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Biomass Yield of 37 Different SRC Poplar Varieties Grown on a Typical Site in North Eastern Germany

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Abstract: A total of 37 different poplar varieties were grown in a randomized mini-rotation short rotation coppice (SRC) (harvest every three years) on a light sandy soil under continental climatic conditions in the south of the Federal State of Brandenburg, Germany. Along with well-known poplar varieties, newly bred ones that have not yet been approved for commercial use were selected for this study. Survival rates were determined after the first growing season in 2013 as well as at the first and second harvests in 2015 and 2018. Furthermore, the number of shoots, plant height, diameter at breast height, dry matter content and biomass yield of the varieties were recorded. After the second rotation period, only seven poplar varieties yielded more than 11 t_{adm} ha^{-1} y^{-1} and can be recommended for commercial use. However, many varieties only reached about 8 t_{adm} ha^{-1} y^{-1}, and six varieties even had less than 4 t_{adm} ha^{-1} y^{-1}, among them newly bred varieties. Given the changing climate conditions, the cultivation of these varieties in SRC is not recommended. Our data also show that the biomass yield of several varieties decreased from the first to the second harvests. Since the survival rates were high and no damage by pest species was observed, the site-specific yield capacities of the individual clones are assumed to be the cause for this.

Keywords: bioenergy plantation; woody biomass; *Populus*; renewable energy

1. Introduction

The use of renewable raw materials is a sustainable and regionally sensible alternative to the continuing use of fossil raw materials. Thus, the European Union supports the transition to a low-carbon energy economy and has set a 27% target for the total share of energy from renewable sources by 2030 [1]. Fast-growing tree species play a particularly important and sustainable role as renewable raw materials in different land use systems, e.g., short rotation coppices (SRC) and agroforestry systems (AFS) [2–6]. They help reduce CO_2 emissions by substituting fossil fuels or the production of biofuels and thereby help to mitigate climate change [7].

SRC crops are defined as high-density plantations of fast-growing trees, managed in different rotation times. Commonly, three different types of rotation periods are distinguished: mini-rotation represents an interval of 2–4 years, midi-rotation of 5–10 years and maxi-rotation of 11–20 years [1,8–10]. Depending on the production target and the associated rotation variant, as well as the particular site conditions, different tree species are used in Europe. From a legal point of view, several species that are capable of resprouting can be grown in the aforementioned farming systems [11]. For a successful management of these types of plantations on a commercial scale, it is essential to maximize the benefits by combining economic viability with environmental sustainability. Over time, three tree species have become the most common ones used for the fast production of woody biomass. Black locust

(*Robinia pseudoacacia* L.) is mainly grown on poor, sandy sites with little rainfall in southern regions of Europe [12–14], whereas willow (*Salix* spec.) and its varieties are preferred in the north, in much more humid and colder regions [15–17]. However, the most common tree species in European SRC and AFS is poplar (*Populus* spec.) and its varieties. There are numerous examples of scientific studies, but their practical and commercial use in different rotation types has also been examined in many different regions in Europe [2,18–22].

In Germany, farmers mainly use sites with low yield expectations to establish SRC and AFS. Such sites are especially abundant in the Federal State of Brandenburg, in which 2000 ha, that is about one third of Germany's SRC, are located [23]. In recent years, the interest in fast-growing tree species, especially in poplar, has increased and new varieties have been brought onto the market. However, these often originated from Southern Europe, e.g., Italy, where climatic and site conditions are more favorable than in Germany, for example, due to higher temperatures, a longer vegetation period, less or no frost periods and a better water supply. For this reason, it was of particular interest to study the growth of the new Italian AF poplar varieties, as well as the new Matrix poplar varieties from Germany under the specific conditions occurring in the Federal State of Brandenburg, and compare them to older varieties.

The aim of this study was to record and compare the major growth parameters of 37 poplar varieties over a period of six years, including two harvests. These included (I) the survival rate, (II) the resprouting capacity, (III) the plant height, (IV) the diameter at breast height, (V) the dry matter content and (VI) the biomass yield. Finally, the suitability of these varieties for SRC and AFS was evaluated.

2. Materials and Methods

2.1. Site Description, Experimental Design and Plant Material

The study site is located near Großthiemig in the northeastern part of Germany (latitude N 51°23′52.9′′, longitude 13°40′11.6′′ E, 43 m a. s. l.). The local climate is mainly a typical inland climate but with a noticeable transition to the continental climate. The mean annual temperature is 8.6 °C with an average annual precipitation of 561 mm [24]. The soil has a sandy texture and consists of 4.8% of clay, 2.9% of silt and 92.3% of sand with a lightly acidic to neutral pH of 5.9 and an organic matter content of about 1.5%. According to Hartmann [25], the soil type is a Gleyic Cambisol.

In the spring of 2012, a randomized field trial including the 37 poplar varieties was established. Most varieties were typical varieties available on the German market in 2012 and bought from the P & P forest nursery (Eitelborn, Germany [E 7°42′ N 50°22′]). Newly bred varieties were obtained from the Italian breeder Alasia Franco Vivai (AFV) (Savigliano, Italy [E 7°38′ N 44°36′]), and the Thünen Institute (TI) (Großhansdorf, Germany [E 10°15′ N 53°39′]; 4 × Göttingen variety bred by the University of Göttingen, Germany, with material originating from INRA Bordeaux, France). Table 1 provides an overview of all poplar varieties included in this study.

Except for the varieties from TI, unrooted cuttings with a length of 20 cm and a minimal diameter of 1 cm were used and placed into the soil manually and evenly with the ground. The three TI varieties (P1, 4 × Göttingen and Esch 5) were delivered as rooted plants in pots, which were removed before planting. Every poplar variety was established in three plots with 33 individuals each, with a random distribution of plots. In total, 32 rows with a row spacing of 1.5 m were created. The distance between plants within a row was 0.5 m. Thus, a theoretical number of 13.333 poplars per hectare were planted. To ensure the success of the establishment, two mechanical weed control measures were carried out during the first growing season.

Table 1. Poplar varieties included in this study and, if known, their parentage (*n* = 99 per variety).

Variety	Parentage	Sex	Source
Androscoggin	*P. maximowiczii* × *P. trichocarpa*	m	P & P
Fritzi Pauley	*P. trichocarpa*	f	
Harff	*P.* × *euramericana*	f	
Heidemij	*P.* × *euramericana*	m	
I 214	*P. deltoides* × *P. nigra*	f	
Isières	*P.* × *euramericana*	m	
Jacometti 78 B	*P.* × *euramericana*	f	
Koltay	*P.* × *euramericana*	m	
Kopecky	*P.* × *euramericana*	m	
Matrix 24	*P. maximowiczii* × *P. trichocarpa*		
Matrix 49	*P. maximowiczii* × *P. trichocarpa*		
Max 1	*P. nigra* × *P. maximowiczii*	f	
Max 3	*P. nigra* × *P. maximowiczii*	f	
Max 4	*P. nigra* × *P. maximowiczii*	f	
Monviso	*P. generosa* × *P. nigra*	f	
Muhle Larsen	*P. trichocarpa*	f	
NE 42 *	*P. maximowiczii* × *P. trichocarpa*	m	
Pannonia	*P.* × *euramericana*	f	
Rochester	*P. maximowicii* × *P. nigra*	f	
Robusta	*P.* × *euramericana*	m	
Weser 6	*P. trichocarpa*		
AF 2	*P.* × *canadensis* Moench	m	AFV
AF 6	*P. generosa* × *P. nigra* A. Henry	f	
AF 8	*P. trichocarpa* × *P.* × *generosa*	f	
AF 13	*P.* × *canadensis*		
AF 15	*P. deltoides* × *P. nigra*		
AF 16	*P.* × *canadensis*		
AF 17	*P. deltoides* × *P. nigra*		
AF 18	*P. deltoides* × *P. nigra*		
AF 19	*P. deltoides* × *P. nigra*		
AF 20	*P. deltoides* × *P. nigra*		
AF 24	*P. deltoides* × *P. nigra*		
AF 27	*P. deltoides* × *P. nigra*		
AF 28	*P. deltoides* × *P. nigra*		
P1	*P.* × *canescens*		TI (UG/INRA 717-1B4)
4 × Göttingen	*P.* × *canescens* (tetraploid)		
Esch 5	*P. tremula* × *P. tremuloides*		

* syn. Hybride 275.

2.2. Determination of Growth Parameters

After the first growing season, the survival rate was determined for all poplar varieties in January 2013. This was repeated at the time of the first harvest in January 2015 and the second harvest in January 2018. At each harvest, the number of shoots per stool was counted, and plant height and diameter at breast height (DBH) were measured with a diameter measurement tape at a height of 1.3 m on each individual shoot. The dry matter content (DMC) of each variety was determined by harvesting three trees of each plot, that is nine trees per variety in total. A sample was taken from each of these trees from the lower, middle and upper sections. These samples were grounded and weighed. Fresh weight after harvest and dry weight after dehydration were measured using an electronic scale with a spring balance (precision ± 1 g). Dry weight was determined by taking a representative, plot-based subsample of each sample and drying it for 48 h in the laboratory at 103.5 °C (DIN 52183 [24]) until a constant weight was reached [25,26]. This subsample was used to estimate the total value of dry woody biomass for each sample by creating a power function for each poplar variety [27] and calculating the dry woody biomass per shoot by means of the DBH. The Y = ax^b power function best fit the curve when using the method of least squares. Once the biomass of each shoot was calculated, we were able to estimate the biomass of each plot. The biomass of each tree is the sum of the biomass of all its shoots, and the plot biomass is therefore the sum of the biomass of all its trees. Thus, the survival rate of each plot was also taken into account. Using the number of trees per hectare, we converted the average total biomass per plot into the biomass per hectare (tons absolute dry biomass, t_{adm} ha^{-1}). The dry matter biomass yield (DBY) (t_{adm} ha^{-1} y^{-1}) resulted from dividing the biomass per hectare by the number of years between each harvest.

2.3. Data Analysis

The collected data were analyzed for normality using the Shapiro–Wilk test ($\alpha = 0.05$). None of the data of the growth parameters followed a Gaussian distribution, so the differences between poplar varieties were analyzed using the non-parametric Kruskal–Wallis test ($\alpha = 0.05$). Fisher's least significant difference procedure was used as post hoc test. Correlation between the six variables was tested using Pearson's product moment coefficient ($\alpha = 0.05$). In addition, we tested the correlation between parameters and the actual plot position. No evidence for spatial autocorrelation was found. All analyses were carried out using R 3.6.3 [28] and the packages *tidyverse* [29] and *ggcorrplot* [30].

3. Results

3.1. Survival Rate

Out of the 37 poplar varieties, 26 varieties had a survival rate of ≥90% and 33 varieties of ≥80%. Thus, the overall survival rate after the first growing season was very high (Table 2). Understandably, the three TI varieties, which came in pots, did particularly well with survival rates between 93% and 100%. However, with up to 98%, for Max 4, similar survival rates were also achieved with unrooted cuttings. With 56% and 57%, the AF 20 and AF 19 varieties had particularly low survival rates. At the first harvest in January 2015, the survival rate of some varieties had drastically decreased. The reduction was most severe for AF 2, AF 24 and AF 15 with a decrease of 53%, 49% and 42%. Even though not as many AF 19 and AF 20 individuals had died, the survival rate was nevertheless reduced to a very low 37% and 17%, respectively. For other varieties, the decrease in individuals was not as drastic but still remarkable. For example, the survival rate of the Hungarian varieties Kopecky, Koltay and Pannonia was reduced by 35%, and 29% for the latter. In contrast, Isières, Max 1 and Max 4 performed very well with a decrease in the survival rate of only 1%, 2% and 3%. In comparison to the first rotation period, there were only marginal decreases in the survival rate of a few varieties.

Table 2. Survival rate of the poplar varieties at the end of the first growing season (2013), after three years (2015) and after six years (2018).

Variety	Survival Rate [%] 2013	2015	2018
Max 4	98	95	95
Fritzi Pauley	84	80	80
Max 3	95	83	83
AF 18	96	84	84
AF 16	77	72	72
AF 17	95	86	86
Matrix 24	91	72	67
Isières	98	97	97
Max 1	97	95	95
AF 28	81	52	52

Table 2. *Cont.*

Variety	Survival Rate [%] 2013	2015	2018
AF 13	90	54	54
Weser 6	96	87	87
Matrix 49	89	81	81
AF 27	95	62	62
Pannonia	93	64	63
Monviso	93	61	61
Rochester	95	82	82
Koltay	91	56	52
P1	100	96	96
Heidemij	94	61	61
AF 24	94	45	45
NE 42	96	87	87
AF 8	83	52	52
Harff	94	80	76
Robusta	90	75	75
AF 19	57	37	37
Kopecky	96	61	60
Jacometti 78 B	88	72	72
AF 2	96	43	43
AF 6	85	46	46
4 × Göttingen	98	85	85
Androscoggin	83	59	59
I 214	96	62	62
AF 15	91	49	48
Muhle Larsen	73	52	52
Esch 5	93	74	74
AF 20	56	17	17

3.2. Resprouting Capacity

In the first rotation period from 2012 to 2015, about 99% of the established poplars had only one shoot. After the first harvest, the number of shoots per stool increased and averaged 1.59 shoots for all poplar varieties (Figure 1). The highest median with 2.59 shoots per stool was recorded for Max 3, followed by Max 4 (2.46) and Heidemij (2.12). While these three varieties did not show any peak values regarding the number of shoots per stool, AF 17 had a maximum number of 13 shoots, followed by Matrix 24 with 11 shoots and Rochester, Isières, Weser 6 and I 214 with 10 shoots. The statistical analysis highlights the high number of shoots of Max 3 and Max 4, whereas, in general, no distinct significant differences were recorded for individual varieties or groups of varieties.

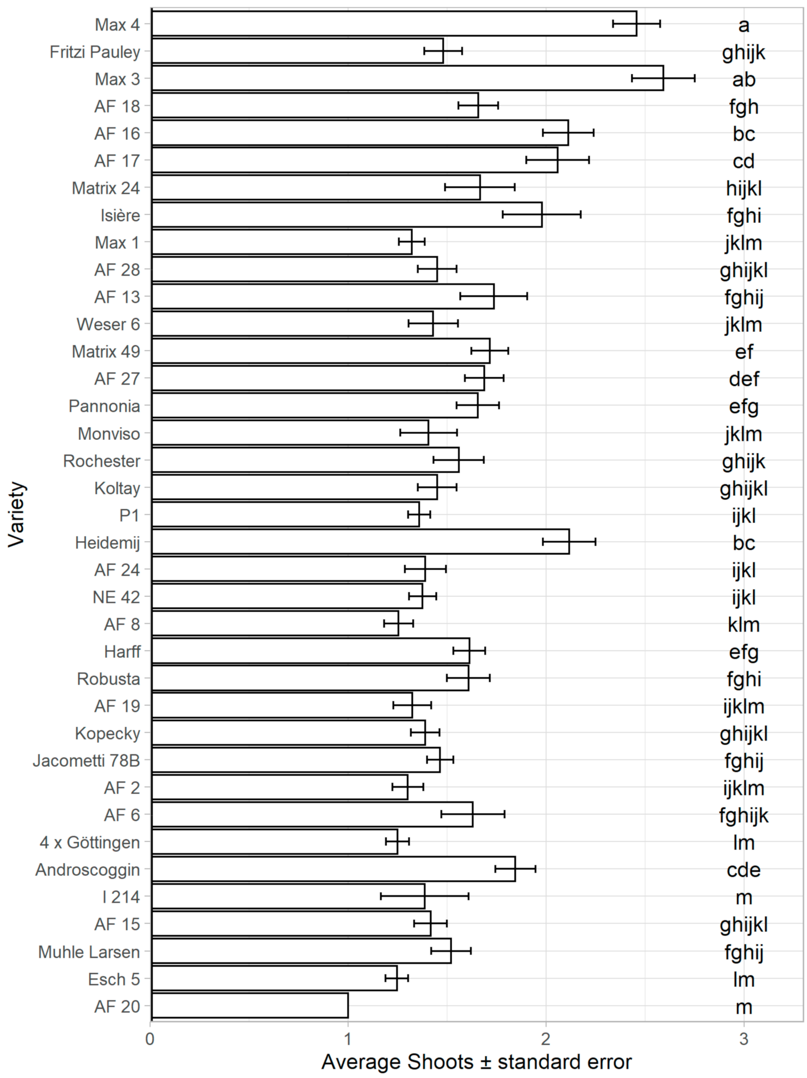

Figure 1. Average (±standard error) number of shoots of the poplar varieties in the winter of 2018, six years after planting and three years after the first harvest. Statistical analysis was carried out using the non-parametric Kruskal–Wallis test (α = 0.05, $n \in$ [17;95]) paired with Fisher's least significant difference procedure to highlight statistically different varieties; the letters on the right-hand side of the figure represent the statistical groups to which each variety belongs.

3.3. Plant Height

At the end of the first growing season, the 37 poplar varieties reached an average height of 1.60 m. The greatest plant heights were achieved by AF 17 with 2.35 m, followed by I 214 (2.20 m) and Max 4 (1.98 m). In contrast, Jacometti 78 B (1.12 m), Rochester (1.11 m) and AF 2 (1.09 m) showed only a weak height growth in the year of establishment. After three years, in 2015, a median height of 6.29 m was recorded for all poplar varieties. AF 13 (7.95 m), Weser 6 (7.76 m) and Fritzi Pauley (7.75 m) were the most successful ones in terms of height gain, while 4 × Göttingen (4.04 m), AF 20 (4.78 m) and Robusta (5.00 m) had achieved the lowest plant height after three growing seasons (Figure 2). In the second rotation period from 2015 to 2018, the average height of the poplar varieties only increased by 0.19 m to 6.48 m. Compared to the first rotation period, 20 varieties showed an increase in height growth at the end of the second rotation period, and 17 varieties a decrease. AF 19 had the greatest increase in height, which was 1.83 m higher than at the end of the first rotation period, followed by AF 13 and AF 24. The lowest plant height after two rotation periods was recorded for Esch 5 (4.49 m), Muhle Larsen (5.12 m) and AF 15 (5.34 m).

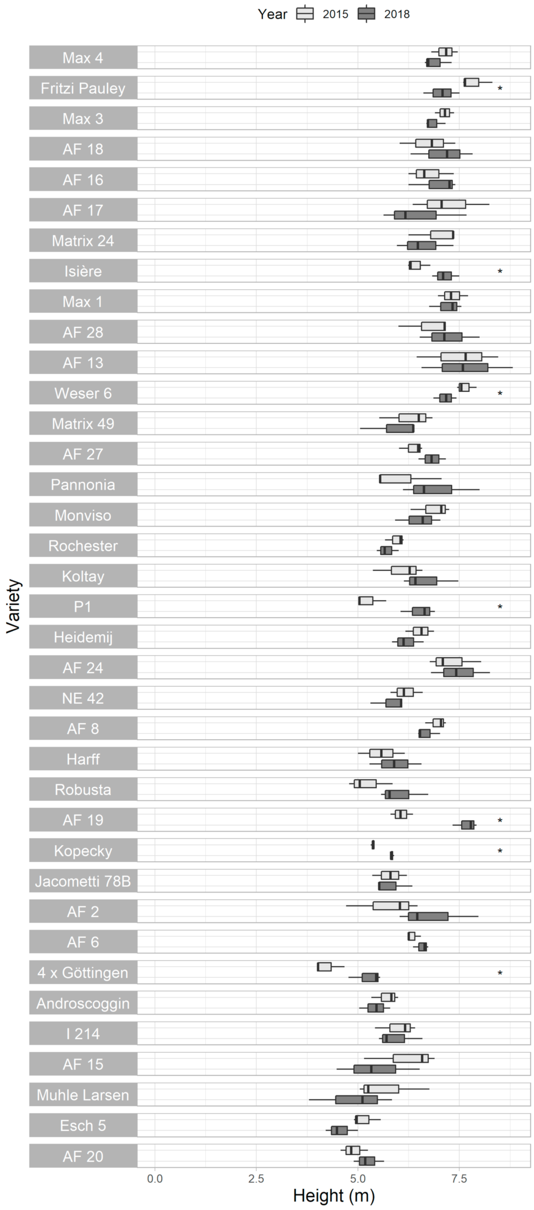

Figure 2. Plant height of the poplar varieties in the winters of 2015 and 2018. For each variety, the difference between the height in 2015 and in 2018 was analyzed using the non-parametric Kruskal–Wallis test (α = 0.05, n = 3). Statistically significant differences are marked with an asterisk.

3.4. Diameter at Breast Height (DBH)

The DBH of the 37 poplar varieties reached an average of 1.0 cm after the first growing season. AF 19 achieved the highest DBH (1.2 cm) followed by AF 13 and AF 17 (both 1.1 cm). Esch 5, Muhle Larsen and Rochester had the lowest DBH with 0.6 cm. By the end of the first rotation period in 2015, the varieties achieved an average DBH of 3.3 cm. The greatest increases in DBH were recorded for AF 13 with 4.7 cm, followed by Fritzi Pauley (4.4 cm) and Max 1 with 4.3 cm. After the second rotation period in 2018, the average DBH decreased by 0.9 cm to 2.4 cm. This decrease applied to all poplar varieties. The greatest DBH at the end of the second rotation period was reached by Max 1 with 4.7 cm, followed by AF 19 and AF 13 with 4.4 cm. The lowest increase in DBH was 1.1 cm for Esch 5, followed by Muhle Larsen (1.6 cm) and Androscoggin (1.7 cm) (Figure 3).

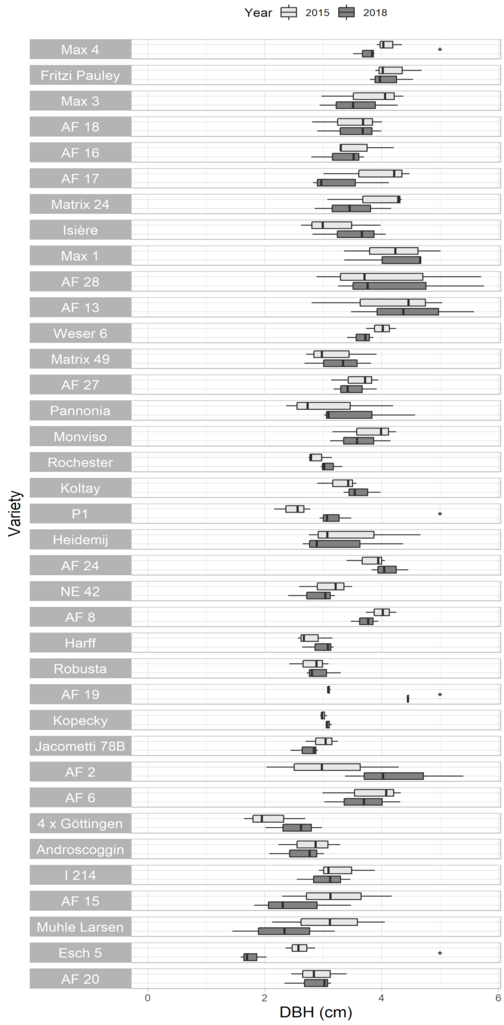

Figure 3. Diameter at breast height of the poplar varieties in the winters of 2015 and 2018. For each variety, the difference between the diameter in 2015 and in 2018 was analyzed using the non-parametric Kruskal–Wallis test ($\alpha = 0.05$, $n = 3$). Statistically significant differences are marked with an asterisk.

3.5. Dry Matter Content (DMC)

After three years, in 2015, the DMC averaged 45.2%, with large differences among the 37 poplar varieties. The greatest DMC was recorded for Rochester with 50.7%, followed by NE 42 (49.5%) and Androscoggin (48.0%). AF 28 had the lowest DMC with 42.2%, followed by Koltay (43.3%) and Max 1 (43.4%). With 44.5%, the average DMC after the second rotation period was similar to that in the first rotation period. Again, Androscoggin (54.6%), NE 42 (49.5%) and Rochester (50.7%) reached the highest DMC values. The lowest DMC was recorded for AF 27 with 38.1%, followed by AF 17 (40.5%) and AF 2 (40.2%).

3.6. Dry Matter Biomass Yield (DBY)

After the first rotation period, in 2015, Fritzi Pauley reached the highest yield with 14.6 t_{adm} ha^{-1} y^{-1}, followed by Weser 6 (14.3 t_{adm} ha^{-1} y^{-1}), Max 3 (12.4 t_{adm} ha^{-1} y^{-1}) and Max 4 (12.0 t_{adm} ha^{-1} y^{-1}) (Figure 4). Moderate yields between 6.8 and 6.9 t_{adm} ha^{-1} y^{-1} were recorded for Pannonia, AF 27 and Matrix 49. AF 20 (2.4 t_{adm} ha^{-1} y^{-1}), 4 × Göttingen (2.8 t_{adm} ha^{-1} y^{-1}) and AF 19 (3.2 t_{adm} ha^{-1} y^{-1}) had the lowest yields. After the second rotation period, in 2018, the highest yield was found for Max 4 with 15.8 t_{adm} ha^{-1} y^{-1}. Fritzi Pauley (14.5 t_{adm} ha^{-1} y^{-1}) and Max 3 (13.3 t_{adm} ha^{-1} y^{-1}) reached only slightly lower yields. With 8.1 t_{adm} ha^{-1} y^{-1}, P1, Pannonia and Koltay showed moderate yields. The lowest yields were recorded for AF 20 (0.8 t_{adm} ha^{-1} y^{-1}), followed by Esch 5 (1.2 t_{adm} ha^{-1} y^{-1})

and AF 15 (2.5 t_{adm} ha^{-1} y^{-1}). Between the first and the second rotation periods, 19 varieties were able to increase their yield, whereas 18 varieties showed a yield reduction. The increases were greatest for AF 18 (4.8 t_{adm} ha^{-1} y^{-1}), AF 16 (4.1 t_{adm} ha^{-1} y^{-1}) and Max 4 (3.8 t_{adm} ha^{-1} y^{-1}). The greatest decreases were recorded for Weser 6 (−5.4 t_{adm} ha^{-1} y^{-1}), Max 1 (−4.1 t_{adm} ha^{-1} y^{-1}) and Esch 5 (−3.0 t_{adm} ha^{-1} y^{-1}).

The statistical analysis does not show any distinct significant differences of individual varieties but allows for dividing the varieties into the groups of high-yielding (a–c) and low-yielding (i–k) varieties (Figure 5).

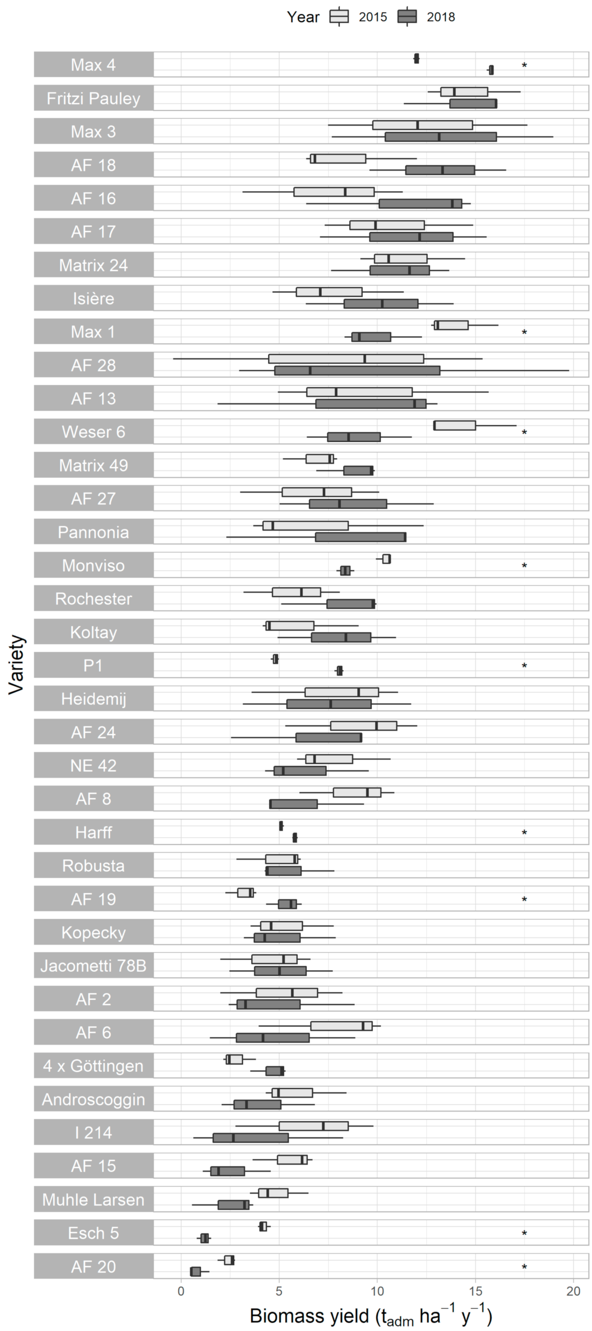

Figure 4. Biomass yield of the poplar varieties in the winters of 2015 and 2018. For each variety, the difference between the biomass yield in 2015 and in 2018 was analyzed using the non-parametric Kruskal–Wallis test (α = 0.05, *n* = 3). Statistically significant differences are marked with an asterisk.

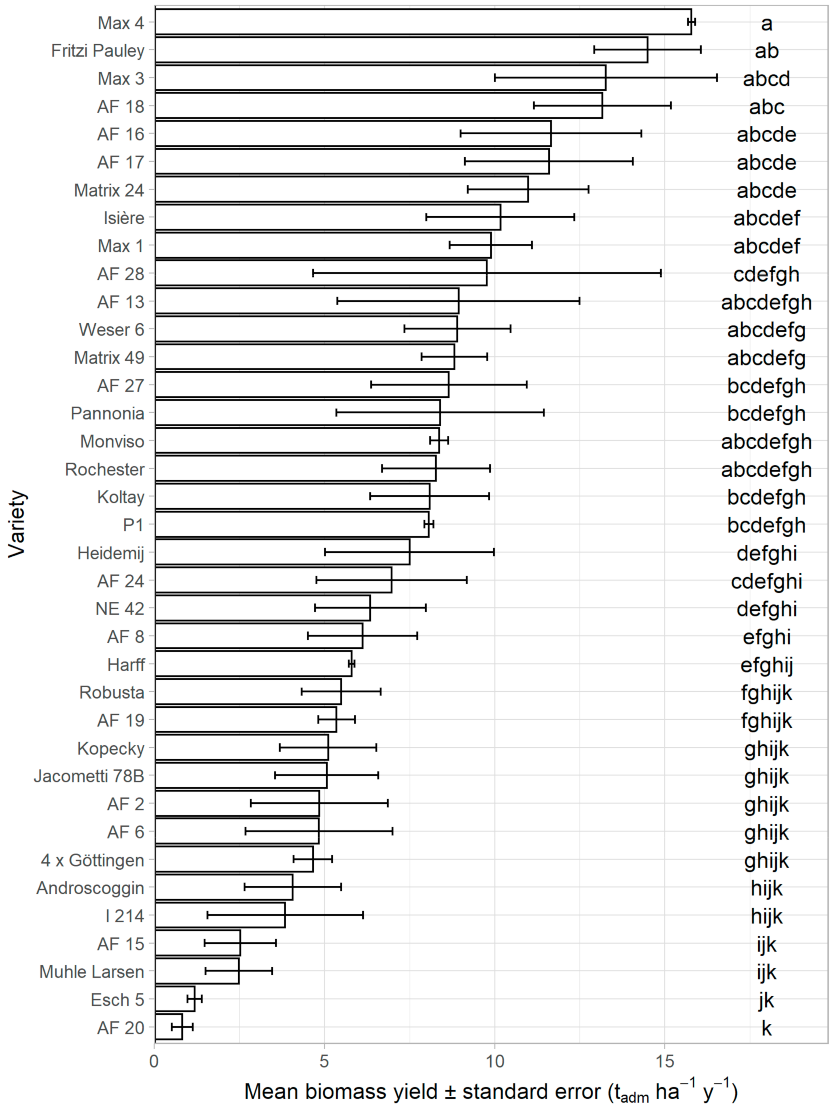

Figure 5. Average (±standard error) biomass yield of the poplar varieties in the winter of 2018, six years after planting and three years after the first harvest. Statistical analysis was carried out using the non-parametric Kruskal–Wallis test ($\alpha = 0.05$, $n \in [17;95]$) paired with Fisher's least significant difference procedure to highlight statistically different varieties; the letters on the right-hand side of the figure represent the statistical groups to which each variety belongs. All presented results are in order of the biomass yield presented in this figure.

Slightly positive correlations between the survival rate and the number of resprouting shoots (0.27), as well as the number of resprouting shoots and the dry matter biomass yield (0.38), were calculated (Figure 6). Furthermore, a strong correlation between plant height and DBH (0.73) was found in this study. This is also affirmed by the close correlations between DBH and biomass yield (0.75), and between plant height and biomass yield (0.69) (Figure 6).

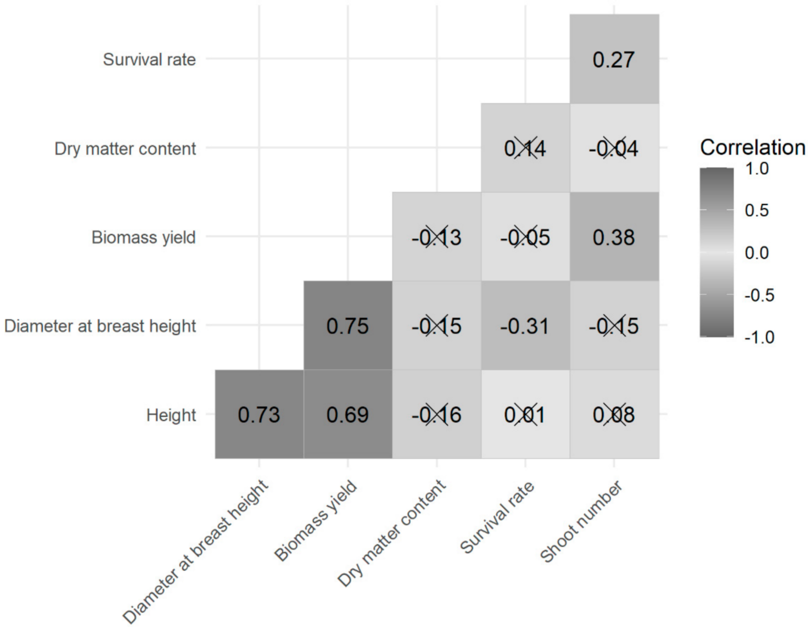

Figure 6. Correlation matrix of all recorded growth parameters of the poplar varieties in the winter of 2018, six years after planting and three years after the first harvest, using Pearson's product moment coefficient. Non-significant correlations ($\alpha \geq 0.05$) are crossed out.

4. Discussion

The economic success of an SRC is determined by the natural site conditions (e.g., soil texture, soil nutrient content, precipitation, ground water level, solar radiation and temperature), which are key factors to be considered during the planning process of an SRC [31], as well as the conditions that arise from, and can be influenced by, the plantation management itself, in particular during the establishment of an SRC, such as site preparation (tillage, herbicide application, etc.) [32], timing of planting (weather conditions, soil water status), planting material (quality of cuttings), planting techniques (setting and depth of planting) and weed control [1,31,32].

The most important and easily visible factor showing a successful management of these parameters is the survival rate of the established plants. In general, our data show very high survival rates at the end of the first growing season when compared with the literature [32]. Since high-quality propagation material and professional cultivation methods were used, the relatively low survival rates of AF 20 (56%), AF 19 (57%) and Muhle Larsen (73%) seem to be variety-specific characteristics [33]. The survival rate of all varieties decreased from the end of the first growing season in 2013 to the first harvest in 2015. The different extent of plant mortality can be assumed to be a reaction of the different poplar varieties to the specific site conditions, since neither major biotic or abiotic damage events occurred, and a proper plantation management was ensured. In the second rotation period from 2015 to 2018, there were only marginal decreases in the survival rate of a few varieties (e.g., −5% for Matrix 24 and −4% for Harff). Overall, the survival rates remained at the same level. Thus, it can be concluded that the variety-specific adaptation to the site is completed at the time of the harvest after the first rotation period.

The number of resprouting shoots after a harvest depends on the poplar variety, the planting density of the selected SRC rotation system and the site conditions [23,25,26,34]. The highest-yielding varieties in this study very often belonged to the most robust species. However, a tripling or quadrupling of the number of shoots as described by Röhle et al. [23] was not observed. The correlations between the survival rate and the number of resprouting shoots, as well the number of resprouting shoots and the dry matter biomass yield, lead to the conclusion that the greater the average number of shoots, the greater the dry matter biomass yield. This also means that the resprouting capacity of poplars does not only compensate the loss of individual plants in SRC but can also increase the yield. These results are consistent with those of Paris et al. [35].

The productivity of poplars is strongly correlated with various stem and leaf traits such as plant height, diameter, total leaf area and individual leaf area, and has been studied multiple times [36–41]. The results from our study confirm these literature results. Even the strong correlation between plant height and DBH found in our study has been described by several authors and ultimately led to various allometric functions to determine the biomass of an SRC by measuring a few, but crucial, parameters.

Aylott et al. [42,43]), Gielen and Ceulemans [44] and Cochard et al. [45] reported biomass yields between 2.0 and 9.6 t_{adm} ha^{-1} yr^{-1} from 16 poplar varieties in England and Wales. Similar results were reported from across Europe (e.g., Rae et al. [46]) and North America (e.g., Dillen et al. [47]). To generate an economically justified income from an SRC, a yield of at least 8 t_{adm} ha^{-1} y^{-1} needs to be achieved [46]. Since the market prices for SRC biomass fluctuate greatly depending on location and time, a reasonable average financial yield cannot be specified. However, the biomass yield of the poplar varieties included in this study can be assessed with regard to the specific site conditions, which also include the occurrence of extreme, climate change-related weather events in recent years. From the first to the second rotation periods, only approximately 50% of the poplar varieties showed increases in biomass yield (e.g., Max 4, AF 18, AF 16), whereas varieties such as Weser 6, Max 1 and AF 6 had decreasing yields. This is opposed to various publications, which reported an increasing yield over the first ten years [48]. Except for Fritzi Pauley, the six highest-yielding varieties increased their yield from the first to the second rotation periods. With 11.5 to 15.6 t_{adm} ha^{-1} y^{-1}, these varieties were able to achieve very good yields under the given site conditions. Many varieties had yields of around 8 t_{adm} ha^{-1} y^{-1}. Some of these varieties were able to increase their yield in the second rotation period, others were not. Since no active management measures were carried out during the second rotation period and no major biotic damage was recorded, it must be assumed that the determined yields represent the variety-specific yields at the study site. The varieties that had yields below 4 t_{adm} ha^{-1} y^{-1} in the first rotation period showed a significant yield decrease in the second rotation period, which can be attributed to a reduction in all growth parameters described above (survival rate, number of shoots per stool, plant height, DBH). In conclusion, these varieties are not suitable for SRC in this location.

Looking at the biomass yield of the harvest in 2018, it is noticeable that the poplar varieties can be divided into two groups, that is into high-yielding and low-yielding varieties. The high-yielding varieties include breeds with *P. deltoides* × *P. nigra* as well as with *P. trichocarpa* × *P. maximowiczii* (i.e., Max 3, Max 4, Matrix 24). The latter is confirmed by other studies [19,49–51]. The very good performance of the *P. deltoides* × *P. nigra* varieties on this low-yield and quite dry site was not expected and, to our knowledge, has not yet been described in the literature. Benetka et al. [49] reported below-average yields of *P. nigra* varieties on low-yielding locations in the Czech Republic. Based on our study, this can be confirmed for other *P. deltoides* × *P. nigra* varieties (e.g., Robusta, Jacometti 78B, AF 2, AF 6, I 214). These varieties are known to be susceptible to fungal diseases, in particular poplar leaf rust, which can have a significant negative impact on the growth of these varieties [52,53]. The very poor performance of the AF 15 and AF 20 varieties was due to a very high plant mortality rate. Since no biotic damage (neither fungal nor insect damage) was found on either variety, we assume that they were not able to cope with the specific site conditions.

Furthermore, the poor performance of the three TI varieties was surprising. Despite the advantage of having been delivered as rooted plants in pots, they did not exhibit a satisfying growth. While P 1 still reached the standard yield with approximately 8 t_{adm} ha^{-1} y^{-1} in the second harvest, 4 × Göttingen and Esch 5 only achieved below-average results with just under 5 and 1 t_{adm} ha^{-1} y^{-1}, respectively. Since the plant mortality rates of these varieties were low and no major biotic damage was noted, the negative performance is most likely also attributed to the site conditions.

5. Conclusions

Our data suggest that the selection of poplar varieties based on the particular site is extremely important for the economic success of an SRC. On the continental-influenced light sandy soil of the study site, only eight out of 37 poplar varieties showed economically sufficient growth in a mini-rotation SRC and produced a biomass yield of more than 10 t_{adm} ha^{-1} y^{-1}. This included older varieties such as Fritzi Pauley, Max 3 and Max 4, as well as newer breeds from Italy, such as AF 16, AF 17 and AF 18, and from Germany, such as Matrix 24. These varieties can be recommended for commercial use in SRC under the specific site conditions. Many varieties had a yield of around 8 t_{adm} ha^{-1} y^{-1}, with some varieties increasing and some decreasing their yield from the first to the second rotation period. Given the current climate change prognosis, we advise against the cultivation of these varieties. Six varieties did not even reach 4 t_{adm} $^{ha-1}$ y^{-1} in the second harvest. This included the old varieties Androscoggin and Muhle Larsen, as well as the new AF 15 and AF 20 varieties from Italy and the Esch 5 variety from TI.

Another data collection to verify these conclusions is planned for 2021 at the end of the third rotation period.

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