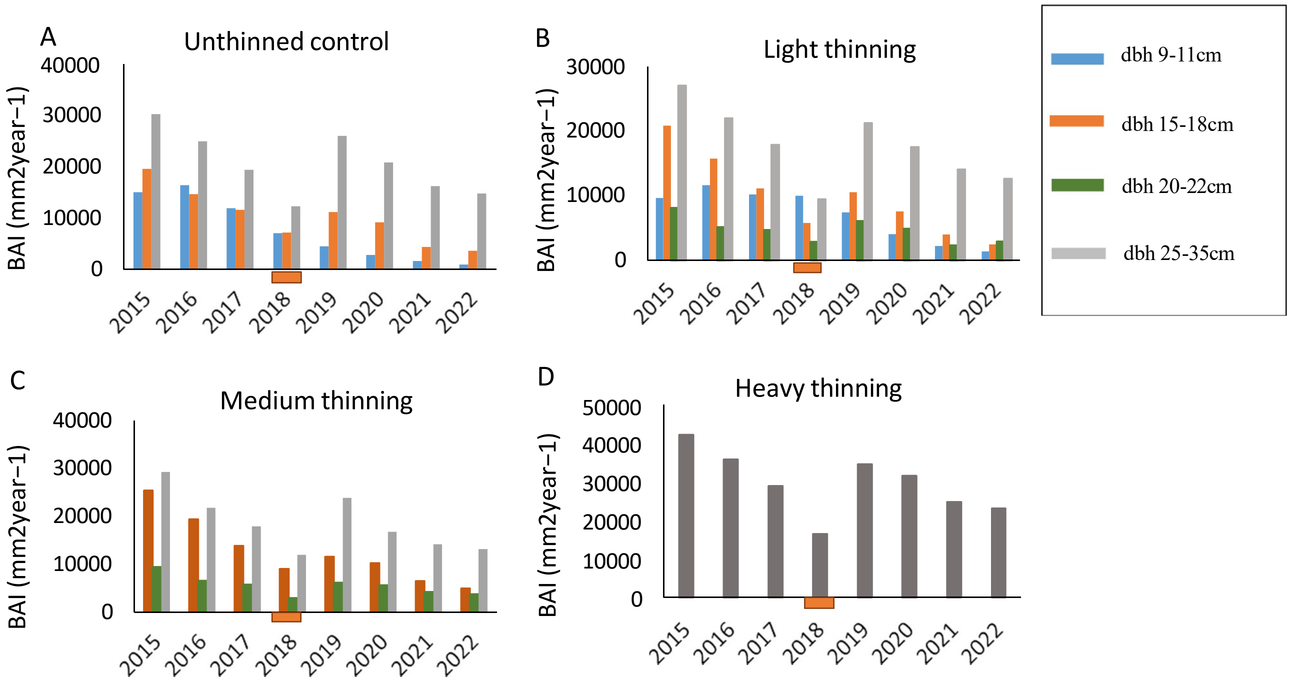

Figure 10.BAI across different thinning treatments; (A) Unthinned control (6000trees/ha.), (B) Light thinning (3000trees/ha.), (C) Medium thinning (1100trees/ha.) and (D) Heavy thinning (550trees/ha.).

In medium thinning treatment, trees with dbh 15-18 cm, dbh 20-22 cm and dbh 25-25 cm (Figure 10.C), showed a reduction in basal area increment in 2018. However, only trees with dbh 15-18 cm and dbh 25-35 cm showed a recovery after the drought.

In heavy thinning treatment, trees with dbh 25-35 cm showed also similar trend of reduction during the drought condition and a gradual recovery at the post-drought period (Figure 10.D).

To recap, the largest trees (dbh 25-35 cm) showed higher recovery in BAI after drought period in 2018 in every management practices. For BAI, other trees with (dbh 9-11 cm, dbh 15-18 cm and dbh 20-22 cm) did not show an overcome from the reduction at the post-drought period.

3.3 Drought response to growth (Resistance to drought)

In case of analysing the drought responses to the tree growth, different tree sizes reacted differently to their drought recovery trajectories. On the other hand, thinning treatments were not significantly different in different thinning treatments, they were similar in four treatments (Table.3).

Table 3. ANOVA of tree growth responds to the drought effects.

Variables	**p-value**
Tree Size	***
Treatment	n.s

Note: *** = $p<0.001$ and n.s. = $p>0.05$(Variance Table with Satterthwaite's method)

3.3.1 Drought response along the gradient of tree size

The deltaDiv value represents the resistance power of trees to drought. The lower the deltaDiv value, the higher the tree is resistant to drought. As a result, the trees with dbh 25-35 cm were the least resistant to the drought recovery. Additionally, bigger trees in control thinning treatments (deltaDiv=~0.8) showed more vulnerability to drought. Conversely, smaller trees (dbh 9-11 cm) in control plot showed the highest resistance power to drought with deltaDiv value around 0.28, where smaller trees in light thinning plots showed deltaDiv =~0.5.

However, in light thinning treatment the trees with dbh group 15-18 cm showed more resistance than trees in medium thinning treatment and control plots. In overall, smaller trees were less responsive to drought than the larger trees (25-35 cm) in the sense of potential tree growth loss (Figure 11), which means that the resistance power of the smaller trees is more than of the larger diameter trees.

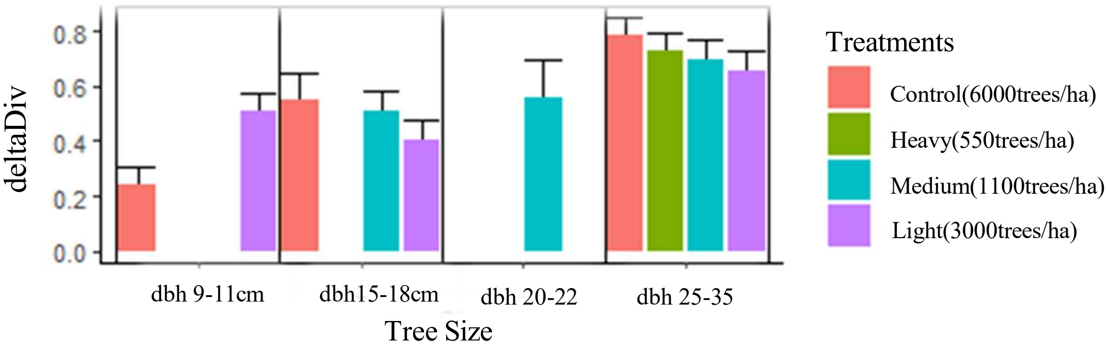

Figure 11.Drought response to the tree growth in across the tree size.

Here, deltaDiv= (projected growth-observed growth)/observed growth, different thinning treatments are Unthinned control, Heavy thinning, Medium thinning and Light thinning; different tree sizes presented according to different dbh groups such as dbh 9-11 cm; dbh 15-18 cm; dbh 20-22 cm and dbh 25-35 cm.

3.3.2 Drought response along the gradient of thinning treatments

The drought response to tree growth loss in different thinning treatments showed variances in different tree sizes. In control plot (6000 stems/ha), smaller diameter trees (9-11 cm) showed higher resistance to drought than the bigger trees (dbh 25-35 cm). However, smaller trees are not always the winner for drought resistance in every thinning treatment; for example, in light thinning treatment the diameter group 15-18 cm showed more resistance than the smaller (dbh 9-11 cm) trees. Conversely, the larger trees (25-35 cm) showed lower resistance power in every thinning treatment (Figure 12).

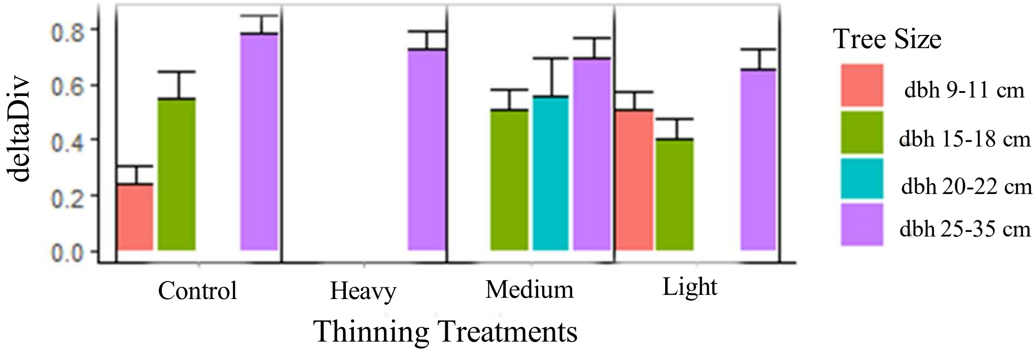

Figure 12.Drought response to the tree growth in across the thinning treatments;

Here, deltaDiv= (projected growth-observed growth)/observed growth, the lower the delaDiv value the higher the drought resistant; different thinning treatments are Unthinned control, Heavy thinning, Medium thinning and Light thinning; different tree sizes presented according to different dbh groups such as dbh 9-11 cm; dbh 15-18 cm; dbh 20-22 cm and dbh 25-35 cm.

Discussion

The result of the study shed light on the intricate dynamics of tree growth, particularly in response to drought stress (2018), within a second rotation poplar plantation in southern Sweden. Our findings revealed resilience from volume and basal area increments and resistance as deltaDiv across different thinning treatments and tree sizes, which represented notable impacts observed during the drought in 2018 in Sweden. The growth pattern in volume increment (VI) and basal are increment (BAI) focuses on the resilience (the capacity to recover) power of trees. It encompasses a decline period during drought with an increasing period after the drought and the changes have been defined as post-drought growth/pre-drought growth. It represents the capability of a tree to overcome from a stress (drought). Where resistance represented as the ability to stay largely unchanged characteristics in a stress (drought); the lower the deltaDiv value, the higher the resistance has shown in this study.

Combining BAI and volume increment measures allows for a more comprehensive assessment of tree growth. While BAI focuses on radial growth, volume increment accounts for the total increase in wood volume, providing a more complete picture of tree growth dynamics (Pretzsch, 2009). Basal area increment analysis, complemented by volume increment measurements, is crucial for assessing the effects of drought on tree growth in second rotation poplar plantations. This integrated approach provides detailed and comprehensive insights into tree growth dynamics, enabling better-informed management decisions to enhance forest resilience and productivity in the face of increasing drought frequency and severity.

The variances observed in volume increments across different thinning treatments underscore the sophisticated relationship between forest management practices and tree growth dynamics, particularly in the drought stress (Table 1). Poplar is vulnerable to the water stress (Laura Rosso, 2023), which has also been observed in this study through reduction in volume growth. The pronounced decline in volume increment during the drought period is indicative of the direct impact of water scarcity on tree physiological processes, including photosynthesis and transpiration (Têtè Sévérien Barigah, 2013).

The differential responses among thinning treatments further emphasize the importance of management strategies in mitigating the adverse effects of drought on tree growth. Heavy thinning, for example, exhibited decrease in volume increment, with a recovery after the drought stress (Table 1, Figure 8). Which suggests that the reduction in stand density may have alleviated completion for limited water resources, thereby enabling the remaining trees to maintain relatively higher growth rates despite adverse environmental conditions (Nguyen, 2018) (Tetiana Svystun, 2024). Conversely, the lack of overcoming for volume increment during and after the drought period in the unthinned control and light thinning treatments highlights the potential of overcrowding and competition-induced stress, intensifying the negative impacts of drought on tree growth (Julia A. Sohn, 2016)

The differential volume growth also observed among tree sizes (Figure 7) further emphasizes complex interplay between tree physiology and environmental stressors. A volume growth reduction in smaller and larger diameter trees during drought period highlight their heightened susceptibility to water stress (Mathias Steckel, 2020). Having said that, this study also revealed the recovery is higher in larger diameter (dbh 25-35cm) trees than the smaller (dbh 9-11cm) due to drought, which represented their resilience power in this study. Conversely, in the Figure 7.A, we can see that, trees with dbh 9-11 cm in unthinned plot showed lower growth without an increment at post-drought period where a normal growth has been observed in light thinning treatment. Which means that, the resilience or overcoming capability of smaller trees are lower than of the larger trees, however, smaller trees in light thinning treatment represented its resistance power (ability to stay unchanged or less affected even in stress due to drought) according to the deltaDiv calculation (Figure 11).

3.4 Basal Area Increment

The significant effect of basal area increments in different thinning treatments and tree sizes (Table 2) underscores the multifaceted nature of tree growth response to environmental stressors. The observed variations in basal area increment among thinning treatments reflect the complex interplay between stand density, resource availability and tree physiological responses to drought stress. While heavy thinning and unthinned control treatments exhibited significant basal area increments, medium thinning and light thinning treatments did not show significant effects, suggesting that intermediate stand density may have provided optimal conditions for growth under drought condition (William R. L. Anderegg, 2020) (Adrian Dănescu, 2018)

Furthermore, the differential responses observed across tree sizes highlight the importance of considering intra-specific competition and resource allocation dynamics in understanding growth patterns in second rotation poplar plantations. The basal area reduction during the drought period followed by gradual recovery means that the resilience is in larger trees (Figure 9.D), which may have greater access to deep soil moisture reserves and exhibit physiological adaptations to water stress; for instance, trembling aspen increases its drought tolerance by growing its branches more stronger with more dense carbon and more leaf tissues (Leander D. L. Anderegg, 2016). In contrast, smaller trees may experience greater susceptibility to drought-induced growth limitations (Figure 9.A), highlighting the need for targeted management interventions to enhance resilience and promote growth recovery in these size classes. However, the subsequent recovery in BAI during favourable post-drought conditions indicates the resilience of trees to bounce back from water stress (Figure 9).

3.5 Drought Response to Growth in poplar plantation

The assessment to drought response (resistance), as indicated by deltaDiv, provides valuable insights into the adaptive capability of second rotation poplar plantation in southern Sweden. The observed deltaDiv (the lower the deltaDiv value, the higher the tree resistance to drought) values highlight the varying levels of drought resistance across different tree sizes, underscoring the complex interactions between the tree physiology and environmental stress. Our findings indicate that smaller trees, particularly those with a dbh of 9-11 cm, exhibit a higher resistance to drought, as evidenced by their lower deltaDiv values (Figure 11).

Conversely, larger trees (dbh 25-35 cm) showed lower resistance to drought across all thinning treatments, with deltaDiv values nearing 0.8. This greater susceptibility may be attributed to several factors, including the higher water demand and greater hydraulic stress experienced by larger trees during drought conditions (Nate McDowell, 2008). The inability of larger trees to sustain growth during drought periods underscores the critical need for targeted forest management practices aimed at mitigating drought impacts on these vital components of forest ecosystems.

Across all thinning treatments, the relationship between tree size and drought resistance is not straightforward. For instance, in light thinning treatment, trees with a dbh of 15-18 cm exhibited higher resistance than both smaller (9-11 cm) and larger trees (25-35 cm) (Figure 12). This suggests that intermediate-sized trees may benefit more from reduced competition for resources such as water, which is particularly critical during drought conditions (Aussenac, 2000).

Interestingly, the lower resistance observed in larger trees across all thinning treatments highlights a consistent trend of increased vulnerability among the largest individuals, irrespective of stand density. This could be indicative of the inherent physiological limitations of large trees under water-limited conditions, further exacerbated by thinning-induced environmental changes (Melanie J. B. Zeppel, 2015).

3.6 Implications for Forest Management

The differential drought resistance observed across tree sizes and thinning treatments has important implications for forest management strategies, particularly in the context of increasing frequency and severity of droughts due to climate change. The higher resilience of smaller trees suggests that maintaining a diverse age and size structure within forest stands could enhance overall forest resilience to drought. Furthermore, selective thinning that prioritizes the retention of intermediate-sized trees may optimize water use efficiency and reduce competition, thereby enhancing the drought resilience of the entire stand.

Our results also highlight the necessity of customized management practices that consider the specific vulnerabilities of larger trees. Given their ecological and structural importance, strategies such as supplemental watering, mulching, or soil amendment could be explored to support the health and survival of larger trees during prolonged drought periods.

4. Conclusion

In conclusion, this comprehensive study delves into the intricate dynamics of tree growth, focusing on the responses of second rotation poplar plantations in southern Sweden to drought stress. This analysis was conducted by examining the annual growth rings of selected trees, which were chosen from four different thinning treatments and four different size classes. A growth model was used to determine the drought response of tree growth, with thinning treatments and tree sizes as the explanatory variables. This assessment provides valuable insights into the impact of the 2018 drought in southern Sweden.

The findings underscore environmental stressors and tree physiological responses. The larger diameter trees (25-35 cm) showed better resilience (the capacity to recover) after drought period than the smaller diameter trees (9-11 cm). Heavy thinning (550 trees/ha) treatment demonstrated a higher volume and basal area increments after the drought period, suggesting the potential for optimizing stand density to mitigate the adverse impacts of drought. However, in terms of plant resistance power, the result was opposite, which means that the smaller trees showed more ability to remain largely unchanged during drought than the bigger ones. For example, trees with dbh 9-11 cm showed more growth resistance facing the drought than the trees with dbh 25-35 cm, which highlight size-dependent vulnerabilities and recovery trajectories.

Overall, this study contributes to a deeper understanding of the complex interactions between management interventions, environmental factors and tree growth dynamics by analysing tree rings in plantation forestry systems. The insight gained hold significant implications for evidence-based decision making and adaptive management strategies aimed at enhancing growth resilience and sustainability in the context of escalating climatic variability and uncertainty.

Moving forward, the significant potential of poplar species necessitates further studies tailored to address climatic challenges. Additionally, in-depth research into the underlying mechanisms and the development of holistic modelling approaches will be crucial for optimizing forest management practices. These efforts are essential to foster resilience in tree populations worldwide.

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Popular science summary

How Second Rotation Poplar Plantations React to Drought?

By Farjana Tanjim

Poplar trees, commonly used as a Short Rotation Crop for biomass or fuel wood production, are widely favored due to their fast growth and adaptability to various site and weather conditions. These trees are increasingly planted on agricultural lands for their quick yield. However, climate change poses significant challenges, particularly drought, which severely impacts tree growth and survival. The 2018 drought in Sweden, for instance, had notable negative effects on tree growth.

In my project, I examined how a second rotation poplar plantation, which began coppicing after 2004, responded to the 2018 drought. The study was conducted at Sångletorp, Skurup, in southern Sweden, with samples collected in 2023. Trees were taken from four different thinning treatments: control thinning (6000 trees/ha), light thinning (3000 trees/ha), medium thinning (1100 trees/ha), and heavy thinning (550 trees/ha). Four tree size categories were selected based on diameter at breast height (dbh) for analysis; the different tree sizes are: dbh 9-11 cm, dbh 15-18 cm, dbh 20-22 cm, and dbh 25-35 cm.

Using dendrochronological analysis (examining tree rings), I identified growth patterns influenced by precipitation. Wider rings indicate higher rainfall, while narrower rings reflect lower rainfall. During the analysis, the rings from the 2018-2019 growth period were notably narrow, indicating reduced growth due to drought. I also assessed the trees' recovery by measuring volume increment and basal area increment, revealing how they responded to water stress.

The Volume Increment (VI) and Basal Area Increment (BAI) results aimed to focus on the drought period to find the resilience (capacity to recover) of trees due to drought. It has been revealed that the larger trees (dbh 25-35 cm) has higher recovery or resilience characteristics than the smaller diameter (9-11 cm) trees. However, the resistance (the ability to remain largely unchanged) to drought has been showed by the smaller trees (dbh 9-11 cm) is higher than the larger trees (dbh 25-35 cm).

This study provides valuable insights into the complex interactions between management practices, environmental factors, and tree growth dynamics. These findings can guide the development of poplar plantations that are more resilient to drought. It is clear that a strategic combination of management approaches can enhance the resistance and resilience of these plantations, ensuring sustainable growth despite changing climate conditions

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Alnarp, 2024

Publishing and archiving