Growth and Development of *Paulownia tomentosa* and *Paulownia elongata x fortunei* in Glasshouse Experiment

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Abstract

The growth potential of *Paulownia tomentosa* and *Paulownia elongata* x *fortunei*, cultivated at three planting densities in a greenhouse was investigated, using conventional field and laboratory methods. Data on the survival percentage, base diameter, total plant height, biomass and leaf area were obtained and analyzed. Differences in growth, productivity, survival and biomass allocation pattern of the tested clones of *Paulownia tomentosa* and *Paulownia elongata* x *fortunei* were found. The results obtained showed that hybrids of *Paulownia elongata* x *fortunei* do not exceed the growth performance of the *Paulownia tomentosa* species for the region of Sofia.

Key words: fast-growing forest trees, plant height, base diameter, biomass allocation

Introduction

Over the last two decades, species and hybrids of genus *Paulownia* have attracted the attention of many researchers, mainly due to the fact that they are fast-growing and suitable for testing at higher planting densities, at short-rotations, and possess potential for repeatable reproduction. According to the literature (Ericsson and Nilsson, 2006), short-rotation plantations will be increasingly used for biomass production in the future, and species or clones with high repetitive regenerative capacity will be particularly valuable. Moreover, Maier and Vetter (2004) reported that, unlike most fast-growing tree species, *Paulownia tomentosa* increases its bioproductivity during the second rotation or after the first 4-year cycle. Advantageous for using hybrid *Paulownia* clones in agroforestry or short rotation cultivation are characteristics such as drought tolerance, unpretentiousness to soil composition, tolerance to wide daily temperature amplitudes, which according to some authors (Tang et al ., 1980), makes them in demand on the world market. In contrast to *Paulownia tomentosa*, which is introduced in the early 20th century and is already naturalized, *Paulownia elongata* x *fortunei* have been tested in Europe just recently (Zuazo et al., 2013; García-Morote et al., 2014). In Bulgaria, the first experiments started in 2004 with the development of *in vitro* propagation protocol. The first experimental plantations for bioproductivity studies on different terrains and in different parts of the country were initiated twelve years ago (Gyuleva, 2008, 2010; Gyuleva et al., 2012; Gyuleva et al., 2013; Gyuleva, 2014; Stankova et al., 2016, 2019).

The growth and development of tree species at a young age in response to the available growing space (number of plants per unit area) is a key aspect in the ecology of trees in forest ecosystems and forest plantations. Higher density reduces light, food and water availability, which has an effect on each individual. The phenotypic changes that occur are expressed by such measurable characteristics as plant height and diameter, and the biomass partitioning to various organs - stem, branches, leaves and roots (Longbrake and McCarthy, 2001; Sinacore et al., 2017). The first results in Bulgaria to model the production of stem biomass at an early age in *Paulownia*, depending on the diameter of the plant, are already known (Stankova et al., 2016). The analysis of the localization of plant biomass in tree organs such as stems, branches, leaves and roots is considered a modern ecological approach to assess the adaptability of the tree species to site conditions (Poorter et al. 2012, 2015). In our country, such an analysis has not been conducted so far.

The aim of the present study is to evaluate and compare growth and productivity parameters of *Paulownia tomentosa* and *Paulownia elongata* x *fortunei* at different ages and stocking levels, and to analyze the biomass localization to leaves, stems and root system during two-year cultivation at uncontrolled greenhouse conditions.

Materials and Methods

At the beginning of April 2017, 500 isolated root cuttings of *Paulownia tomentosa* (clone group based on isolated roots of half-sib saplings) and *Paulownia elongata* x *fortunei* (clone group based on three clones) were planted in flower pots. The roots were obtained from experimental four-year-old plantations, established on the territory of Strumyani, (Mikrevo nursery) and Zlatna Panega. Alluvial soil, enriched with manure, was used (pH= 7.2 and low N content before enrichment). After two months of cultivation, the newly developed plants were replanted in 7-liter containers and arranged in a scheme, providing three variants of growing space: 0.018 m^2, 0.027 m^2 and 0.053 m^2 of growing area in one container, respectively. The pots were placed in greenhouse beds filled with 15 cm - layer of sand. The depth of each container was 18 cm. The number of containers for each variant was 12, and the numbers of the measured platns were 12, 24 and 36, respectively. The surviving plants of the different variants were replanted in 20-liter containers with 28 cm of depth in April 2018, for further measurements. The newly provided area was 0.024 m^2, 0.035 m^2 and 0.071 m^2, respectively. Biometric measurements were performed with an electronic caliper and a metal roulette. The electronic scale Mettler - Toledo with an accuracy of 0.00001 g was used to measure the fresh weights *in situ*. The oven-dried weight (g) was obtained using the moisture content of the obtained stem, leaf and root samples. Individual plant leaves were isolated from each variant, scanned and measured using AutoCad2014 and a scaling factor of 0.01 to define leaf area, leaf length and leaf width.

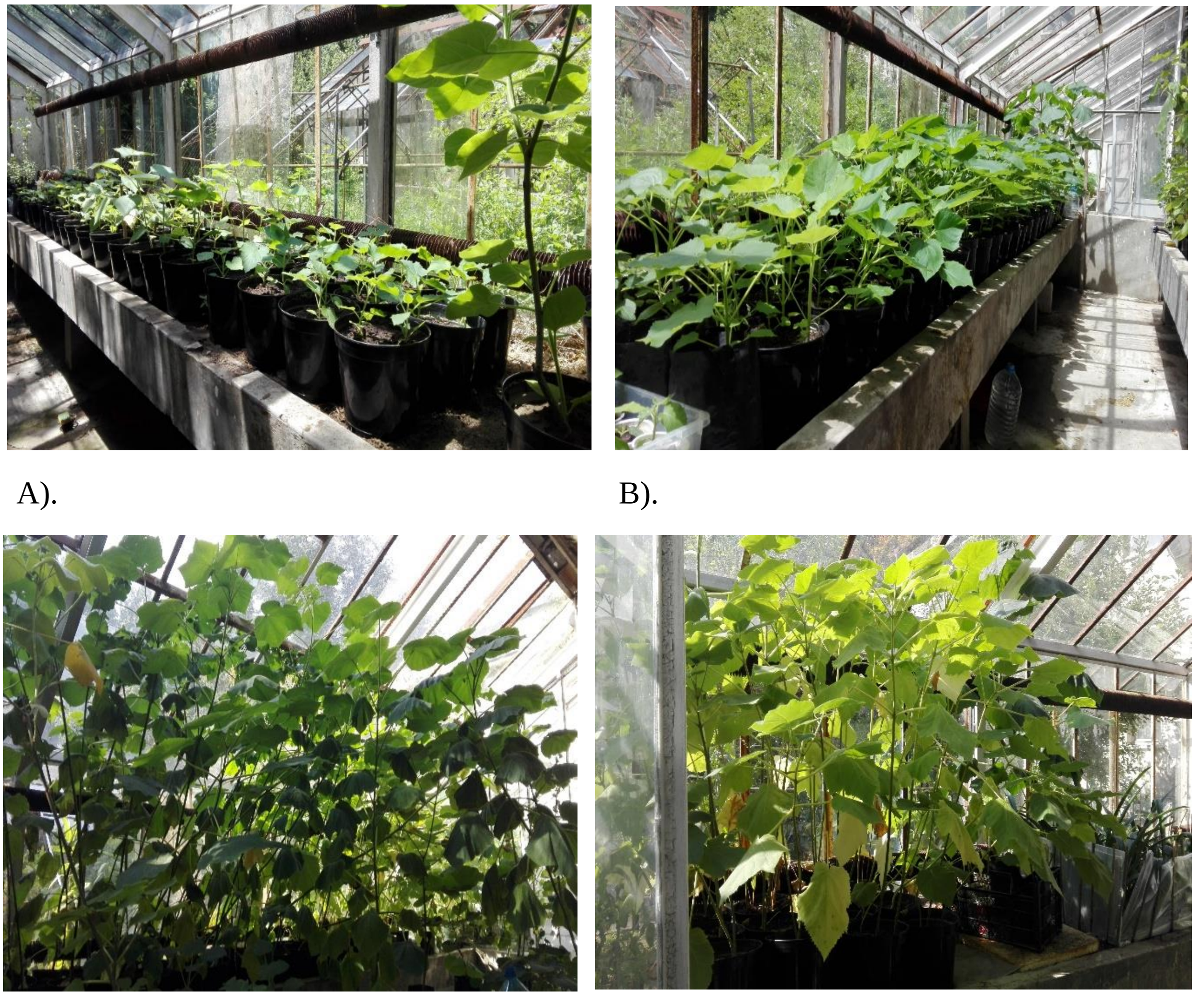
The experiment was conducted in two stages. During the first growing season, height, diameter, leaf area per tree per variant were analyzed three times (June, July and October), and survival during the winter season was assessed. During the second stage, the biomass allocation by fractions (root, stem and leaves) was studied in order to evaluate the environmental adaptability of the two clonal populations and to estimate specific leaf area (cm^2/g), leaf area ratio (LAR) and Root-Shoot-Ratio (RSR).

Analysis of variance (ANOVA) with main factors of growth (height and diameter): age (month), clonal population and growing space was applied during the first study stage. Linear regression analysis to study the relationship between biomass fractions and measurable quantitative characteristics, such as diameter at the base and height of the plant, was used during the second stage of the study.

Statistical data processing was performed using software packages R “stats” and “agricolae” (R Core Team 2019; de Mendiburu 2020), and the visualization of the data was carried out with graphical functions of the R package “ggplot2” and “dplyr” (Wickham, 2016; Wickham et al., 2020).

Results and Discussion

The diameter at the base of the plant stem for the two clonal populations was measured three times in 2017 (Fig.1), and an analysis of variance (ANOVA) was applied (Table 1).



A). B).

C). D).

Fig. 1. *Measurements during season 2017: A). P. tomentosa and P. elongata x fortunei- June 2017; B). Intermediate measurement – July 2017; C) P. elongata x fortunei – September 2017; D) Paulownia tomentosa – September 2017 before the last measurement.*

ANOVA identified significant variation in the base diameter between the two clonal populations (F = 9,272 df = 1, p-value: 0,003) in the first studied month. At this early stage of the experiment, the base diameter of the clonal population of *Paulownia tomentosa* was significantly higher than that of the hybrid *Paulownia elongata* x *fortunei* in all three tested variants of growth area (Fig.2).

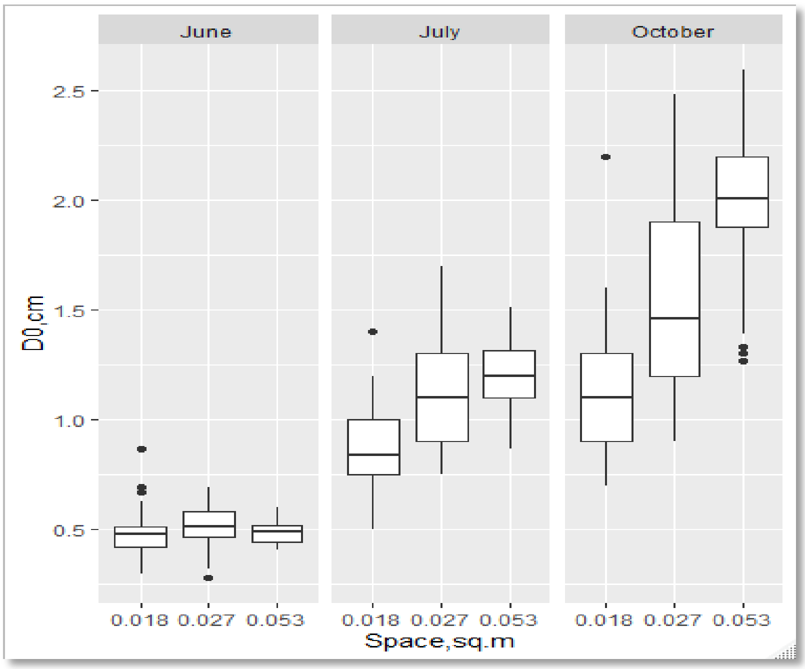


Fig. 2. *Effect of growing space (m^2) on the base diameter D0 (cm) of paulownia plants according to age (month of measurement 2017).*

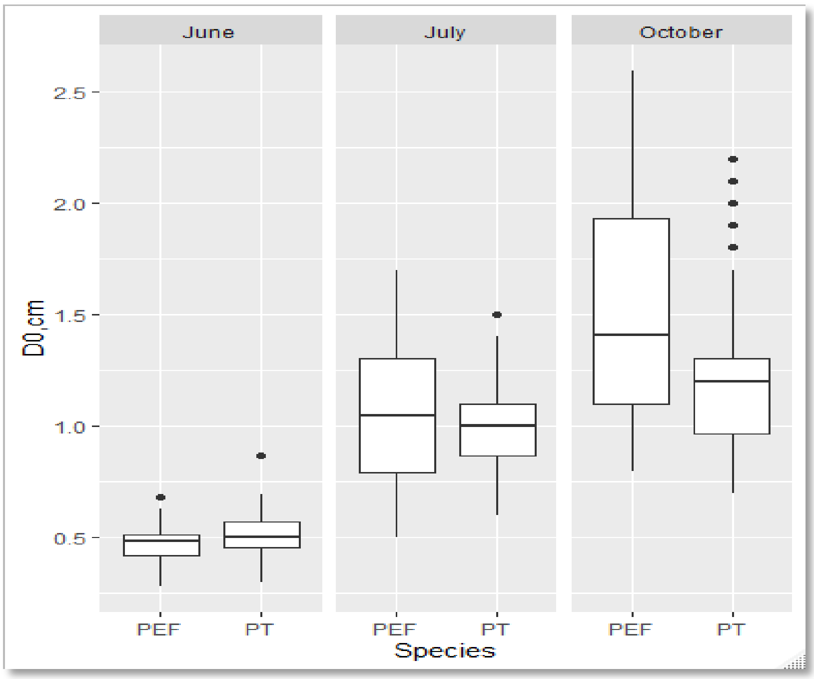


Fig. 3. *Effect of the clonal population (Paulownia tomentosa (PT) and Paulownia elongata x fortunei (PEF)) on the base diameter D0 (cm) according to age (month of measurement 2017).*

The factor growing space at this early stage has no significant effect (F = 2.636 and df=2, p-value: 0,075). With an average minimum temperature of 4.8^{0}C and an average maximum temperature of 16.6^{0}C for the preceding April, and an average minimum temperature of 9.5^{0}C and an average maximum temperature of 20.5^{0}C for the preceding May, this difference in favor of *Paulownia tomentosa* is not surprising. In our opinion, the main reason is the species differences between the two clonal populations. *Paulownia tomentosa* tolerated significantly better than *Paulownia elongata* x *fortunei* the lower temperatures in April and May. As the growing season progressed, the effect of the growth area as a factor increased (Fig. 1), and the effect of the clonal group weakened (Table 1).

Table 1. *Analysis of Variance for the variable base diameter (D0, cm) as affected by factors Growing space and Clonal population*

Month	Factors	Df	Sum Sq	Mean Sq	F value	Pr(>F)
June	Growing space	2	0,1547	0,0773	2,636	0,075
	Clonal population	1	0,2720	0,2720	9,272	0,003**
	Growing space X Clonal population	2	0,1483	0,0741	2,527	0,085
	Residuals	138	4,0489	0,0293		
July	Growing space	2	3,2601	1,6301	47,238	2,353e-16***
	Clonal population	1	0,1980	0,1980	5,739	0,018*
	Growing space X Clonal population	2	1,2530	0,6265	18,156	1,000e-07***
	Residuals	138	4,7620	0,0345		
October	Growing space	2	6,8738	3,4369	81,247	2,2e-16***
	Clonal population	1	1,4275	1,4275	33,474	4,140e-08***
	Growing space X Clonal population	2	0,9505	0,4753	11,235	3,016e-05***
	Residuals	138	5,8377	0,0423		

Significance level: '***' – P < 0,001 '**' – P < 0,01 '*' P – < 0,05

At an average minimum temperature of 14.3^{0}C and an average maximum temperature of 27.1^{0}C for the anterior June, *Paulownia elongata* x *fortunei* produced in July lower base diameter only at the variant of growth area of 0.027 m^2, compared to *Paulownia tomentosa*. Under the conditions of the other two variants of growing space *Paulownia elongata* x *fortunei* produced base diameter superior to that by *Paulownia tomentosa* and the differences were statistically significant. At the end of the growing season, the influence of the two factors growth area and clonal group, as well as the interaction between them, was clearly expressed (Table 1). At an average minimum temperature of 15.6^{0}C and an average maximum temperature of 29.0^{0}C for the preceding August, and an average minimum temperature of 11.5^{0}C and an average maximum temperature of 23.6 ^{0}C for the preceding September, *Paulownia elongata* x *fortunei* continued to produce significantly higher stem base diameter than that of *Paulownia tomentosa* (Fig. 3).

The effect of the growing space as a factor for the variable total tree height was also studied during the first growing season (Table 2).

Table 2. *Analysis of Variance for the variable height (H, cm) as affected by factors Growing space and Clonal population.*

Month	Factors	Df	Sum Sq	Mean Sq	F value	Pr(>F)
June	Growing space	2	1899,63	949,81	70,363	2,2e-16***
	Clonal population	1	266,83	266,83	19,767	1,784e-05***
	Growing space X Clonal population	2	1553,91	766,96	57,557	2,2e-16***
	Residuals	138	1862,83	13,50		
July	Growing space	2	177849	88925	188,205	2,2e-16***
	Clonal population	1	5700	5700	12,064	0,001***
	Growing space X Clonal population	2	39	19	0,041	0,960
	Residuals	138	65203	472		
October	Growing space	2	198347	99173	431,124	2,2e-16***
	Clonal population	1	12916	12916	56,150	7,304e-12***
	Growing space X Clonal population	2	68	68	0,297	0,744
	Residuals	138	230	230		

Significance level: ‘***’ – P < 0,001 ‘**’ – P < 0,01 ‘*’ P – < 0,05

ANOVA identified significant variation in the height, depending on the growing space, in June (F = 70.363 and df=2, p-value: < 2.2e-16). The maximum height was registered at the intermediate variant of stocking - 0,027 m^2 (Fig. 4). Its value was significantly higher than those obtained for the other two variants of growing space.

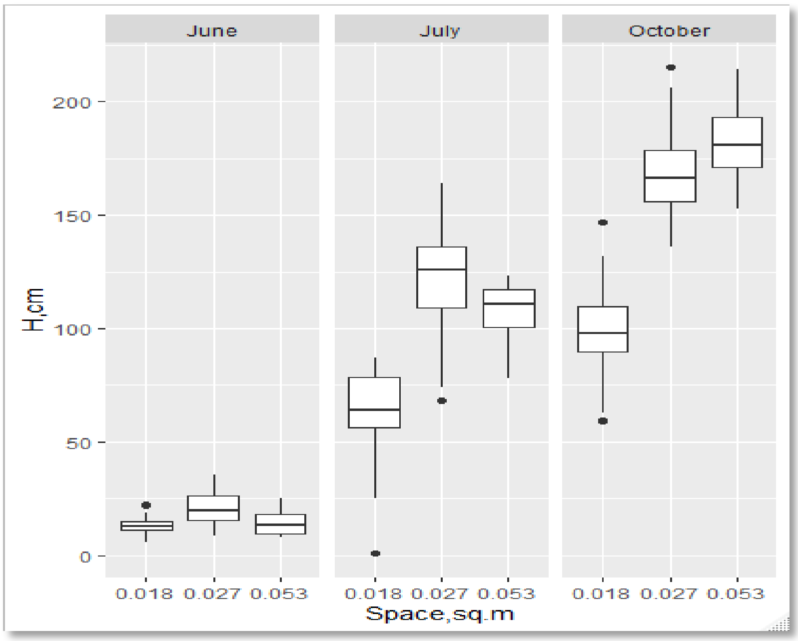


Fig. 4.*Effect of the growing space (m^2) on the height H (cm) of paulownia plants according to age (month of measurement 2017).*

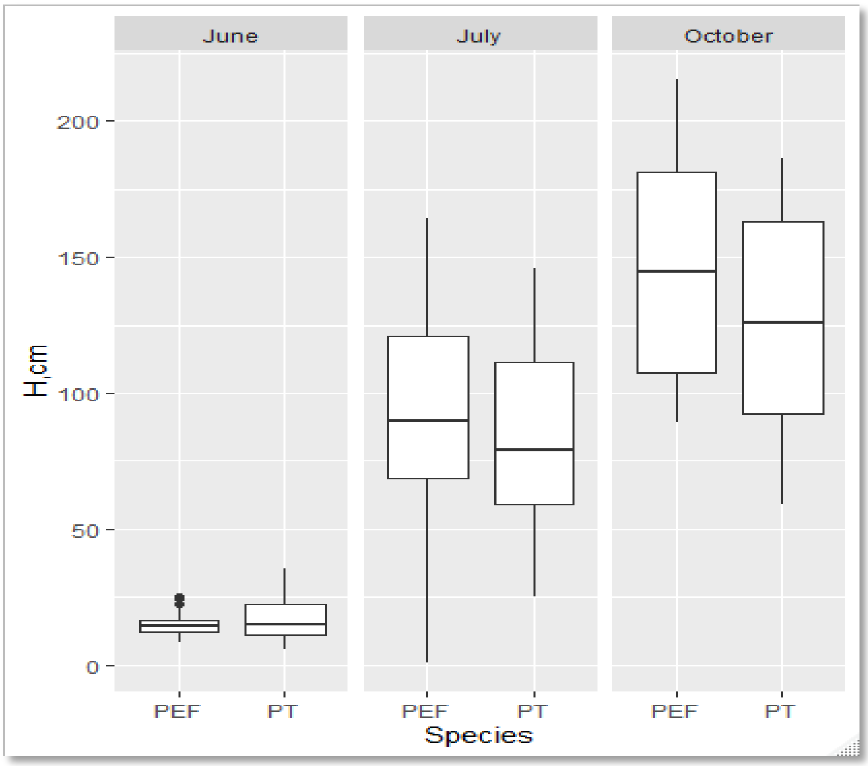
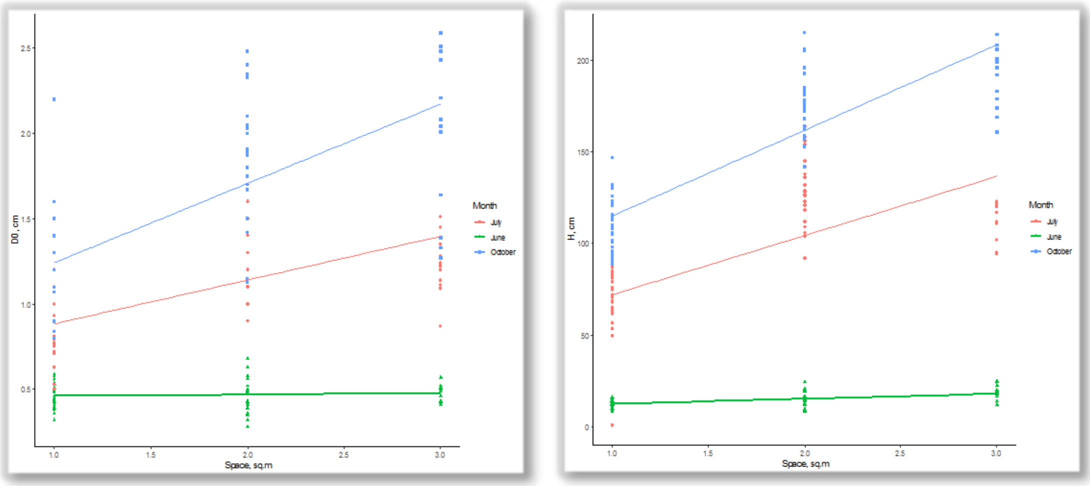


Fig. 5. Effect *of the clonal population (Paulownia tomentosa (PT) and Paulownia elongata x fortunei (PEF)) on the height H (cm) according to age (month of measurement 2017).*

Also, ANOVA identified high variation in height, depending on the clonal population (F = 19.767 and df=1, p-value: 1.784e-05). The difference in the values of the heights was again statistically significant and was in favor of Paulownia tomentosa (Fig. 5).

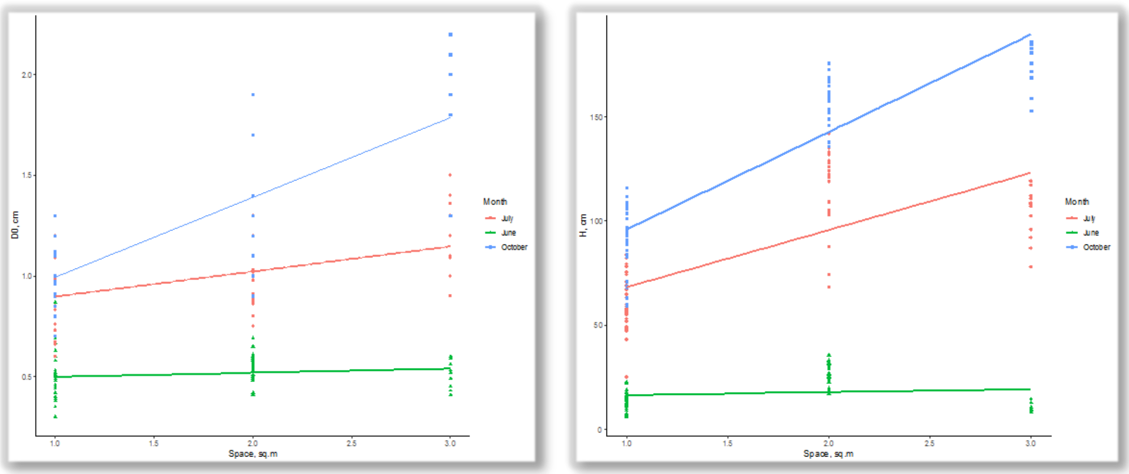
The temperature conditions mentioned earlier should be considered for this result as well. In July, ANOVA identified significant variation in heights depending on both factors, growing space (F = 188.205 and df=2, p-value: 2.2e-16) and clonal population (F = 12.064 and df=1, p-value: 0.00069). There was no indication for significant interaction between them. The maximum value of the height was registered again under the conditions of the second variant of stocking – 0.027 m^2 (Fig.4). This result, as well as the result of the first measurement in June, showed that individuals compete successfully with each other. In addition, all mean height values obtained differed significantly from each other, under the influence of the available growing space. At this stage, *Paulownia elongata* x *fortunei* is already taller than *Paulownia tomentosa* and the difference in the heights of the clonal populations was statistically significant (Fig.5). In October, ANOVA identified again a significant variation for this parameter, both for the growing space factor (F = 431.124 and df=2, p-value: 2.2e-16) and for the clonal population factor (F = 56.149 and df=1, p-value: 7.304e-12). The interaction between the two factors was absent. At this stage, the effect of the growing space is tangible. The maximum average height was reached by the two clonal populations at the largest available growing space – 0.053m^2. As the growing space decreased, the average height also decreased and the differences between the three studied variants were statistically significant. *Paulownia elongata* x *fortunei* again exceeded the mean height of *Paulownia tomentosa* by 18.94 cm.

More detailed study of the variation of the base diameter of the plant and its height with age and growing space showed that the two clonal populations follow the same pattern of growth and development, but both factors have a differentiated effect on the studied clonal populations (Figures 6 and 7).



A). B).

Fig. 6. *Response of the base diameter D0, cm (A) and height H, cm (B) of Paulownia elongata x fortunei to the three spacings tested during the growth period June - October 2017.*



A). B).

Fig. 7. *Response of the base diameter D0, cm (A) and height H, cm (B) of Paulownia tomentosa to the three spacings tested during the growth period June - October 2017.*

The positive response of age on the base diameter and height was apparent and explained more 70% of the variation in all cases. The response to the applied growing space was obvious too, but for the clonal population of *Paulownia elongata* x *fortunei* the smallest growing space differed for both parameters. The effect of the growing space becomes more noticeable with increasing of age (figures 2, 4, 6, 7) due to the larger sizes of the plants, which require larger growth area for their development. The growing space as a factor explained more than 15% of the variation in the height and less than 10% of the variation in the base diameter. The base diameter increased in proportion to the growing space but total height reached maximum values under the conditions of the second variant – 0.027 m^2. The last is in agreement with the findings of Panetsos (1980) for the growth pattern in different poplar genotypes. It was clearly demonstrated that the maximum values of tree heights were reached at the intermediate growth space.

For the period studied, the clonal population of *Paulownia tomentosa* completed its growth phase earlier. The yellowing of the leaves and their final fall ended by the end of October, when the average minimum temperature for the month was 6.57^{0}C, and the maximum average was 19.37^{0}C (Figure 1). The clonal population of *Paulownia elongata* x *fortunei* completed its growth phase with a month delay, when the mean minimum temperature was 2.2^{0}C and the mean maximum temperature was 10.1^{0}C. The last leaves fell in early December. Compared to *Paulownia tomentosa*, *Paulownia elongata* x *fortunei* required longer time to enter dormant state, which at the climatic conditions for the region of Sofia, is an unfavorable feature.

At the end of the growing season of 2017 was found that the number of leaves per tree in the *Paulownia elongata* x *fortunei* hybrids at spacings 0.053 m^2 and 0.027 m^2 was 18. The average number of leaves per stem at the smallest space - 0.018 m^2 was 9.83. The leaf area, after an increase under the conditions of the intermediate variant, where it reached 342.54 cm^2, substantially decreased under the conditions of the smallest growing space - 47.084 cm^2. The mean number of leaves per stem of *Paulownia tomentosa* decreased from 15 to 9.25 from the larger to the smaller growing space. The same trend was found for the leaf area of *Paulownia tomentosa* - from 450,102 cm^2 at growing space 0.053 m^2, the leaf area decreased to 210.297 cm^2 at the growing space 0.018 m^2. The large size of the leaves, developed on *Paulownia tomentosa* at the growing space 0.053 m^2 was impressive. Under suitable growing conditions, the presence of large leaves in the first year is very distinctive of *Paulownia* species (Zhu et al., 1986).

The assessment of the survival rate of *Paulownia elongata* x *fortunei* during the relatively mild and warm winter (2017-2018) showed that at the spacings of 0.027 m^2 and 0.018 m^2 the percentage of frozen stems was 25% and 75%, respectively. The survival rate of *Paulownia tomentosa* per stocking variant was quite similar, but the percentage of the frozen stems differed and varied from 20% to 47%. The main difference, observed between the two clonal populations, was that the frost injuries of the stems of *Paulownia tomentosa* at all three tested spacings were partial, while in *Paulownia elongata* x *fortunei* the frost injuries of the stems were complete. The experiment clearly demonstrated that plants with a base diameter less than 1 cm did not survive after the end of the winter. The reported lowest minimum temperatures for January 2018 and February 2018 were -12.7^{0}C and -10.3^{0}C, respectively. The maximum temperatures for the same months were 13.6^{0}C and 16.2^{0}C, respectively. Under this temperature regime, the root systems of the both populations remained viable and after the cutting of the brownish (frozen) stems, retained their regenerative capacity to produce new shoots in the next growing season.

At the beginning of August 2018, various plants originated from the three growing space were subjected to destructive sampling in order to study the localization of the plant biomass to leaves, stems and roots (Fig. 8).

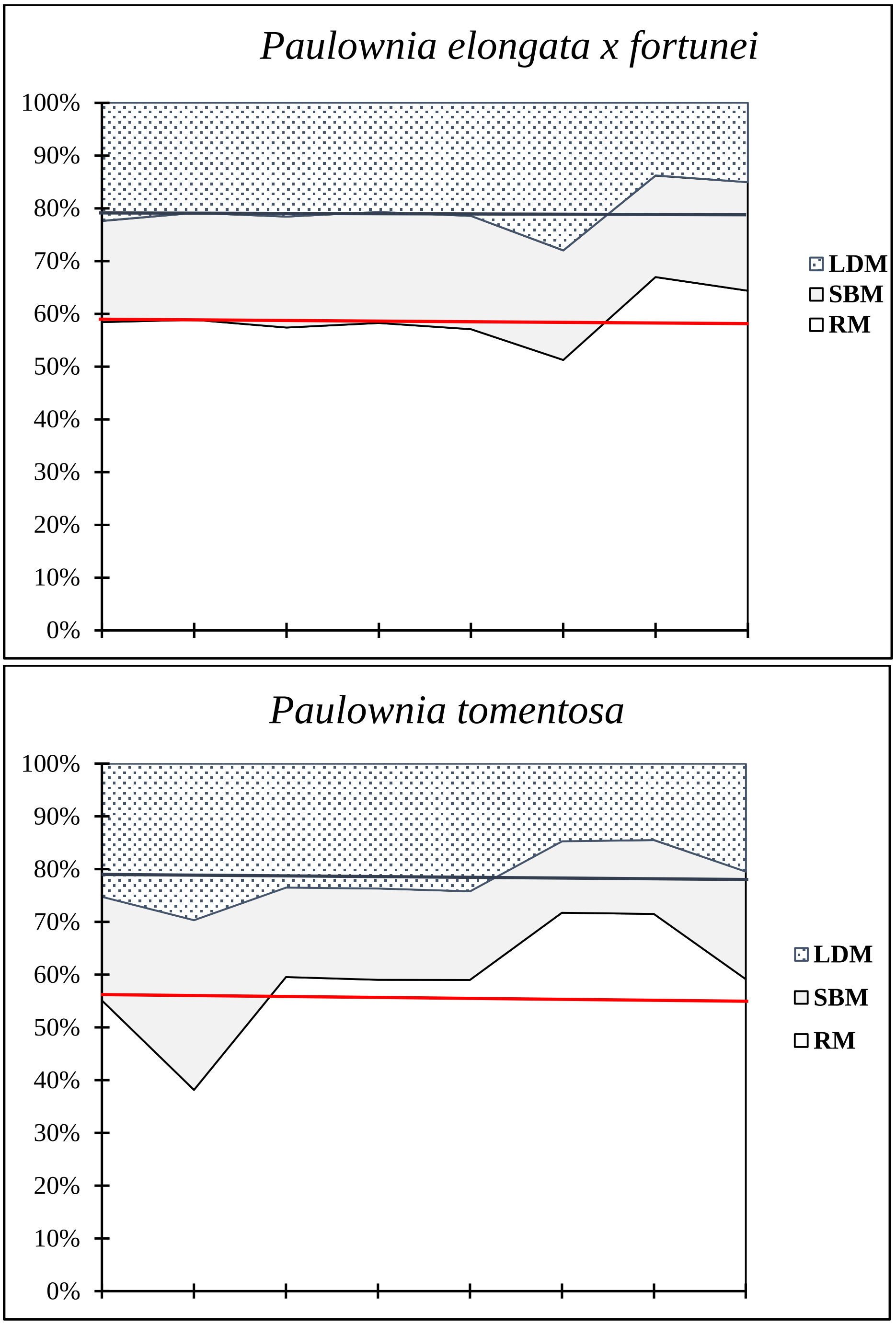
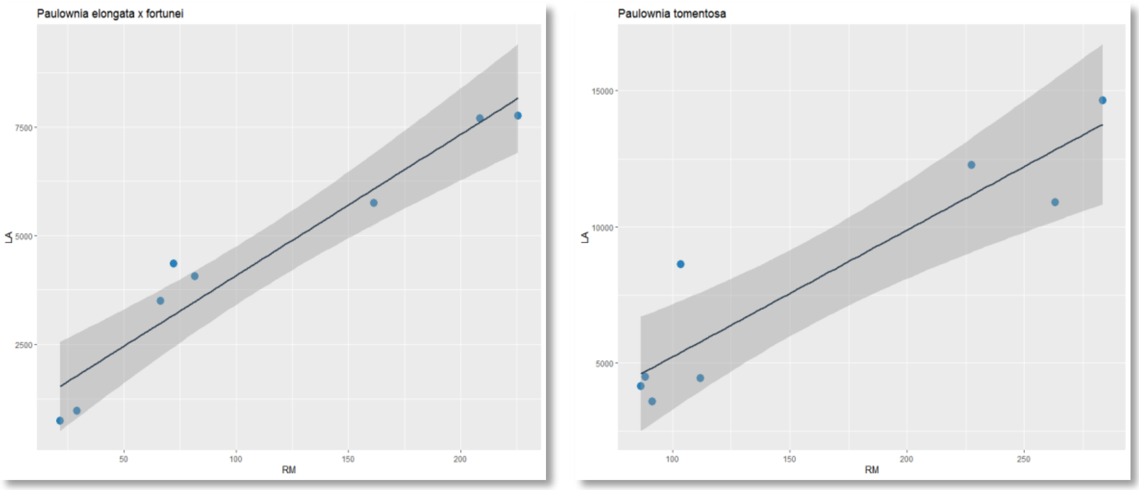


Fig. 8. *Oven-dry biomass allocation (%) in leaves (LDM), stems (SBM) and roots (RM) of Paulownia elongata x fortunei and Paulownia tomentosa clonal populations.*

During the study period, both clonal populations accumulated the largest amount of dry biomass in their root system. The largest fraction of the root system, as compared to the stem and leaves, has already been observed for *Paulownia tomentosa*, grown at different light gradients (Longbrake and McCarthy, 2001). The main difference that discriminated *Paulownia elongata* x *fortunei* and *Paulownia tomentosa* in our study was the amount of dry biomass accumulated in the stem and the leaves. At this early stage, *Paulownia tomentosa* accumulated more leaf dry mass, while *Paulownia elongata* x *fortunei* accumulated more stem mass.

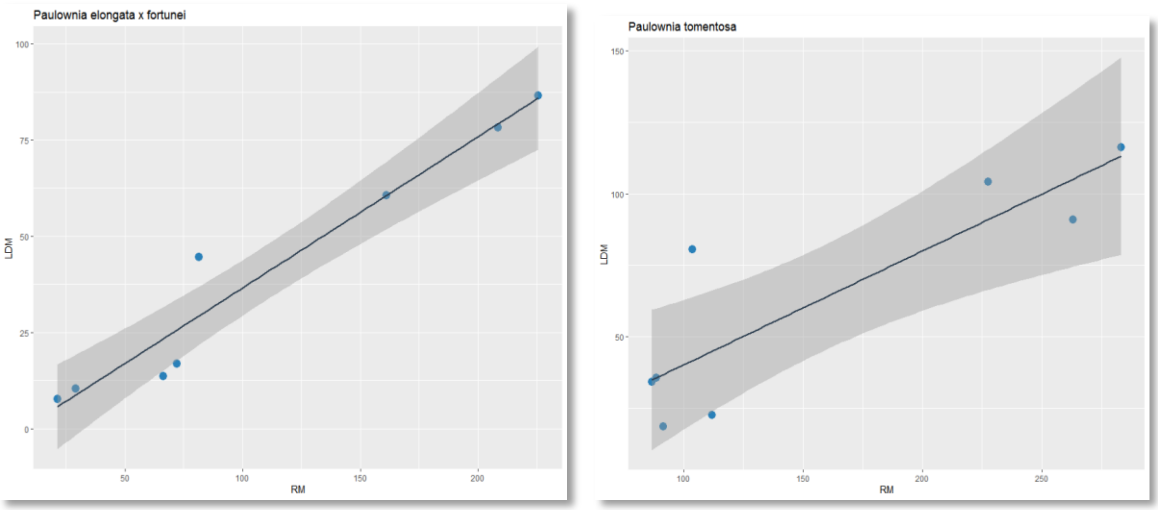
In fact, such differentiated biomass localization indirectly explained the better growth performance of *Paulownia elongata*, as well as its hybrids with *Paulownia fortunei*, that has already been reported in the literature (Zhu et al., 1986). For the climatic and light conditions of Sofia, however, the hybrid *Paulownia elongata* x *fortunei* failed to realize its full growth potential. There was a strong restraining effect of the environment.

The relationship between different biomass fractions and measurable quantitative characteristics, such as base diameter, plant height and leaf area, was analyzed. The linear relationship between root mass and leaf area in the two clonal populations was studied. The linear regression model showed that the accumulation of dry biomass in the root system leads to an increase in leaf area (Fig. 9).



A). B).

Fig. 9. *Linear relationship between root biomass (RM) and leaf area (LA) observed for Paulownia elongata x fortunei (A) and Paulownia tomentosa (B). The gray bands around the line represent the standard error of the regression line.*



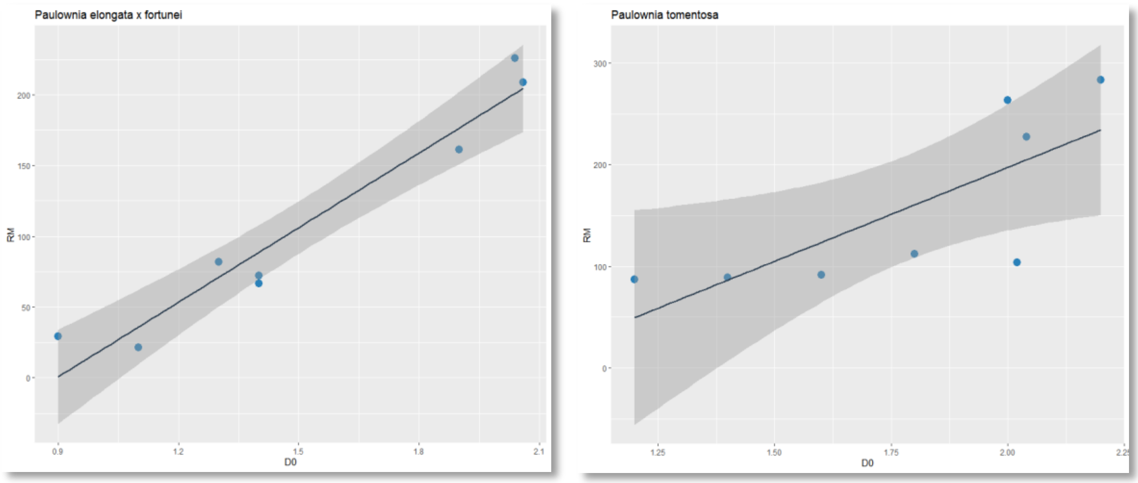
A). B).

Fig. 10. *Linear relationship between root biomass (RM) and leaf mass (LM) observed for Paulownia elongata x fortunei (A) and Paulownia tomentosa (B). The gray bands around the line represent the standard error of the regression line.*

This relationship is significantly better expressed in *Paulownia elongata* x *fortunei* (F = 78.75 on 1 and 6 = df, p = 0.000114 and adj. R^2 = 0.9174) than in *Paulownia tomentosa* (F = 33.5 on 1 and 6 = df, p = 0.0012 and adj. R^2 = 0.8228), but in the last the leaf area increases faster (coefficient for the slope of the lines 46.63 vs. 32.45).

The regression analysis showed also that the accumulation of root biomass leads to an increase in leaf mass (Fig. 10). This relationship is again better expressed in *Paulownia elongata* x *fortunei* (F = 99.9 on 1 and 6 = df, p = 5.809e-05 and adj. R^2 = 0.9339) than in *Paulownia tomentosa* (F = 17.8 on 1 and 6 = df, p = 0.005569 and adj. R^2 = 0.7059). At the same weight of the root system, *Paulownia tomentosa* maintains a larger amount of leaf mass (values for intercept and slope of the lines 0.418 and 0.398 vs -2.729 and 0.393). These results indicate that root mass is a good predictor of the leaf mass and leaf area in both clonal populations tested, which has already been demonstrated in *Populus tremuloides* (Caldwell and O'Hara, 2017).

Linear regression analysis also showed that as the base diameter increased, so did the root dry mass (Fig. 11).



A). B).

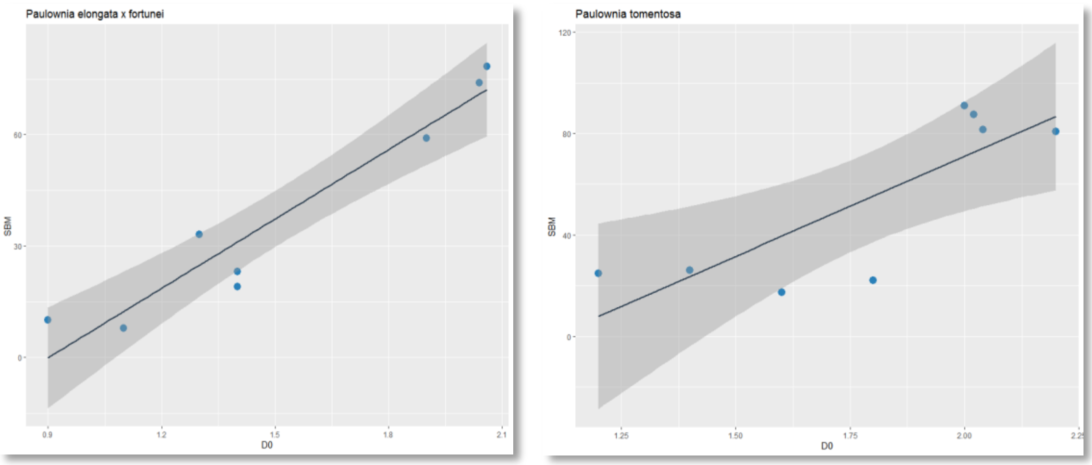
Fig. 11. *Linear relationship between base diameter (D0) and root mass (RM) observed for Paulownia elongata x fortunei (A) and Paulownia tomentosa (B). The gray bands around the line represent the standard error of the regression line.*

This relationship is much better expressed in the clonal population of *Paulownia elongata* x *fortunei* (F = 90.85 on 1 and 6 = df, p = 7,609e-05 and adj. R^2 = 0.9277) than in *Paulownia tomentosa* (F = 8.221 on 1 and 6 = df, p = 0.02853 and adj. R^2 = 0.5078). This probably was due to the small number of samples in the current analysis. While the height in *Paulownia elongata* x *fortunei* was also proved as a good predictor of the accumulated root biomass (F = 78.77, at 1 and 6 = df, p = 0.0001139 and adj. R^2 = 0.9174), no good linear relationship of root mass to height was found for the clonal population of *Paulownia tomentosa*.

Of the two parameters - base diameter and height - the first one described significantly better the amount of dry stem biomass for both clonal groups (Fig. 12).

This result is in agreement with the already published scientific information about different paulownia clones at juvenile age using nonlinear regression models (Stankova et al.

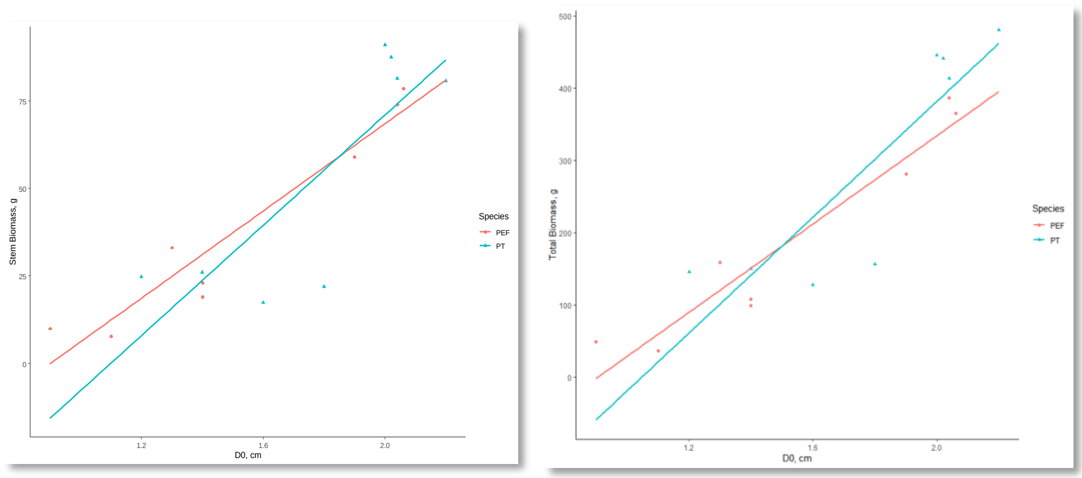
2016, Stankova et al. 2019). The linear relationship on the base diameter was significantly better expressed in the clonal population of *Paulownia elongata* x *fortunei* (F = 68.37 on 1 and 6 = df, p = 0.000169 and adj. R^2 = 0.9059) than in *Paulownia tomentosa* (F = 12.39 on 1 and 6 = df, p = 0.01252 and adj. R^2 = 0.6193). The total height as a parameter was also a good predictor of the stem biomass of *Paulownia elongata* x *fortunei* (F = 158 on 1 and 6 = df, p = 1.522 and adj.R^2 = 0.9573).



A). B).

Fig. 12. *Linear relationship between base diameter (D0) and stem biomass (SM) observed for Paulownia elongata x fortunei (A) and Paulownia tomentosa (B). The gray bands around the line represent the standard error of the regression line.*

The base diameter was also a better predictor of the total dry biomass produced by both *Paulownia elongata* x *fortunei* and *Paulownia tomentosa* clonal populations. The linear model for *Paulownia elongata* x *fortunei* expressed this relationship significantly better (F = 65.75, at 1 and 6 = df, p = 0.000189 and adj. R^2 = 0.9024) than in *Paulownia tomentosa* (F = 18.73, at 1 and 6 = df, p = 0.004942 and adj. R^2 = 0.7169).



A). B).

Fig. 13. *Response of stem biomass (A) and total biomass (B) to the base diameter D0, cm of Paulownia elongata x fortunei (PEF) and Paulownia tomentosa (PT).*

Similar to the result above, height as a parameter described better the linear relationship to the total dry biomass produced in the clonal population of *Paulownia elongata* x *fortunei* (F = 94.16, at 1 and 6 = df, p = 6,873e-05 and adj. R^2 = 0.9301). In conclusion, it can be confidently accepted that the base diameter is a good predictor of stem biomass and total dry biomass produced in *Paulownia tomentosa*. This was even more strongly valid for the clonal group of *Paulownia elongata* x *fortunei*, for which the height was also proven as a predictor. All linear models in the clonal population of *Paulownia elongata* x *fortunei* were more accurate than those in *Paulownia tomentosa*. It can be concluded that plants with a base diameter more than 1.5 cm accumulate a larger amount of total dry biomass in *Paulownia tomentosa* at this early stage of their development (Fig. 13).

No linear relationship was found between LAR and RHR and either base diameter or height of the plants. Significant differences between LAR and RSR of *Paulownia elongata* x *fortunei* and those of *Paulownia tomentosa* also were not found. The mean value of the specific leaf area obtained were 137.996±34.515 (cm^2/g) and 134,691±75,428 (cm^2/g) for *Paulownia tomentosa* and *Paulownia elongata* x *fortunei*, respectively. These values are significantly lower than those found for *Populus nigra* at the same age, grown under the same environmental conditions (Gyuleva et al., 2020). The mean values of RSR were 1.58±0.643 and 1.47± 0.304 for *Paulownia tomentosa* and *Paulownia elongata* x *fortunei*, respectively.

The lower values of the specific leaf area and LAR are considered indicators of the growth on poorer soils (North et al., 2007). This is not the case of the present study due to the preliminary enrichment of the soil with manure. It can be assumed, however, with high probability, that the climatic conditions and the light in our environment were of the main factors arresting the growth and development of the *Paulownia* species tested (Frey, 2004; Anderegg et al., 2012; Caldwell and O'Hara, 2017). It can be concluded that *Paulownia tomentosa* and *Paulownia elongata* x *fortunei* were cultivated in marginal, to their native areal, zone. As it is known from the literature (Zhu et al. 1986), *Paulownia* species develop a deep root system. The root biomass accumulation, proven here, indicates its function of a reservoir of vital building components (Caldwell and O'Hara, 2017; Landhäusser and Lieffers, 2002; Shepperd and Smith,, 1993; Zhu et al., 1986) that possesses reliable mechanism to maintain high regenerative capacity after removal of the frozen stems.

Conclusion

During the first stage of this study, height and diameter growth were assessed depending on the growing area and age during the first growing season, the leaf area and the survival of *Paulownia tomentosa* and *Paulownia elongata x fortunei* clonal groups during the winter season were evaluated. Undoubtedly, the age factor had stronger influence on growth, than the growing space and respectively explained high percentage of the variation. The growing space as a factor explained a higher percentage of the variation in height and a smaller percentage of the variation in diameter. *Paulownia elongata* x *fortunei* lost a much higher percentage of stems due to frost compared to *Paulownia tomentosa*, but both clonal populations maintained a high regenerative capacity of their root systems during the next growing season. During the second stage of this study, an analysis of the localization of plant biomass to the leaves, stems and roots of the two clonal populations was performed. It was shown that *Paulownia elongata* x *fortunei* clonal population accumulated more stem dry biomass and *Paulownia tomentosa* clonal population accumulated more leaf mass. Both clonal populations accumulated more than half of the total biomass in their root systems. By using linear relationships between the different functional and metric traits of the plants, it was proven that the base diameter is a good predictor of total biomass, and the leaf area and mass are well predicted through the root biomass for both clonal populations.

Some species peculiarities were also found, such as the larger amount of leaf mass of *Paulownia tomentosa* than *Paulownia elongata* x *fortunei* for the same root weight and the larger leaf area for the same tree height. The results showed that the tested clonal population of *Paulownia elongata* x *fortunei* is not appropriate for bioenergy purposes cultivation in areas with climatic conditions and altitude, identical with the Sofia region. The study outcomes would benefit environmentalists, carbon sequestration of plants, policy-makers and various land users.

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References

Caldwell, B. T., K. L. O'Hara, 2017. Correlation of Leaf Area Index to Root Biomass in *Populus tremuloides* Michx supports the Pipe Model Theory. Journal of Biodiversity Management and Forestry, 6(4). https://doi.org/ 10.4172/2327-4417.1000186

De Mendiburu, F., 2020."agricolae": Statistical Procedures for Agricultural Research. R package version 1.3-2. https://CRAN.R-project.org/package=agricolae

Ericsson, K., L. J. Nilsson, 2006. Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass and bioenergy, 30, 1 – 15.

Frey, B. R., V. J. Lieffers, E. H. T. Hogg, S. M. Landhäusser, 2004. Predicting landscape patterns of aspen dieback: mechanisms and knowledge gaps. Canadian Journal of Forest Research, 34, 1379 -1390.

García-Morote, F.A., F. R. López-Serrano, E. Martínez-García, M. Andrés-Abellán, T. Dadi, D. Candel, E. Rubio, M. E. Lucas-Borja, 2014. Stem Biomass Production of *Paulownia elongata* × *P. fortunei* under Low Irrigation in a Semi-Arid Environment. Forests, 5, 2505-2520; https://doi.org/10.3390/f5102505

Gyuleva, V., 2008. Project "Establishment of geographical plantations of Paulownia elongata hybrids in Bulgaria" - Contract 37 with State Agency of Forests (2007-2010). Bulgarian Academy of Sciences. News, 12, 2-4. ISSN 1312-2436.

Gyuleva, V., 2010. Micropropagation of hybrid *Paulownia* from long-term preserved seeds. *Silva Balcanica* ,11(1), 45-58.

Gyuleva, V., 2014. Choice and testing of fast-growing trees for wood feedstock production: preliminary results from Zlatna Panega plantations. Proceedings of Forest Research Institute "145 Years Bulgarian Academy of Sciences", ISBN 978-954-91423-8-9, Sofia, 239-245 (in Bulgarian).

Gyuleva, V., M. Tchorbadjieva, M. Gluschkova, K. Velinova, 2012. Esterase discrimination and growth of *Paulownia elongata* and its hybrids in three different regions in Bulgaria. In: Proceedings of the International conference “Ecology – interdisciplinary science and practice”. Sofia, 25-26 October 2012, Part One: 152-161.

Gyuleva V., T. Stankova, E. Popov, 2013. Development of short rotation plantations of fast growing forest tree species in Bulgaria for energy. Science & Technologies. Plant studies. 3(6), 96-100. (in Bulgarian)

Gyuleva, V., T. Stankova, E. Andonova, 2020. Bioproductivity of *Populus nigra* in early age. Research Report. Forest Research Institute, Sofia, 11p. (in Bulgarian)

Landhäusser, S. M., V. J. Lieffers, 2002. Leaf area renewal, root retention and carbohydrate reserves in a clonal tree species following above-ground disturbance. Journal of Ecology, 90, 658-665.

Longbrake, A. C. W., B.C. McCarthy, 2001. Biomass Allocation and Resprouting Ability of Princess Tree (*Paulownia tomentosa*: Scrophulariaceae) Across a Light Gradient. The American Midland Naturalist, 146 (2), 388-403. https://doi.org/10.1674/0003-0031(2001)146[0388:BAARAO]2.0.CO;2

Maier, J., R. and Vetter, 2004. Biomass yield and fuel characteristics of short-rotation coppice (willow, poplar, empress tree). Institute for Land Management Compatible to Environmental Requirements. 2004 Jul 1.

North, M., J. Innes, H. Zald, 2007. Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. Canadian Journal of Forest Research, 37, 331-342.

Panetsos, K. P., 1980. Selection of New Poplar clones under various Spacings. Silvae Genetica, 29 (3-4), 130-135.

Poorter, H., K. J. Niklas, P. B Reich, J. Oleksyn, P. Poot, L. Mommer, 2012. Biomass Allocation to Leaves, Stems and Roots: Meta-Analyses of Interspecific Variation and Environmental Control. New Phytologist, 193(1), 30-50, https://doi.org/10.1111/j.1469-8137.2011.03952.

Poorter, H., P. Ryser, 2015. The limits to leaf and root plasticity: what is so special about specific root length? New Phytologist, 206, 1188–1190.

R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Shepperd, W. D., F. W. Smith, 1993. The role of near-surface lateral roots in the life cycle of aspen in the central Rocky Mountains. Forest Ecology and Management, 61, 157-170.

Sinacore, K., S. H. Jefferson, C. Potvin, A. A. Royo, M. J. Ducey, M.S. Ashton, 2017. Unearthing the hidden world of roots: Root biomass and architecture differ among species within the same guild. PLoS One 12, e0185934. https://doi.org/10.1371/journal.pone.0185934

Stankova, T., V. Gyuleva, D. N. Dimitrov, H. Hristova, E. Andonova, 2016. Aboveground dendromass estimation of juvenile Paulownia sp. Bulletin of the Forestry Faculty, University of Banja Luka, 24, 5-18. https://dx.doi.org/10.7251/GSF1624005S

Stankova, T., V. Gyuleva, D. N. Dimitrov, E. Popov, 2019. Allometric relationship for estimation of aboveground woody biomass of two clones *Paulownia* at juvenile age. Forest science (Sofia), 55 (2), 43-54. (in Bulgarian)

Tang, R.C., S. B. Carpenter, R. F. Wittwer, D. H. Graves, 1980. Paulownia—A Crop Tree for Wood Products and Reclamation of Surface-Mined Land. Southern Journal of Applied Forestry, 4(1), 19–24. https://doi.org/10.1093/sjaf/4.1.19.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wickham, H., Romain F., Lionel H. and K. Müller, 2020. dplyr: A Grammar of Data Manipulation. R package version 0.8.4. https://CRAN.R-project.org/package=dplyr

Zhu, Z. H., C. J. Chao, X. Y. Lu, Y. G. Xiong, 1986. Paulownia in China: Cultivation and utilization. Chinese Academy of Forestry. Published by Asian Network for Biological Sciences and International Development Research Centre, ISBN 9971-84-546-6, 1-72.

Zuazo, V.H.D, J. A. J. Bocanegra, F. P. Torres, C. R. R. Pleguezuelo, J. R. F. Martínez, 2013. Biomass Yield Potential of Paulownia Trees in a Semi-Arid Mediterranean Environment (S Spain). International Journal of Renewable Energy, 3 (4), 789-793.