Productivity of 15 poplar clones in short rotation forestry

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Abstract

Short Rotation Forestry (SRF) employing fast-growing tree species such as poplars is recognized as a sustainable strategy to address the growing demand for renewable energy. While Europe lags behind South America in plantation forestry, there's a growing trend, especially in Northern Europe, driven by factors like carbon neutrality goals and agricultural land availability. To reach the zero carbon emission goal, biomass could play key role in production of high performing clones. An experiment conducted in Skåne, Sweden, evaluated 15 poplar clones across 43 plots over a ten-year period, with biometric parameters measured annually and additional data collected in 2024 to enhance the dataset.

Results indicate variability in biomass production, mortality rates, and growth trajectories among the evaluated clones. Skado, OP-42, and S23K9040089 are the top-performing clones, while Baldo, AF 34, and Brenta are the least productive. Production dynamics are strongly influenced by mortality rates, where lower mortality correlates with heightened yields. My final results further suggest that rotation length of 10-15 years provides faster financial returns and mitigate wind damage risk, which is a common concern in Southern Sweden. Diversification in clone selection enhances plantation resilience, with cultivars like Skado demonstrating promising performance.

SRF with poplars offers advantages in biomass production, particularly on agricultural land. Clone selection is crucial, with certain hybrids showing better adaptation and productivity. Optimizing stem density and rotation length can enhance efficiency and profitability in SRF. Diversifying clone selection improves resilience and adaptability, reducing vulnerability to pests and environmental stressors. Developing clones better suited to local conditions is essential for the commercial success of SRF using fast-growing poplar plantations in Southern Sweden. These findings provide practical implications for stakeholders seeking to optimize the efficiency and profitability of poplar based SRF initiatives in Southern Sweden, emphasizing the importance of careful clone selection, planting density management, and adherence to optimal rotation lengths. SRF with poplars holds promise for renewable energy production and sustainable land use, with careful clone selection and proper management practices as the key to maximize its benefits.

Keywords: Poplar, *Populus*, cultivars, plantation, productivity, short rotation forestry, biomass, density, rotation, adaptation

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Abbreviations

ANOVA	Analysis of Variance
CAI	Current Annual Increment
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization of the United Nations
MAI	Mean Annual Increment
SRF	Short Rotation Forestry

1. Introduction

1.1 Fast growing plantations

Short Rotation Forestry (SRF) is gaining global recognition as a strategy to meet the escalating demand for energy from renewable resources (Tullus et al. 2013). This silvicultural practice involves the cultivation of fast-growing tree species under intensive management (Johansson & Karačić 2011), presenting a sustainable solution to tackle climate change challenges (Christersson 2010). Fast growing tree plantations with short rotation periods and high harvest rates are considered to be a booming phenomenon worldwide, being a significant way to reduce fossil fuels consumption (Sardón 2012). In South America, plantation forests dominate the landscape, comprising 99% of the total planted-forest area and 2% of the overall forest cover (FAO 2020). European realities however diverge far from what is presented on the new world's continents and exhibit the lowest proportion of plantation forest, accounting for merely 6% of the planted forest estate and a mere 0.4% of the total forest area (FAO 2020). In spite of these facts, there is a notable trend in Europe towards the expansion of plantation forestry, accompanied by an increase in the utilization of roundwood and other ecosystem services provided by these managed forests (Smith et al. 2019). Northern European region exhibits especially promising grounds for that, having area of productive agricultural land to be estimated from 300 000 to 500 000 ha on the example of Sweden (Stener & Westin 2017). In Nordic countries, SRF aligns closely with their commitment to achieving carbon neutrality by 2050 (Stener & Westin 2017), building upon their rich tradition of cultivating fast growing species since the late 1930s (Christersson 1996). In Sweden, a combination of factors such as biofuel shortages (Böhlenius et al. 2023), fluctuations in wood exports from Russia to Europe, extensive unused agricultural land, and evolving concepts of intensified silviculture are serving as key motivators for the cultivation of rapid-growth poplar clones on suitable terrain (Christersson 2010). Thus utilizing fast-growing plantations on a limited portion of the landscape may act as a strategy to alleviate stress on natural forests (Paquette & Messier 2010).

1.2 Poplars' potential

Poplar (*Populus*) species and their hybrids are leading the way in short-rotation forestry due to their fast initial growth rates, widespread availability, significant genetic diversity, ease of hybridization, and high yield of biomass (Guo & Zhang 2010). The majority of these plantations are set up on former agricultural plots that are no longer in use (Truax et al. 2014), and sometimes such plantations are also situated on forested areas (McCarthy et al. 2017). The most common native poplar species naturally thrive along riverbanks and are prevalent across a broad geographic range in North America (including *Populus deltoides* and *Populus trichocarpa*), Europe (*Populus nigra*) (Souch & Stephens 1998), and Asia (*Populus maximowiczii*) (Dickmann 2001).

All poplars planted in the region of northern Europe exhibit a high demand for nutrients and thrive best in well-drained soils with consistent water availability and low acidity levels, typically within a pH range of 5.5 to 7.5 (Tullus et al. 2013). Being one of the fastest-growing tree species in temperate regions, the rapid growth of poplar is linked especially to its high water requirements, making it susceptible to water shortages (Xi et al. 2021). This indicates that poplar trees could be vulnerable to drought conditions (Tschaplinski et al. 1998) because of their limited water use efficiency (Marron et al. 2008). The first years are known to be crucial for the success of poplar plantations due to their high sensitivity to competition from weeds (Tullus et al. 2012). Recent research has found that the choice of seedling type, with emphasis on a properly developed root system, is critical for fast and secure establishment (Böhlenius & Övergaard 2016). Failure is frequently linked to improper soil management methods, inadequate vegetation control, or a combination of these (Böhlenius & Övergaard 2015).

Hybrid poplar plantations have been known to be highly effective in converting solar radiation into chemical energy stored in wood (Stener & Westin 2017). They have been found to react to environmental changes by adjusting canopy structure and leaf development, allowing them to take advantage of the extended growing seasons or favourable environmental conditions (Karačić, 2005). Rapid growth rates and productivity potential of poplars are unfortunately accompanied by many shortcomings, such as vulnerability to stress, insects, and herbivores (Autumn & Pugnaire 1993). Poplars possess the ability to regenerate through the development of numerous stump sprouts and root sprouts; however, the latter are less common (Svystun & Böhlenius 2024). Vegetative reproduction of hybrid poplars in the first generation through shoot cuttings is known to be fairly cheap (Stanton et al. 2019) and simple (Bergante et al. 2016), which may put them in an advantageous position compared to aspen, which is commonly established through micro-propagated clonal plants in the first generation (Tullus et al. 2013). Recent studies show that hybrid poplar plantations can generate substantial biomass on agricultural land not only in the first rotation but also in subsequent ones, which holds promise for expected climate change-induced droughts in Northern Europe (Svystun & Böhlenius 2024). Poplar plantations, particularly those established on arable lands, play a significant role in mitigating anthropogenic carbon dioxide emissions by creating carbon sinks and offering a constructive solution to environmental challenges associated with anthropogenic carbon dioxide emissions (Rytter 2012). It has been highlighted that poplar cultivars show great potential as a future source for biofuel production in Sweden (Johansson & Karačić 2011).

The key value for the evaluation of harvesting time is MAI (mean annual increment) for volume, and it's usually represented along with CAI (current annual increment), which is the annual growth in yield per unit of land area (Puettmann et al. 2012). One method of defining harvest time is noticing the intersection of MAI and CAI lines (Puettmann et al. 2012). The goal of a short-rotation system is to reduce the age of the stand at which it reaches the optimal rotation time, so the time when MAI and CAI curves intersect (FORM 1988). It has been proved that shorter rotations go in harmony with higher planting densities and what comes with that, higher biomass yield (Dillen et al. 2013). Shorter rotation cycles offer more frequent and rapid returns on investment, minimize the risk of stand loss, and allow quick incorporation of yield enhancements like superior genetic clones (FORM 1988). Given the importance of short rotation periods and the high fertility of agricultural land, suitable tree species should have the ability to grow rapidly and prioritize above-ground growth (Telenius 1999). Increasing plant density leads to quicker formation of the canopy and comparatively greater yields per unit of land (Hauk et al. 2014). Wider spacing speeds up the growth of the trees by reducing competition for resources between trees; however, it also leads to inadequate soil protection, which might have a negative effect on the trees in the first years of plantation (Niemczyk 2021). In southern Sweden, dense hybrid poplar stands achieved high production levels already after 6 years of growth (Karacic et al. 2003). When it comes to growth patterns, the typical rotation period for hybrid poplars ranges from 10 to 25 years and highly depends on planting density, geographical location, and local climate conditions (Stanturf & Oostem 2014). Hybrid poplars can reach an MAI of around 23 m^3/ha of stem volume with initial densities between 700-1000 trees/ha in southern and central Sweden (Christersson 2010; Karacic et al. 2003), and even up to 27 m^3/ha with higher density plantations (Svystun & Böhlenius 2024).

Many studies have identified significant variations in growth, phenology, and health between different *Populus* species and hybrid cultivars (Nielsen et al. 2014). As a result, breeding programs have been initiated to identify and select the most favorable genotypes (Dillen et al. 2007). Plant material is chosen based on its strong growth vigor, ability to produce abundant biomass, and resistance to diseases, which in the end helps to determine superior clones, matching them with suitable locations for their optimal growth (Guo & Zhang 2010). Determining whether specific poplar cultivars are more suitable for shorter or longer rotations requires site-specific evaluations before implementing them on a commercial scale (Ghezehei et al. 2020; Stener & Westin 2017).

1.3 Study objectives

This thesis examines the productivity of various poplar cultivars grown in high-density plantations in Southern Sweden and involves an in-depth analysis of how differently they perform compared to each other. Additionally, the study encompasses the possible implications and the role of fast-growing poplar plantations in a short-rotation forestry system.

1.3.1 Hypotheses

-There are no differences in productivity between poplar clones.
-Drought has an effect on biomass production.
-Optimal rotation length for SRF determined by the intersection of MAI and CAI, varies between clones.

2. Materials and methods

2.1 Site and experimental design

The experiment was conducted at Trollehom experimental area in Skåne, (55°54'23.3"N 13°18'17.3"E), initiated in the spring of 2014. It comprised of three blocks: two blocks containing 15 plots each with randomized design, and one block containing 13 plots. Each plot contained one clone, replicated three times in a block design, planted with a spacing of 1 m x 2.5 m between clones, resulting in a final density of 4000 stems per hectare (Figure 1). Each plot measured 10 m x 10 m, corresponding to an experimental area of 4300 m^2 across 43 plots. Each measurement contained a buffer zone of one tree row. After the experiment was set up, the site was enclosed by a fence, which was subsequently removed after 2 years.

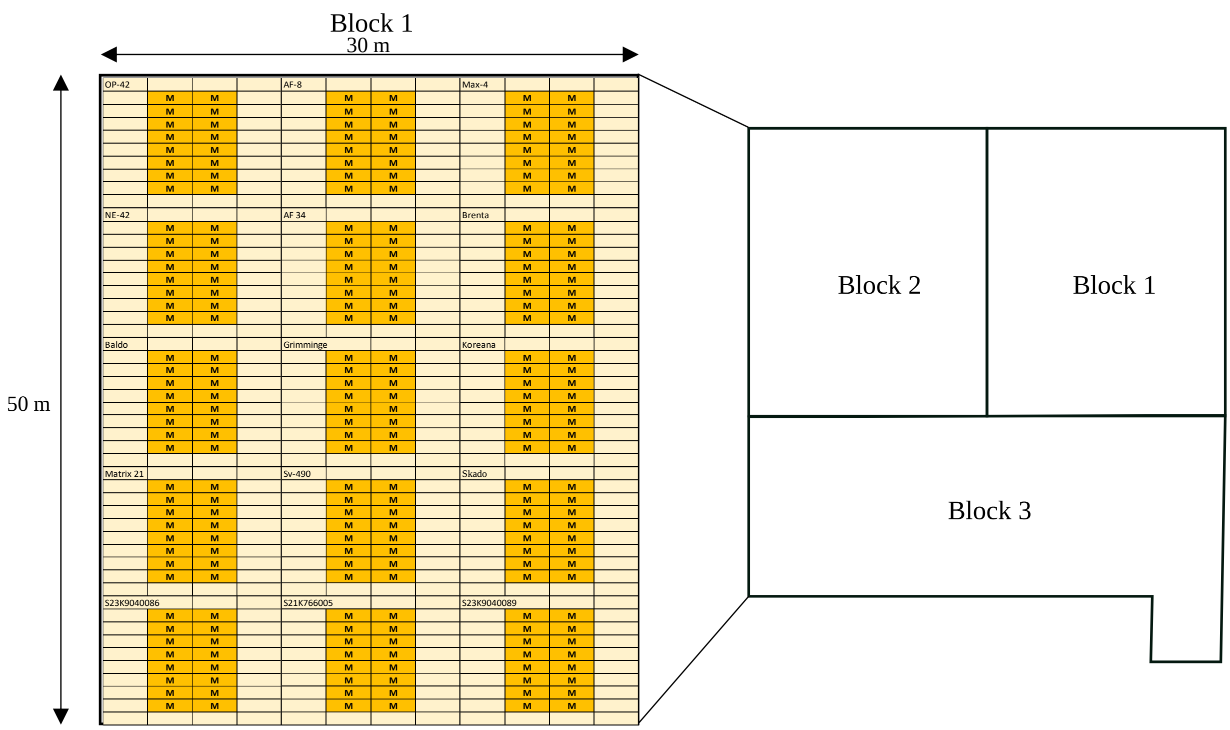

Figure 1. Illustration of the experimental design. The yellow rows indicate buffer zones and orange rows with letter ‘M’ indicate measured trees.

The latitude of the experimental site is 55°, with an altitude of 100 meters (Figure 2). Fine and clay soil structure typical for these lands indicated high soil fertility. The terrain is well drained and proved limited weed pressure. The average monthly temperature ranged from -2°C in January to 16°C in July, with an average annual temperature of 8.4°C. The average monthly rainfall varied between 59 mm and 81 mm, contributing to an average annual rainfall of 757 mm. These climatic conditions were observed based on data from the nearest urban center, Eslöv.

Figure 2. Localization of the experiment on the map showing local region.

2.2 Material

The experiment involved 15 different clones (Table 1) originating from various locations across Europe, including Belgium (2), Germany (3), Hungary (1), Italy (4), Korea (1), and Sweden (4). These clones belonged to four *Populus* species: *Populus maximowiczii* (*M*), *Populus trichocarpa* (*T*), *Populus deltoides* (*D*), and *Populus nigra* (*N*).

Table 1. Clones' names with the country origin and species composition. Species are mixes of P.maximowiczii (M), P.trichocarpa (T), Populus deltoides (D) and Populus nigra (N)

Country	Species	Name
Belgium	*T x M*	Skado
Belgium	*T x M*	Grimminge
Germany	*T x M*	Matrix 21
Germany	*N x M*	NE-42
Germany	*N x M*	Max-4
Hungary	*T x D*	Sv-490
Italy	*D x D*	Baldo
Italy	*D x N*	Brenta
Italy	*T x D*	AF 8
Italy	*D x N*	AF 34
Korea	*T x koreana*	Koreana
Sweden	*T x M*	S21K766005
Sweden	*T x M*	S23K9040086
Sweden	*T x M*	S23K9040089
Sweden	*T x M*	OP42

2.3 Data

Data collection spanned from 2014 to 2024, with biometric parameters such as height and diameter at breast height measured annually, excluding 2022. In 2024, additional measurements of all the trees' heights and diameters were taken to broaden and improve the dataset used for ANOVA test and Tukey test. All the measurements were consistently put in excel spreadsheets.

2.4 Statistical analysis

Volume was calculated for each individual tree, by using hybrid aspen’s volume equation (Johnsson, 1953) due to lack of specific equation for hybrid poplar. Height and diameter were the only parameters taken into consideration in this equation. Volume was computed for all the clones by distinguishing the blocks in order to later obtain the standard deviation.

- $V = 0.03186D^2H + 0.43H + 0.0551D^2 - 0.4148D$

Where:
H = height [m]
D = diameter at breast height [cm]
V = volume [dm^3]

Having the volume, CAI, and MAI of volume/ha was calculated to assess the optimal rotation lengths and growth of the forest. CAI and MAI of dbh and height to assess increment culmination and analyse the possible drought effect were conducted, and at the later stage of the research, vertical lines indicating the drought occurrence were added. Biomass was calculated knowing the volumes and densities (Table 2) of each clone in order to have standard deviation and was distinguished by blocks to see the differences between them and compute the standard deviation. The nominal densities of each clone were taken from scientific articles. For two cases, the data about density of clones was insufficient; therefore, the mean out of the other thirteen clones was computed and used for these two cases.

Table 2. Densities of clones expressed in kg/m³.

Clone	Density [kg/m³]	Reference
Skado	400	(M. Steenackers & W. De Clercq 2020)
Grimminge	365	-
Matrix 21	390	(Dinko et al. 2017)
NE-42	365	(Dinko et al. 2017)
Max-4	379	(Dinko et al. 2017)
Sv-490	383	(Dinko et al. 2017)
Baldo	358	(Dinko et al. 2017)
Brenta	350	(Corona et al. 2023)
AF 8	320	(Corona et al. 2023)
AF 34	365	-
Koreana	387	(Dinko et al. 2023)
S21K766005	354	(Liziniewicz 2023)
S23K904008	354	(Liziniewicz 2023)
S23K904008	354	(Liziniewicz 2023)
OP42	354	(Liziniewicz 2023)

The aboveground carbon stock, measured in tonnes of carbon per hectare, was determined by calculating the biomass values for each block, including the standard deviation. This was achieved by multiplying the aboveground biomass density, expressed in tonnes per hectare, by a factor of 0.5 to obtain the aboveground carbon stock in tonnes of carbon per hectare (Fritschle 2013). Mortality was counted by distinguishing the dead clones and calculating the percentage of the living ones.

As the last stage, to detect differences between clones, we used the mixed model from lme4 package (Bates et al. 2015) implemented in R studio (Rstudio Team, 2022) followed by analysis of variance by ANOVA function. Following the ANOVA test, a Tukey test was performed using the lsmeans package (Lenth, 2016) to examine the extent to which clones differentiate from each other. This was performed for year 2, 5 and 10. A significance level of $p < 0.05$ indicated that results were deemed statistically significant.

3. Results

3.1 Clonal performance in 45 m^2 plots

In 45 m^2 plots, there were significant differences between clones, namely when the plantation was 2, 5 and 10 years old, for all the analised variables (Volume/ha, Survival, Diameter, Height) (Table 3).

Table 3. ANOVA test results for clones in 45 m^2 plots.

	Growth characteristics 2 Y/O (45 m^2 plot)							
	Volume/ha		Survival		Diameter		Height	
	F	p	F	p	F	p	F	p
Clones	12.6017	<0.0001	12.5223	<0.0001	10.0364	<0.0001	16.389	<0.0001
	Growth characteristics 5 Y/O							
Clones	18.6018	<0.0001	10.7865	<0.0001	15.5462	<0.0001	32.9259	<0.0001
	Growth characteristics 10 Y/O							
Clones	13.6359	<0.0001	11.1946	<0.0001	4.856	<0.0001	6.7613	<0.0001

Tukey test had been conducted for the plantation's age 2, 5, and 10 as a part of the ANOVA test results. The results for the 2-year-old plantation indicated that clones S23K9040089, S21K766005, OP-42, S23K9040086, NE-42, and Max-4 had the highest values with regard to all the parameters (Table 4). Clones AF 8, Koreana, Grimminge, and Skado presented mediocre values with regard to all the parameters, whereas the rest of the clones presented values below average, with one exception where Baldo proved to have high diameter in comparison to other Italian clones. The results for the 5-year-old plantation indicated similar values, proving clones S23K9040089, S23K9040086, S21K766005, OP-42, and Skado not to be any different to each other and to have higher values than the other clones. Mediocre values were represented by NE-42, Max-4, Koreana, Sv-490, and Grimminge. The lowest square mean values had all the Italian clones and Matrix 21.The results for the 10-year-old with trees measured in the center indicated that the highest values with regard to all the measured parameters have all the clones Skado, S23K9040089, S21K766005, OP-42, S23K9040086, NE-42, and Koreana with Skado being the clone in the lead. Among the clones that represented intermediate values, we can distinguish Max-4 and Matrix 21. The lowest values were proved by the group belonging to western and southern European origin like AF 8, Grimminge, Sv-490, Brenta, AF 34, and Baldo.

Table 4. Least square mean values within the 2-, 5- and 10-years old plantation, derived from Tukey test along with the standard deviation values. Little letters indicate the degree to which clones are alike.

Tukey test 2 y/o (45 m² plot)				
Clone	Volume/ha	Trees/ha	Diameter	Height
S23K9040089	3.5±0.4[a]	4000±0[a]	1.4±0.4[a]	2.6±0.3[a]
S21K766005	3.4±0.3[a]	3834±289[ab]	1.2±0.5[abc]	2.7±0.4[a]
OP-42	3.2±0.2[ab]	3917±145[a]	1.1±0.4[abcd]	2.5±0.4[ab]
S23K9040086	2.9±0.1[abc]	4000±0[a]	1±0.4[bcd]	2.3±0.3[bc]
NE-42	2.9±0.5[abcd]	3667±382[ab]	0.9±0.4[cd]	2.4±0.4[abc]
Max-4	2.7±0.1[abcd]	3834±145[ab]	0.9±0.3[d]	2.2±0.3[bcd]
AF 8	2.3±0.6[abcde]	3167±578[ab]	1±0.6[abcd]	2.1±0.6[bcd]
Koreana	2.3±0.4[abcde]	3417±382[ab]	0.9±0.5[d]	2.1±0.5[cd]
Grimminge	2.3±0.5[abcde]	2834±804[ab]	1.3±0.7[ab]	2.4±0.7[abc]
Skado	2±0.4[bcdef]	2584±289[abc]	1±0.7[bcd]	2.2±0.7[bcd]
Sv-490	1.7±0.9[cdef]	2417±878[bc]	0.9±0.4[cd]	2.2±0.6[bcd]
Brenta	1.4±0.5[def]	2375±884[bcd]	0.6±0.3[de]	1.8±0.4[de]
Matrix 21	1.2±0.3[ef]	2667±382[ab]	0.4±0.3[e]	1.3±0.5[e]
Baldo	0.7±0.3[f]	1167±382[cd]	1.2±05[abcd]	2±0.4[cd]
AF 34	0.5±0.2[f]	750±354[d]	0.7±0.3[de]	2±0.3[cde]
Tukey test 5 y/o (45 m² plot)				
S23K9040089	62±6[a]	4000±0[a]	6.7±1[a]	8.1±0.6[a]
S23K9040086	53±7[ab]	3750±433[ab]	6.4±1.3[ab]	8±0.7[a]
S21K766005	52±10[ab]	3834±289[ab]	5.9±1.6[ab]	8.2±1.2[a]
OP-42	49±15[ab]	3834±289[ab]	5.9±1.3[abc]	8±1[a]
Skado	41±12[abc]	2584±289[ab]	6.5±1.5[abc]	8±1.2[ab]
NE-42	39±12[bc]	3667±382[ab]	5.5±1.3[bcd]	7.2±1[abc]
Max-4	34±6[bcd]	3500±250[ab]	5.6±1.2[bcd]	6.9±0.9[bcd]
Koreana	34±2[bcd]	3417±382[ab]	5.2±1.3[bcde]	7.4±1[cd]
Sv-490	25±10[cde]	2417±878[abc]	5.4±1.5[bcdef]	7.1±1.2[cd]
Grimminge	21±1[cdef]	2834±804[ab]	4.6±1.6[cdef]	6.4±1.4[de]
Matrix 21	16±11[def]	2334±145[bcd]	4.3±1.8[def]	6±2[de]
AF 8	16±9[def]	2250±1000[bcd]	4.6±1.7[def]	5.8±1.3[e]
AF 34	8±6[ef]	750±354[cd]	5.3±2.5[efg]	6.3±1.7[e]
Brenta	6±2[ef]	2375±884[abcd]	2.9±0.9[fg]	4.4±0.8[f]
Baldo	2±2[f]	667±521[d]	3.4±1.3[g]	4.2±1[f]
Tukey test 10 y/o (45 m² plot)				
Skado	292±29[a]	2584±289[abc]	13.4±3[a]	15.9±2.8[a]
S23K9040089	271±20[a]	4000±0[a]	11±2[ab]	14.7±1.4[ab]
OP-42	268±32[a]	3834±289[ab]	10.8±2.8[ab]	14.3±2.6[abc]

S23K9040086	266±41^{a}	3750±433^{ab}	11±2.8^{b}	14.3±2.5^{abc}
NE-42	257±54^{a}	3667±382^{abc}	10.9±2.7^{b}	14.4±2.3^{abc}
S21K766005	245±29^{ab}	3834±289^{ab}	10.4±2.9^{b}	14.1±2.8^{abc}
Koreana	218±49^{abc}	3417±382^{abc}	10.5±3.3^{b}	13.4±3.3^{abc}
Max-4	213±37^{abc}	3500±250^{abc}	10.9±2.6^{b}	12.7±2^{abc}
Matrix 21	185±35^{abcd}	2334±145^{bcd}	11.6±3.2^{b}	14.1±3^{bc}
AF 8	133±80^{bcde}	2084±878^{cde}	10.6±3.8^{b}	12.5±2^{c}
Grimminge	125±21^{cde}	2834±804^{abc}	8.7±.4^{b}	12.1±2.8^{c}
Sv-490	124±50^{cde}	2417±878^{abcd}	9.8±2.7^{b}	12.6±2.5^{c}
Brenta	89±16^{cde}	2250±1061^{bcde}	8.6±2.7^{b}	12 2±4^{c}
AF 34	77±30de	750±354de	12.8±4.5^{b}	14.5±3.1^{c}
Baldo	24±22^{e}	667±521^{e}	8.1±3.5^{b}	10.7±3.4^{c}

3.2 Clonal performance in 100 m^2 plots

Similarly to the 45 m^2 plots, the ANOVA test results showed significant differences between clones when plot size was increased to 100 m^2 (Volume/ha, Survival, Diameter, Height) (Table 5).

Table 5. ANOVA test results for clones in 100 m^2 plots.

	Growth characteristics 10 Y/O (100 m^2 plot)							
	Volume/ha		Survival		Diameter		Height	
	F	p	F	p	F	p	F	p
Clones	21.196	<0.0001	12.9936	<0.0001	19.004	<0.0001	26.464	<0.0001

The results for the 10-year-old plantation with trees measured in the bigger plots (Table 6) indicated that OP-42, Skado, S23K9040086, S23K9040089, and NE-42 had the highest values, with OP-42 proving to be in the lead. Among the clones that represented intermediate values, we can distinguish NE-42, Koreana, S21K766005, and Max-4. The lowest values were proved by the group belonging to western and southern European origin like Grimminge, AF 8, AF 34, Brenta, and Baldo.

Table 6. Least square mean values for the 10-year-old plantation with trees measured in the bigger plots, derived from Tukey test along with the standard deviation values. Little letters indicate the degree to which clones are alike.

Tukey test 10 y/o (100 m^2 plot)				
Clone	Volume/ha	Trees/ha	Diameter	Height
OP-42	358 ± 55^{a}	3834 ± 116^{ab}	12.3 ± 3.3^{b}	15.2 ± 2.5^{ab}
Skado	334 ± 7^{b}	2400 ± 200^{cd}	14.7 ± 3.8^{a}	16.2 ± 3.1^{a}
S23K9040086	329 ± 46^{ab}	3834 ± 208^{ab}	11.9 ± 3.3^{bc}	14.8 ± 2.4^{bc}
S23K9040089	311 ± 6^{abc}	3967 ± 58^{a}	11.9 ± 2.6^{bc}	14.6 ± 1.3^{bc}
NE-42	284 ± 37^{abc}	3267 ± 321^{abc}	12.0 ± 3.4^{bc}	14.7 ± 2.5^{bc}
Koreana	265 ± 29^{abc}	3333 ± 322^{abc}	11.8 ± 3.4^{bc}	14.0 ± 2.6^{c}
S21K766005	259 ± 39^{abc}	3833 ± 208^{ab}	10.6 ± 3.1^{cd}	14.2 ± 2.5^{bc}
Max-4	221 ± 68^{bcd}	3567 ± 116^{abc}	10.8 ± 3.5^{bcd}	12.2 ± 2.4^{de}
Matrix 21	194 ± 27^{cde}	2467 ± 58^{bcd}	11.5 ± 3.7^{bcd}	13.8 ± 2.9^{cd}
Sv-490	122 ± 40^{def}	2400 ± 900^{cd}	9.6 ± 3^{de}	12.3 ± 2.7^{de}
Grimminge	121 ± 24^{def}	2967 ± 586^{abc}	8.5 ± 3.1^{e}	12.2 ± 2.3^{de}
AF 8	121 ± 58^{def}	2333 ± 569^{cd}	9.6 ± 3.6^{de}	11.8 ± 2.8^{e}
AF 34	88 ± 13^{ef}	1100 ± 566^{de}	11.5 ± 3.6^{bcd}	13.8 ± 3^{cd}
Brenta	86 ± 49^{ef}	2100 ± 990^{cde}	8.9 ± 2.7^{de}	12.1 ± 2.1^{de}
Baldo	26 ± 13^{f}	867 ± 577^{e}	7.8 ± 2.3^{e}	10.8 ± 2.3^{e}

3.3 Mean annual and current increment

Mean annual increment (MAI) and current annual increment (CAI) calculated from the experiment showed that Skado, S23K9040089, OP-42, S23K9040086, NE-42, S21K766005, and Koreana respectively had the highest MAI values that revolved between 21-29 m^3/ha (Figure 3). Max-4 and Matrix 21 indicated mediocre values between 18-21 m^3/ha. The lowest values were represented by Italian clones, Grimminge, and Sv-490, whose MAI was below 14 m^3/ha. None of the lines intersected for any of the clones.

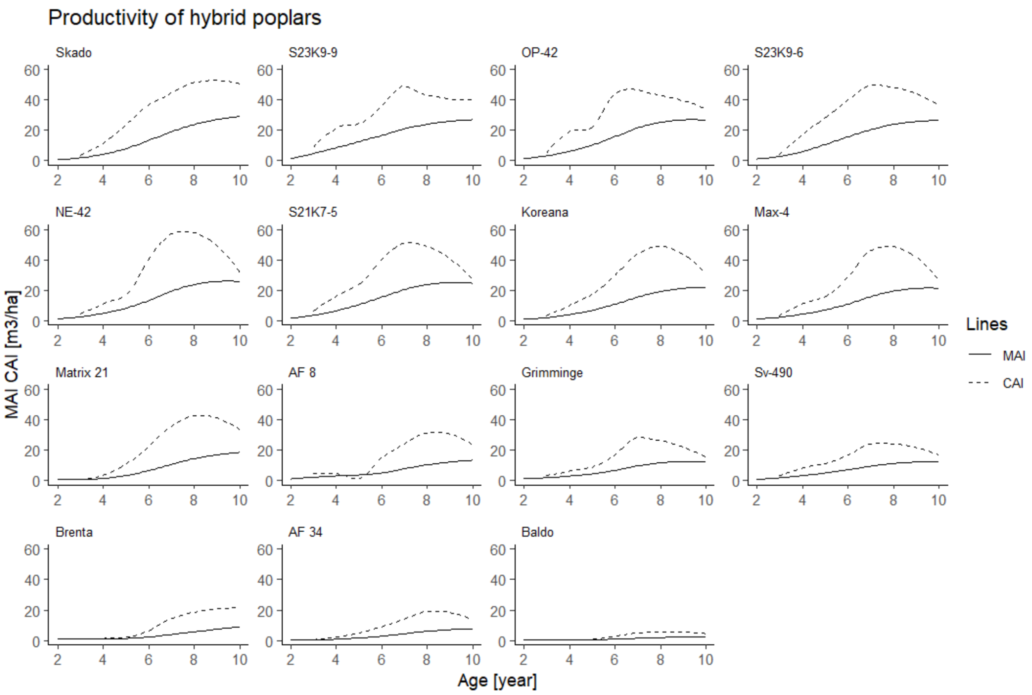

Figure 3. Productivity of hybrid poplars displaying MAI and CAI of volume m^3/ha.

3.4 Volume production, biomass, and carbon storage

The highest volume production was seen in clones Skado, S23K9040089, OP-42, S23K9040086, NE-42, and S21K766005, with volumes ranging between 245-291 m^3/ha (Figure 4). Among the mediocre production values, we can distinguish Koreana, Max-4, and Matrix 21 revolving around 184-218 m^3/ha. The lowest values, below 133 m^3/ha, were presented by Italian clones, Grimminge, and Sv-490.

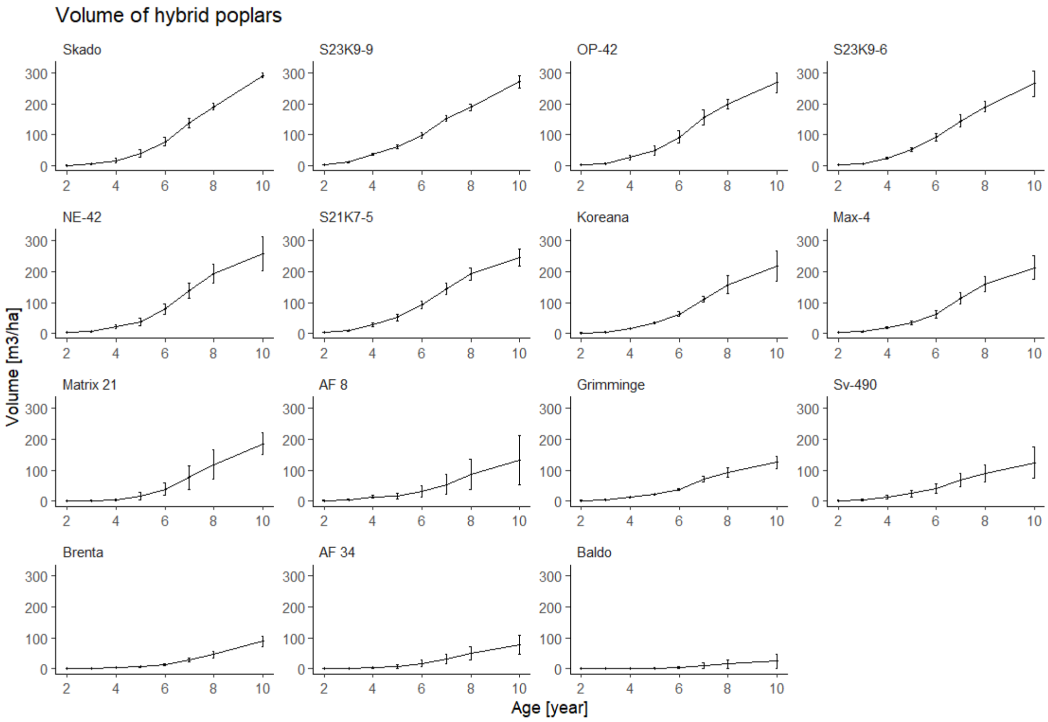

Figure 4. Volume production of hybrid poplars in m^3/ha.

Similar to volume, clones Skado, S23K9040089, OP-42, S23K9040086, NE-42, S21K766005, and Koreana demonstrated the highest biomass values, ranging between 84 to 116 tons per hectare (Figure 5). Max-4 and Matrix 21, on the other hand, displayed average biomass levels, falling within the range of 80 to 72 tons per hectare. The remaining clones – Sv-490, Grimminge, AF 8, Brenta, AF 34, and Baldo exhibited biomass values lower than 43 tons per hectare.

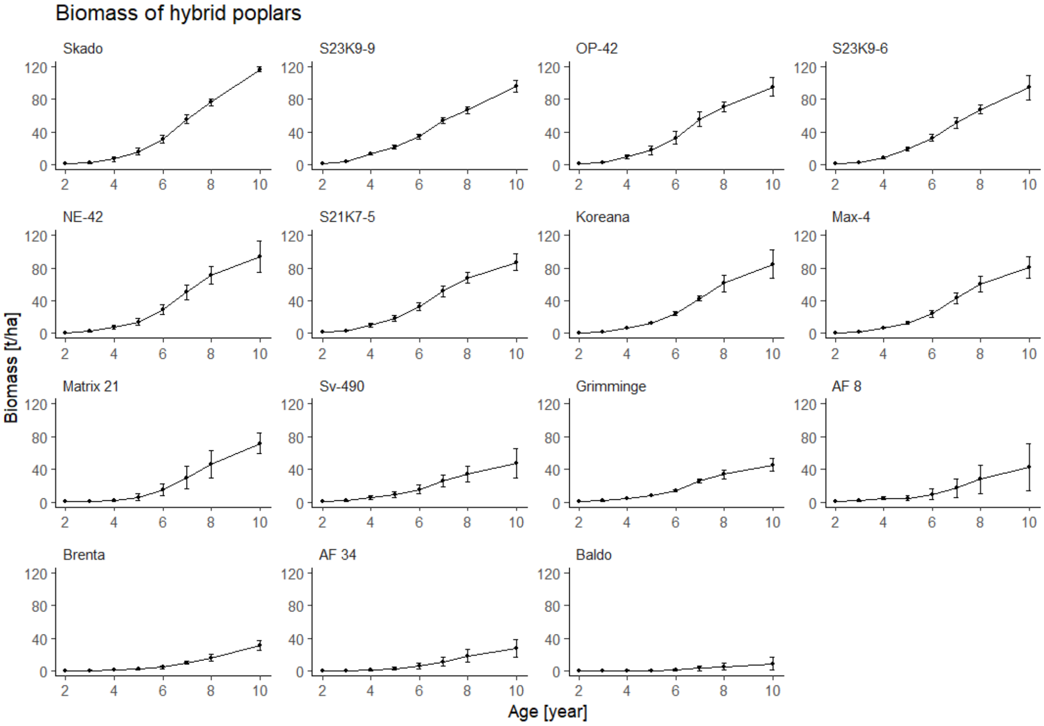

Figure 5. Biomass of hybrid poplar calculated in t/ha.

Skado, alongside the clones S23K9040089, OP-42, S23K9040086 NE-42, S21K766005 and Koreana, demonstrated the highest carbon values, ranging between 42 to 58 tons per hectare (Figure 6). Max-4 and Matrix 21, on the other hand, showcased average carbon levels, falling within the range of 36 to 40 tons per hectare. The remaining clones exhibited carbon values lower than 23 tons per hectare.

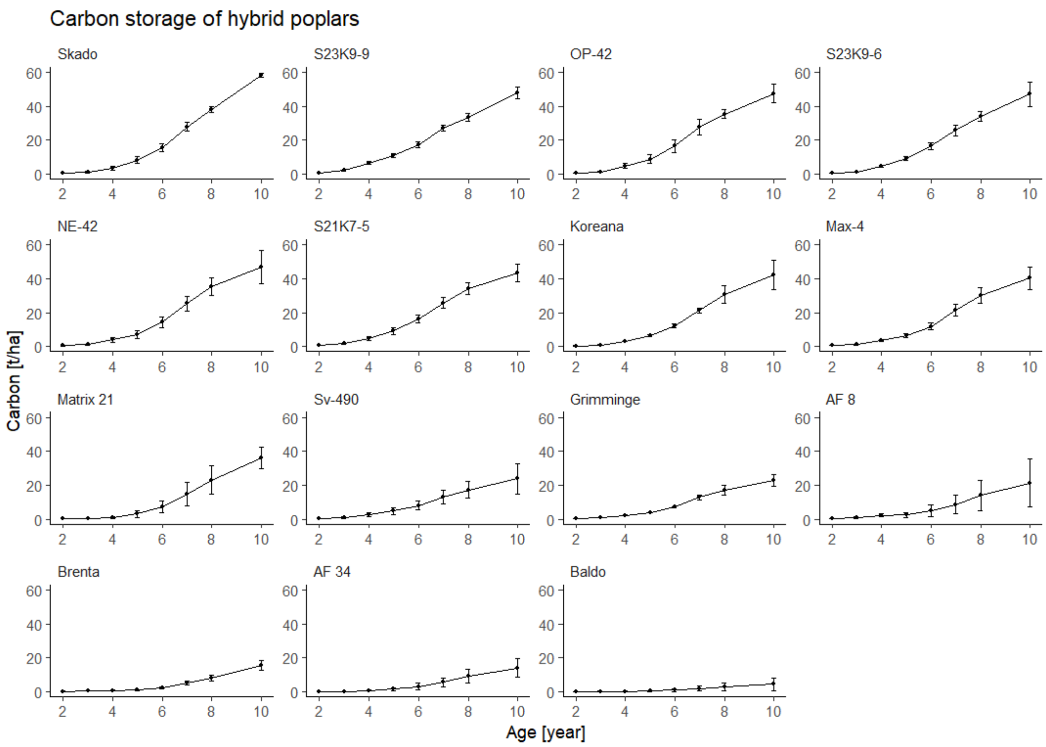

Figure 6. Above ground carbon storage of hybrid poplar clones, measured in t/ha.

3.5 Plant survival

The highest survivability was proved by S23K9040089, OP-42, S21K766005, S23K9040086, NE-42, Max-4 and Koreana having at least 85% living trees (Figure 7). Following closely behind, clones Grimminge, Skado, and Sv-490 demonstrated average survival rates, with at least 60% of trees remaining alive. Trees with survival between 52-59% were presented by Matrix 21, AF 8 and Brenta. The remaining clones – Baldo and AF 34 displayed lower survivability, with less than 52% of their trees still alive 10 years after planting.

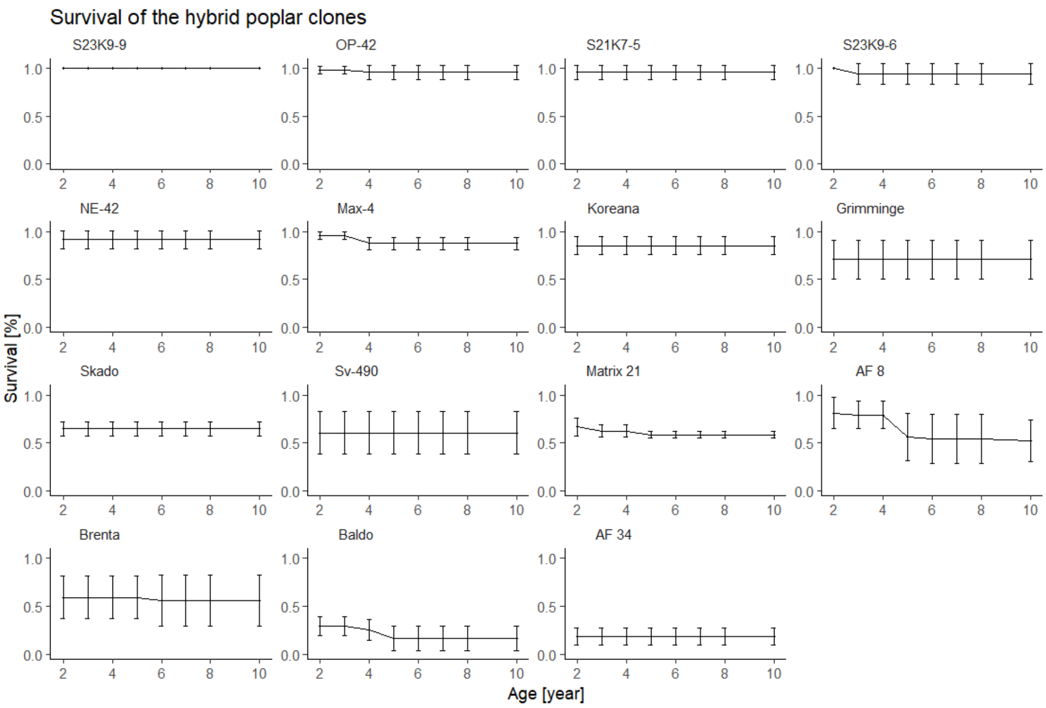

Figure 7. Survival of clones displayed in %.

3.6 MAI and CAI of DBH (Diameter at breast height) and Height

Distinct patterns in the Mean Annual Increment (MAI) and Current Annual Increment (CAI) of DBH (diameter at breast height) were observed in the growth trajectories of various clones, particularly when assessing their CAI performance at the age of 5, coinciding with the year of the drought (Figure 8). Matrix, AF 34, Baldo, Grimminge, Brenta, Skado, and Max 4 showed relatively minor declines in DBH growth. Conversely, clones such as S23K9040089, OP42, AF 8, NE-42, and Koreana experienced more visible reductions in growth, specifically in terms of DBH.

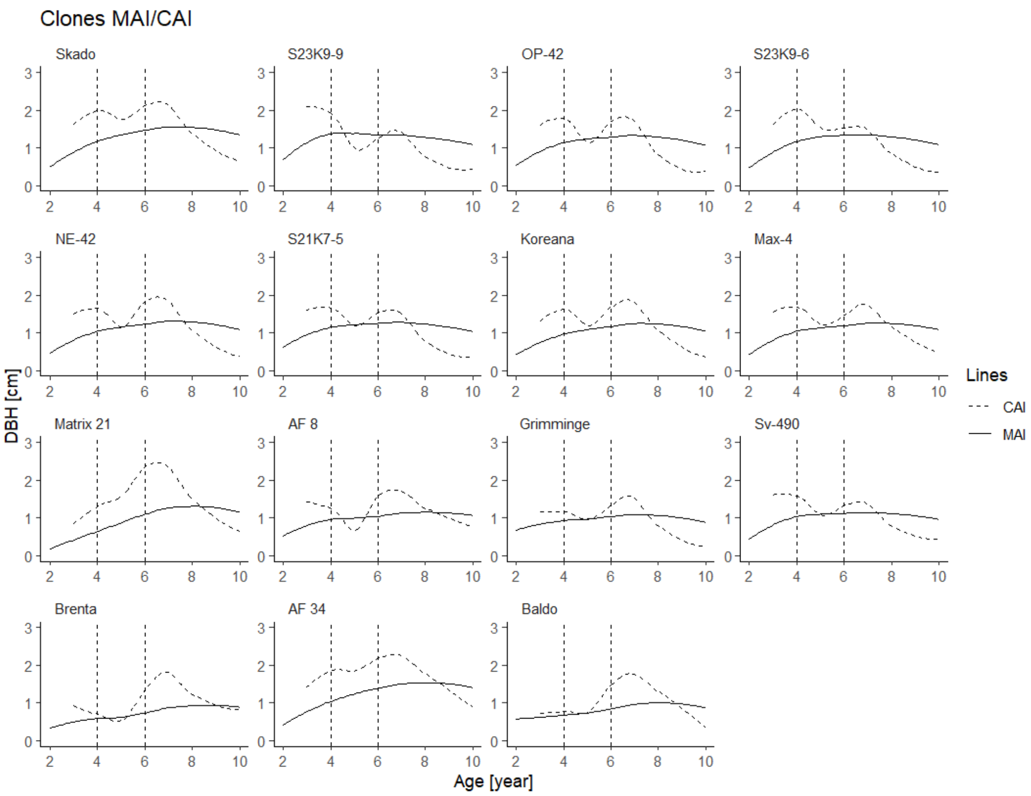

Figure 8. The MAI (mean annual increment) and CAI (current annual increment) of DBH (diameter measured at breast height) displayed in cm. Dashed lines highlight the drought season in 2018.

Distinct trends in the Mean Annual Increment (MAI) and Current Annual Increment (CAI) of height were visible in the growth patterns of various clones, especially when evaluating their CAI performance at the age of 5, coinciding with the drought year (Figure 9). Matrix, AF 34, Baldo, Grimminge, Brenta, Skado, and Max 4 exhibited relatively slight decreases in height growth. Conversely, clones such as S23K9040089, OP42, AF 8, NE-42, and Koreana displayed more notable declines in height growth.

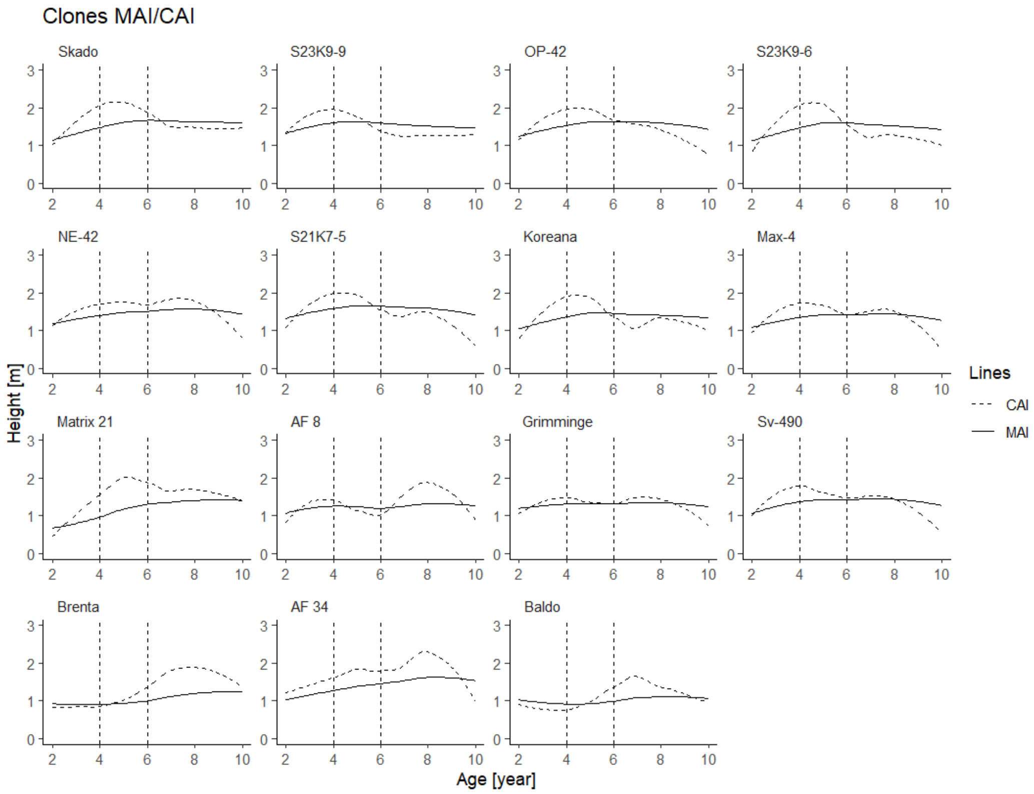

Figure 9. The MAI (mean annual increment) and CAI (current annual increment) of H (height of the clones) displayed in cm.

4. Discussion

4.1 Biomass production

Biomass production refers to the process of generating organic matter, typically from plants or organic waste, which can be used as a source of renewable energy or various bioproducts (Barot 2022). Sweden happens to be among the northern European countries that stand out with regard to high potential supply of woody biomass per unit of land (Verkerk et al. 2019). That aligns with the results presented in this study (Figure 4; Figure 5; Figure 6) indicating that the high biomass yield has been achieved, putting on the pedestal clones like Skado, S23K9040089, OP-42, S23K9040086 and NE-42. Results derived from Swedish plantations indicate that poplar stands can produce the biomass between 70 to 105 tons/ha after only 10-15 years of growth (Johansson & Karačić, 2011), which indicates that findings in this study (Figure 5) are consistent with previous research and prove even higher yield in the case of Skado reaching up to 117 tons/ha.

The literature suggests that maximizing production involves achieving a balance between high survival rates and high productivity per plant (Guo & Zhang 2010). In this study, poor productivity (Figure 3), represented by some clones, was strongly linked to the high mortality rate of trees, with AF 34 and Baldo reaching up to 80% of mortality (Figure 7) by the end fourth year of plantation. Mortality is a common issue while establishing broad-leaved species, especially on agricultural land and might be the result of high competition from herbaceous species (Czapowskyj & Safford 1993), increasing competition for essential resources like light, water, and nutrients (Stener & Westin 2017), or poor climatic adaptation (Stener & Westin, 2017). There is no evidence in this study suggesting that competition for light was the primary cause of mortality, as the majority of clones that experienced mortality died within the first two years of plantation, when the seedlings were still short and didn't need to compete for light (Figure 7). Therefore, these studies might indicate that the increased mortality rate which occurred during the first 5 years of plantation establishment was mostly due to increased competition for soil resources, which is especially represented by clone AF 8 whose mortality surged by 20% following the extreme drought that occurred in 2018 (Figure 7).

Studies show that it is often difficult to judge whether mortality is density dependent (Karacic et al 2003). However, understanding the significance of different spacing in poplar plantations is essential in order to successfully achieve desired biomass productivity (Christersson, 2010). Examples of evaluation of commercial poplar plantations in southern Sweden established with lower densities (1000 trees/ha) indicate comparable production potential to densely spaced plantations (5000 trees/ha), although at 3-5 years longer rotations (Karacić, 2005).

This study highlights that a high initial stem density of 4000 stems/ha in a 10-year short rotation has led to the highest volume of 292 m^3/ha (Figure 4) for best performing clones in the established plantation. In comparison, plantations with much lower density of 1333 stems/ha achieved a volume of 250 m3/ha for the same age, as indicated by Niemczyk (2021). These findings indicate small variations in productivity with regard to density, which is consistent with previous research findings. According to the other studies, however, exceptionally low densities of 410 stems/ha may not yield high production, achieving only half of what could be attained with density of 2500 stems/ha, as observed by Christersson's (2010) study. By principle, opting for a high planting density could be economically challenging due to increased costs for both establishment and harvest. While closer spacing can result in greater economic returns because the biomass is achieved in much shorter rotation period, the high planting density might be a driver for early competition and density dependent mortality (Karacic et al. 2003), which necessitates the use of well-selected cultivars in order to maintain high yield.

4.2 Optimum rotation length

The results of this study indicate that the average yearly production can vary between 2 to 29 m3 ha^{-1} yr^{-1} (Figure 3) by the time the trees reach 10 years old, promoting the hybrid clone Skado (*Populus maximowiczii x trichocarpa)* (Table 1), as the best performing cultivar (Table 4). Results also show that other clones of the species *Populus trichocarpa, Populus maximowiczii* (Table 1) or both, had a high productivity by the age of 10 years old (Figure 3). Specifically, clones Skado, S23K9040089, OP-42, S23K9040086, and NE-42 exhibited similarly high volume values and were proved to be statistically indistinguishable from each other (Table 4). In experiments evaluating poplar growth, significant volume increments were observed after 8 years, with most cultivars achieving their highest Mean Annual Increment (MAI) by the age 10 (Figure 3), which aligns with other studies

(Niemczyk 2021). This implies that a rotation length of 10-15 years is biologically optimal, as indicated by the trajectories of MAI (Mean Annual Increment) and CAI (Current Annual Increment) lines. This is particularly true for northern regions, where longer rotations could enhance biomass production. Considering economic matters, studies show that poplar plantations with a 10-year rotation using high-performing cultivars could prove to be profitable and sustainable investments for landowners (Niemczyk 2021).

The optimal rotation period for poplar plantations is a crucial factor affecting both productivity and risk mitigation. Shorter rotation periods can decrease the risks associated with storm damage while providing stakeholders with early and regular income, thereby enhancing the flexibility of the entire venture (Karacic et al. 2003). In different studies, the correlation between wind damage and harvest time is emphasized, suggesting that an earlier harvest is preferable to mitigate potential losses, that are especially likely to happen in regions of Southern Sweden (Karačić, 2005). Harvest practices also play a significant role in plantation management. Sources from literature recommend the first or final felling to occur after 10 to 15 years from planting, with the timing dependent on the initial stand density (Tulus et al. 2013). The growth of poplars is heavily influenced by the length of rotation and their adaptation to local conditions (Tulus et al. 2013). Rotations of 8 to 12 years are common, but issues such as damages in young trees indicate insufficient adaptation to the northern-European climate (Christersson 2006; Tulus et al. 2013).

4.3 Climate adaptation of planting material

The results of this experiment indicates that the differences between clones do occur when it comes to survival, diameter, height, and volumes (Table 3). These outcomes align very well with the current knowledge, that there is a large variation in yield within clones of different origin. This emphasises the importance of superior clones (Stener & Westin 2017). There is substantial evidence in the literature that indicates superiority of hybrid clones (Ceulemans et al. 1992), which only validates this way of thinking. It is crucial to know, however, that not all clones are equally as adaptable (Christersson 2010). The need for careful selection of clones is highlighted in the study, displaying all the hybrids of *Populus deltoides* as the ones with the highest mortality reaching up to 83% (Figure 7). This alarming trend known from other studies, suggests a vulnerability inherent in these hybrids, which may have significant implications for the overall success and sustainability of plantation forests (Christersson 2010). Moreover, the general pattern observed across studies indicates that hybrids utilizing *Populus maximowiczii* as a parent tend to perform well, whereas pure species of *Populus nigra* and *Populus deltoides*, along with their hybrids, exhibit lower production rates (Nielsen et al. 2014). With that being said, studies indicate that hybrid poplar clones originating from southern regions, such as 'Baldo' and 'Brenta', may not thrive well in central and northern Sweden due to their lack of adaptation to the specific photoperiodic and temperature conditions of these areas (Karačić 2005). This may indicate that when introduced poplar clones begin growth too early in spring and delay bud setting until late autumn, they become highly vulnerable to frost damage, especially late spring frosts at the start of the growing season and early autumn frosts towards the end. Sources in the literature emphasise the fact that in the face of ongoing intensive breeding and rapid genetic changes, it is important to have better understanding about the genetic control and physiology of important traits (Christersson 1996). Other studies also show that in Denmark and Sweden, the most commonly and almost exclusively used is the poplar cultivar called OP-42 *(Populus maximowiczii × Populus trichocarpa)* (Table 1) (Stener & Westin 2017). The results suggest that adopting a variety of cultivars can effectively mitigate economic risks and enhance plantation biodiversity, particularly in anticipation of potential climate-induced maladaptation. A good example from this study is the success of clone Skado, which, unlike the commonly planted OP-42, demonstrated even better performance. This suggests that introducing a range of clones such as Skado could prevent excessive reliance on a single species in plantation forestry. This, in turn, decreases the likelihood of vulnerability to potential pathogen or pest outbreaks that may target specific species.

Another finding from this study focused on the drought that happened on 2018. The tested cultivars showed large variability in drought resistance. After the drought event in 2018, distinct patterns emerged in the growth curves of various clones within the plantation, particularly when assessing their performance at the age of five which is when the drought occurred. The divergence underlines variability in drought resistance among the clones. Notably, Matrix, AF 34, Baldo, Grimminge, Brenta, Skado, and Max 4 displayed relatively minor declines in growth of DBH (Figure 8) and height (Figure 9), showing better degree of resilience to drought stress. Conversely, clones such as S23K9040089, OP42, AF 8, NE-42, and Koreana exhibited more significant growth declines in terms of their diameter at breast height (DBH) and height. Interestingly, there were no consistent patterns based on the origin of the species. Sometimes Italian clones performed better in drought conditions, while other times they did not. Additionally, the parent species forming a particular cultivar did not indicate to influence its drought resistance. This inconsistency might be due to the small sample size of the experiment. Even a small number of dead trees, whose mortality can occur randomly, could significantly affect the data. To address this issue, additional trees in 2023 have been measured, ignoring the "edge effect" where trees on the experiment's border tend to have higher growth due to higher sunlight exposure and less competition. The results from the extra measured trees' plots showed different outcomes, with clone OP-42 emerging as the best performer (Table 6). As a consequence, the study revealed a discrepancy in total volume production of clones between plots containing only centered trees and those encompassing the entire plot area (Table 4; Table 6). The varying outcomes suggest that having a slightly higher number of replicates would provide more robust data, especially concerning mortality, which can occur randomly. This indication can also correspond to the unpredictable and irregular performance of clones in terms of their ability to resist drought, regardless of their adaptability to local conditions.

4.4 Validity of SRF and implications for poplars

Short rotation forestry (SRF) is mainly associated with fast growing broadleaved species from *Populus* genus and is known to involve rotation length of approximately 20 years (Böhlenius et al. 2023). That, in comparison to long rotation species like Spruce or Pine with the rotation length revolving around 60-120 years (Perttu 1998), puts them into different category not only when it comes to the time space management but also commercial purposes. Differentiating between these silvicultural methods and the species' characteristics can be challenging when comparing them directly, mainly because of their distinct purposes, where long rotation systems involve attaining goods like sawlogs and timber veneer (Truax et al. 2014) , whereas short rotation forestry aims more towards achieving biomass for bioenergy (Nordborg et al. 2018) and pulpwood (Valerio 2012). On a more detailed level, within short rotation forestry, rotation periods can also vary. A rotation period of 10 years is considered short (Niemczyk 2021), while a 20-year period might be regarded as long within the context of SRF (Böhlenius et al. 2023). There are examples in literature describing fairly negative or neutral consequences of lowering rotation length of the main production species in Sweden, however they never evaluated shortened rotations stemming from the use of faster-growing species (Roberge et al. 2016), which might indicate that it doesn't bring any potential negative consequences. Described fast growing species, in fact, have rather favourable connection with SRF which goes in harmony with their early growth and phenology (Stener & Westin, 2017). Commercial SRF by using poplars offers a valuable option for utilizing surplus agricultural land which has potential to generate multiple societal benefits through its high biomass and fibre production and makes positive effects on the environment (Karačić 2005). My results (Figure 4) support the idea that poplars are better at producing biomass than other tree species typically grown on former agricultural lands that Sweden has in abundance at the latitude of the experiment (Karacic et al. 2003; Stener & Westin 2017). Establishing fast growing deciduous tree plantations like poplars and their cultivars on unused farmlands can offer a solution to address various challenges including low profitability of agriculture, the greenhouse effect, energy crisis, or even groundwater contamination (Christersson et al. 1993). These indications may suggest that placing SRF along with poplars in the lead offers advantageous position compared to other silvicultural systems in this region of Europe.

4.5 Practical implications

Achieving the optimal density of poplar stems is crucial for maximizing the efficiency and profitbaility of short rotation forestry in Southern Sweden. The results indicate that the plantation densities of about 4000 stems per hectare can result in high biomass production. However, seedlings' survival after establishing phase, plays crucial role, having an impact on biomass/volume production. Poplars can also be planted with lower densities starting from 1000 stems per hectare. This way, clone selection should be carefully considered, as well as the objectives when selecting densities – both systems will produce high levels of biomass, but will vary in optimal harvesting time.

The short rotation length of 10 to 15 years, will also have an impact on economy and storm risks. Reducing the rotation length will increase financial returns and mitigate the potential wind damage and pathogen outbreaks.

Diversifying clone selection is another key strategy for enhancing the resilience and adaptability of poplar plantations. Introducing poplar cultivars like Skado alongside traditional clones planted in Sweden, can add genetic diversity, and reduce vulnerability to pests, diseases, and environmental stressors. However, caution should be taken by using Skado as the result derived from one experimental site located in fertile soil in Southern Sweden.

In this study, I analyzed 15 clones, of which 5 showed similar high biomass production, indicating a need to select new poplar clones better adapted to different climate conditions across Southern Sweden. By achieving this, large volumes of biomass can be produced, replacing black carbon with green in the bio-based industry.

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Popular science summary

Are poplar plantations the key to sustainable energy?

Michał Kibitlewski

Short Rotation Forestry (SRF) is becoming an increasingly popular method for producing renewable energy and combating climate change. This practice involves growing fast-growing tree species, such as poplars, under intensive management. These trees are harvested in short cycles, typically around 10 to 20 years, which helps reduce our reliance on fossil fuels and addresses environmental challenges.

Around the world, the use of SRF is expanding. In South America, plantation forests cover vast areas, while in Europe, they make up a smaller percentage of the total forest area. However, European countries, especially in the north, are showing a growing interest in SRF due to its potential for achieving carbon neutrality by 2050. Sweden, for instance, has large areas of unused agricultural land that are now being converted into productive poplar plantations.

One of the main challenges with poplar plantations is their high water requirement, which makes them vulnerable to drought. Proper soil management and weed control are crucial in the early years of plantation to ensure the trees establish well. Using well-developed seedlings and maintaining high planting densities can also help maximize biomass production.

SRF with poplars offers numerous benefits. Economically, it provides a quicker return on investment compared to traditional forestry due to shorter rotation cycles. Environmentally, these plantations act as carbon sinks, absorbing carbon dioxide from the atmosphere. They also offer an alternative to natural forests, reducing the pressure on these ecosystems.

Recent studies in Southern Sweden have shown promising results for poplar plantations. High-density plantations (about 4000 stems per hectare) have achieved impressive biomass yields. Some poplar clones, like 'Skado', have proven particularly successful, producing up to 117 tons of biomass per hectare within a

10-year rotation. This makes them an excellent choice for biofuel production and other uses.

The success of poplar plantations also depends on their adaptability to local climate conditions. For instance, some clones are more drought-resistant than others, which is crucial as climate change brings more frequent and severe droughts. Diversifying the types of poplar clones planted can help mitigate risks and ensure stable production.

Short Rotation Forestry with poplars represents a sustainable and efficient approach to producing renewable energy and addressing environmental issues. By leveraging the fast growth and high biomass yield of poplars, regions like Southern Sweden can make significant strides towards sustainability and carbon neutrality. The key to success lies in careful selection of tree clones, optimal plantation management, and adapting to local climate conditions.

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