

Influence of the amount of water on the growth of one species and four hybrids of Paulownia in the first year of cultivation in Central Europe

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Abstract: A lack or, conversely, an excess of water during the first growing seasons can bring about a slowdown in the growth of plants, their stagnation or even death. The necessary amount of water is not known for most hybrids of Paulownia. Therefore, one species and four hybrids were subjected to three regimes of watering to find out their impacts on plant height, radial growth, the amount of leaf biomass and leaf area. We planted 30 plants of each species/hybrid into plant pots under a shelter. At the end of the growing season, we measured the above-mentioned parameters. Our results showed that: (i) generally, a mean precipitation of 50 mm per month in the growing season ('per month') seems to be insufficient for optimal growth of Paulownia plants in the first years after planting; (ii) each species/hybrid reacts differently to the amount of water – *P. Shan Tong* grows better with 100 mm per month, *P. tomentosa* with 150 mm (and more) per month and the growth parameters of the others did not change (and remained low) with different amounts of water (*P. Hybrid 9502*, *P. Bellissia*® and *P. Clon in vitro 112*®).

Keywords: crown projection area; height; leaf area; leaf biomass; radial growth

In the past decades, forestry has been contending with many forest disasters that arise due to the current global climate change (Sahoo et al. 2023). Long drought periods, gusty winds, windstorms, twist-ers, downbursts etc. damage forest stands more

powerfully, more widely and more often than in the past (Seidl et al. 2014; Patacca et al. 2023). Moreover, secondary pests – bark beetles and other bi-otic factors – follow on these events (Kozhoridze et al. 2023). Forest management reacts to the given

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situation with a change of tree composition and methods of forest economy (Millar et al. 2007), which is a very slow and lengthy process. It is likely that the production of fast-growing species plantations is capable of compensating for the future lack of wood. *Paulownia* spp. ranks among the fast-growing species as well (Armstrong et al. 1999; Sixto et al. 2007). It originated in China, Laos and Vietnam (Bergmann et al. 1997) and was gradually planted as a decorative tree – mainly *P. tomentosa* – on all continents, except for Antarctica. The species and newly cultivated hybrids of *Paulownia* are divided into three types, according to the degree of breeding, namely: wild, semi-wild and art (Mařová et al. 2016). Wild species are not suitable for growing in plantations because they do not have good growth characteristics (Zhao-Hua et al. 1986; Mařová et al. 2016). Semi-wild species [*Paulownia fortunei* (Seem) Hemsl., *P. elongata* S.Y. Hu, *P. tomentosa* (Thunb.) Steud., etc.] have better growth characteristics, greater resistance to disease, and can therefore be grown in smaller plantations (Zhao-Hua et al. 1986; Mařová et al. 2016). However, art species (also known as hybrid) have been bred to maximise the yield of energy wood and saw-timber (Mařová et al. 2016; BIO TREE 2022; iPaulownia 2022). There are dozens of art species on the market, and they differ in their growth characteristics and ecological demand, for example: *Paulownia* Shan Tong (hybrid of *P. fortunei* and *P. tomentosa*), *P. Bellissia*® (hybrid of *P. elongata* and *P. fortunei*), *P. Hybrid 9501*, *P. Hybrid 9502* and *P. Hybrid 9503* (hybrids of *P. fortunei* and *P. tomentosa*), or *P. Clon in vitro 112*® (hybrid of *P. elongata* and *P. tomentosa*). Since the 1980s, hybrids suitable for saw-timber production have been cultivated (Mařová et al. 2016). Due to this, many *Paulownia* plantations have been established throughout the world, including the Czech Republic (CR), where the first plantations have been established in the past ca 10 years (Görner 2017).

Paulownia spp. is relatively demanding regarding the amount of water (Clatterbuck, Hodges 2004). Zhao-Hua et al. (1986) described that it grows in areas with precipitation of 500–3 000 mm per year, depending on the species. However, there is no information on the amount of precipitation required or the water that should be supplied to individual hybrids. One of the very few hybrids, where the amount of required water is known, is *P. Clon in vitro 112*®:

- 750 mm per year (UCLM 2013);
- 800 mm per year (Jabłoński 2016);
- at least 150 mm per month in the first three years from planting and at least 50 mm per month in other years (TGG 2011).

Many authors consider the amount of precipitation which falls during the growing season as more important than the annual precipitation (Zhao-Hua et al. 1986; TGG 2011; BIO TREE 2022).

The water intake-to-output ratio is called water balance. If the water output is greater than the intake, then the water balance is disrupted, thus bringing about a water deficit, which can occur either due to reduced water intake caused by a lack of water or high salt concentration in the soil, or a higher water output caused by higher temperatures, higher irradiance, faster air flow, lower air humidity, etc. (Kaufmann 1985; Kirkham 2023). The water deficit, among other things, increases the content of abscisic acid in the leaves, closes the stomata and reduces photosynthetic activity, which decelerates cell growth, reduces the growth increment of the above-ground parts, thus accelerating cell ageing or even, in extreme cases, causes plant death (Udomprasert et al. 2005; Spiecker, Kahle 2023).

When there is an excess of water in the soil, the plants are also stressed (Barickman et al. 2019). First, the hydraulic conductivity of the roots drops (Tournaire-Roux et al. 2003), the production of high-energy phosphate compounds slows down (Gibbs, Greenway 2003), and the rate of photosynthesis decreases (Kang et al. 2009). As a result, the water intake and oxygen availability become limited (Tournaire-Roux et al. 2003; Ding, Du 2024). Finally, hypoxia occurs when only the above-ground part of the plant has access to oxygen (Mustroph, Albrecht 2003). The plants respond to the excess water in the soil by slowing down physiological performance, which reduces growth and yield (Armstrong 1979; Mustroph, Albrecht 2003; Barickman et al. 2019; de Andrade et al. 2023).

Since the amount of water that is required by other hybrids is not known, we decided to perform an experiment where we wanted to determine the diversity in water needs. We used one of the most common species in the world (*P. tomentosa*) and four hybrids (*P. Bellissia*®, *P. Clon in vitro 112*®, *P. Shan Tong* and *P. Hybrid 9502*) with the aim of finding out:

- (i) how the amount of water affects the height and thickness increment, the amount of leaf biomass and leaf area of Paulownia, and
- (ii) whether the reactions of the plants to the amounts of water differ within the selected species.

MATERIAL AND METHODS

Study site. The fenced research area where we conducted this research (located in Bohdalov; 49°28'25.0"N, 15°52'40.6"E) was established in the autumn of 2018. This area had a mean temperature of around 8 °C and a mean relative air humidity of around 73% in the 2019 growing season (Table 1). The 5 × 7.5 m area was dug to a depth of 70 cm. A total of one-hundred-and-fifty 114-litre non-perforated plant pots were placed at the bottom of the area and the space between the pots was filled with soil. Each pot was filled with the same soil up to approx. 5 cm below the rim. While planting (in the spring of 2019), the soil was sufficiently compacted. We then built a transparent polyethylene foil shelter (that eliminated atmospheric precipitation) at a height of 2.5 m to ensure natural air circulation.

Experimental design. We used one-year-old container-grown cutting transplants of *P. tomentosa* ('Tomentosa') as semi-wild, which has spread worldwide, and four hybrids: *P. Bellissia*® ('Bellissia'), *P. Clon in vitro* 112® ('Clon 112'), *P. Shan Tong* ('Shan tong') and *P. Hybrid* 9502 ('Hybrid 9502') as art, all cultivated for the production of saw-timber. These transplants were grown from root cuttings that were placed into perforated plant pots in the spring of 2018. We cultivated 110 juvenile plants of each species/hybrid and, in the spring of 2019 (before budbreak), we measured the heights

of the plants, the height of the live part of each stem (i.e. the distance from the ground to the part of the stem which did not freeze), and the radial growth 10 cm above ground (Table 2). Based on the results, we eliminated the 15 plants of each species/hybrid with the smallest values and the 15 with the greatest (leaving 80 of each species/hybrid). We randomly selected 30 from each of the remaining species/hybrids, and, in the spring of 2019, we transplanted them into the plant pots under the shelter where each one received 10 L of water.

We divided the plants of each species/hybrid into three irrigation groups and watered them at two-day intervals with the following amounts of water: – 150 L·m⁻²·month⁻¹ (maximum) – the recommended amount of water for good growth of Paulownia in the first years after planting (TGG 2011); – 50 L·m⁻²·month⁻¹ (minimum) – the recommended amount of water for good growth of Paulownia from the fourth year onwards (TGG 2011); – 100 L·m⁻²·month⁻¹ (medium) – the average of the above.

In the early evening, the irrigation was carried out with rainwater. During the growing season, we removed newly created branches and weeds.

At the end of the growing season, we measured the total heights of the plants (*H*), the lengths (*L*) and radial growth (*RG*; 10 cm from where they had grown out of the stem the previous year) of the current-year shoots, and the distances of the ends of the leaves furthest from the stem in the directions of all of the four cardinal points (*CPA*). We picked, scanned, and inserted into marked paper bags all of the leaves from each plant separately, dried them (at 80 °C for two days and then at 105 °C, until they achieved a constant weight) and then weighed them.

Table 1. Mean, minimum and maximum values of relative air humidity and temperature in Bohdalov during April–October 2019

Parameter	Value	April	May	June	July	August	September	October
Relative air humidity (%)	AVG	63.3	75.1	68.4	67.8	72.3	78.1	85.4
	MAX	92.3 Apr 29	97.5 May 20	87.4 June 6	90.2 July 12	90.2 Aug 3	96.2 Sept 2	97.5 Oct 9
	MIN	43.7 Apr 19	55.4 May 7	44.6 June 27	45.5 July 6	57.7 Aug 15	56.7 Sept 22	72.6 Oct 7
Temperature (°C)	AVG	2.4	5.2	13.6	11.6	12.2	7.7	3.6
	MAX	8.3 Apr 26	10.9 May 28	18.5 June 27	17.4 July 30	16.6 Aug 29	14.2 Sept 1	9.3 Oct 9
	MIN	–3.4 Apr 16	–2.6 May 7	8.1 June 29	5.2 July 11	5.9 Aug 15	–0.6 Sept 20	–1.7 Oct 31

AVG – mean; MAX – maximum; MIN – minimum

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Table 2. Mean values of the total height, the height of the live part of the stem and the radial growth (10 cm above ground) according to species and irrigation group for all plants and the same parameters according to species and irrigation group for chosen plants and their statistical significance

Species	irrigation group	All plants				Selected plants				
		total height (± SD) (cm)	height of the live part of the stem (± SD) (cm)	radial growth (± SD) (mm)	total height (± SD) (cm)	SS	height of the live part of the stem (± SD) (cm)	SS	radial growth (± SD) (mm)	SS
Tomentosa	maximum				56 (± 3.3)	ns	25 (± 1.8)	ns	10.2 (± 1.2)	ns
	medium	60 (± 9.2)	24 (± 4.7)	10.1 (± 3.7)	55 (± 1.8)	ns	25 (± 2.1)	ns	10.5 (± 1.2)	ns
	minimum				52 (± 3.5)	ns	23 (± 1.9)	ns	11.0 (± 0.8)	ns
Bellissia	maximum				55 (± 3.6)	ns	25 (± 2.6)	ns	10.1 (± 0.5)	ns
	medium	56 (± 11.0)	28 (± 5.8)	10.7 (± 1.7)	54 (± 5.1)	ns	23 (± 2.8)	ns	10.1 (± 0.7)	ns
	minimum				53 (± 4.2)	ns	23 (± 3.4)	ns	10.5 (± 0.7)	ns
Clon 112	maximum				54 (± 3.2)	ns	24 (± 3.2)	ns	10.5 (± 0.5)	ns
	medium	53 (± 10.3)	25 (± 2.7)	9.5 (± 1.6)	56 (± 2.2)	ns	25 (± 2.6)	ns	10.7 (± 0.6)	ns
	minimum				53 (± 4.7)	ns	22 (± 4.9)	ns	10.3 (± 0.4)	ns
Shan tong	maximum				54 (± 6.0)	ns	24 (± 5.5)	ns	9.9 (± 0.4)	ns
	medium	56 (± 10.3)	23 (± 3.5)	11.0 (± 2.9)	56 (± 3.4)	ns	27 (± 3.7)	ns	10.8 (± 0.9)	ns
	minimum				55 (± 6.4)	ns	25 (± 5.0)	ns	10.3 (± 1.1)	ns
Hybrid 9502	maximum				56 (± 3.7)	ns	26 (± 1.4)	ns	10.0 (± 1.1)	ns
	medium	50 (± 14.3)	30 (± 6.9)	11.6 (± 3.7)	56 (± 4.3)	ns	27 (± 4.4)	ns	10.2 (± 1.1)	ns
	minimum				55 (± 2.7)	ns	24 (± 1.2)	ns	10.6 (± 0.5)	ns

SD – standard deviation; SS – statistical significance; ns – no statistical significance

Leaf biomass (*LB*) was determined as the sum of all dried leaves from one plant. Leaf area (*LA*) was measured from scanned pictures (ACC Software, SOFO, Czech Republic); *CPA* was calculated as the average of the measured distances squared and multiplied by π ; the leaf area index (*LAI*) was calculated as *LA* divided by *CPA*, all divided by 2.

Statistical analysis. Statistical analysis of the data for the selection of the plants and of the results was performed using TIBCO Statistica™ (Version 14.0.0, 2020) with a confidence interval of 95%. Normality of the data distribution was examined before the main analysis. The main effects were analysed using the analysis of variance (ANOVA), after which Fisher's LSD test was applied, in order to identify differences among the main effects and interactions.

RESULTS

The total height and the length of the current-year shoot. Shan tong (*H*: 215 ± 10 cm; *L*: 169 ± 5 cm) and Clon 112 (*H*: 158 ± 10 cm; *L*: 169 ± 5 cm) grew the tallest with medium watering [(Figure 1A, B; Tables S1 and S2 in the Electronic Supplementary Material (ESM)], Hybrid 9502 (*H*: 159 ± 7 cm; *L*: 111 ± 7 cm) and Tomentosa (*H*: 202 ± 8 cm; *L*: 159 ± 7 cm) were the tallest when we used maximum watering and Bellissia had no statistically significant differences in both parameters among the amounts of the supplied water. Comparing the species and hybrids with one another, Bellissia grew the tallest (142 ± 10 cm), and Bellissia (89 ± 7 mm) and Shan tong (90 ± 2 mm) had the longest current-year shoot with minimum watering, Shan tong grew tallest with medium watering and Tomentosa grew tallest with maximum watering.

The radial growth of the current-year shoot. Shan tong had the thickest *RG* with medium watering (35 ± 7 mm), Tomentosa (13 ± 4 mm) had the thinnest with minimum watering, Bellissia (12 ± 2 mm) had the thinnest with maximum watering, and Clon 112 and Hybrid 9502 did not show any differences (Figure 1C; Tables S1 and S2 in the ESM). A mutual comparison of the species and hybrids showed that, under medium treatment, Shan tong had thickest the current-year shoot and, under the maximum amount of the water, Tomentosa (23 ± 4 mm) and Shan tong (24 ± 3 mm) were thicker than Bellissia, Clon 112 and Hybrid 9502 (Figure 1C).

Leaf biomass. The plants of all species (except Bellissia) had the greatest amount of *LB* (Tomentosa: 822 ± 60 g; Hybrid 9502: 191 ± 23 g; Clon 112: 410 ± 27 g; Shan tong: 674 ± 54 g) with medium watering (Figure 2A; Tables S3 and S4 in the ESM). Comparing the species and hybrids that received minimum watering with one another, Hybrid 9502 (110 ± 13 g) had the least amount of *LB*. When we applied medium watering, Tomentosa and Shan tong had the greatest amount of *LB*, and with maximum watering, Tomentosa (413 ± 48 g) had the greatest amount of *LB*.

Leaf area. The differences in the *LA* were very similar to those of the *LB*, but with greater dispersion. Almost all species/hybrids with medium watering had the largest *LAs* (Tomentosa: 4.63 ± 1.34 m²; Hybrid 9502: 1.36 ± 0.25 m²; Clon 112: 2.53 ± 1.43 m²; Shan tong: 3.99 ± 2.11 m²), however, there were statistically significant differences only in the cases of Tomentosa and Hybrid 9502 (Figure 2B; Tables S3 and S4 in the ESM). A mutual comparison of the species and hybrids showed that under all three types of watering, Hybrid 9502 had the smallest *LA* (minimum: 0.85 ± 0.01 m²; medium: 1.36 ± 0.25 m²; maximum: 0.99 ± 0.15 m²).

Crown projection area. The plants of all species/hybrids had the largest *CPA* with medium watering (Tomentosa: 2.22 ± 0.33 m²; Hybrid 9502: 1.22 ± 0.37 m²; Clon 112: 1.08 ± 0.07 m²; Shan tong: 1.13 ± 0.17 m²), except for Bellissia, where there were no statistically significant differences among the *CPAs* of the plants grown under all three types of watering (Figure 2C; Tables S3 and S4 in the ESM). Comparing the species and hybrids with one another, the largest *CPA* was achieved by Bellissia (1.07 ± 0.34 m²) with minimum watering, by Tomentosa with medium, and by Tomentosa (1.03 ± 0.08 m²) and Bellissia (1.17 ± 0.09 m²) with maximum watering.

Leaf area index. Although there were some differences in the *LAI* (caused by the type of watering on the individual species), they were not statistically significant. A mutual comparison of the species and hybrids showed that when we supplied the minimum or medium amount of water, it was Shan tong (minimum: 1.79 ± 0.39 m²; medium: 2.47 ± 0.3 m²) that had the highest value of *LAI* (Figure 2D; Tables S3 and S4 in the ESM) and with maximum watering it was Bellissia (1.87 ± 0.3 m²).

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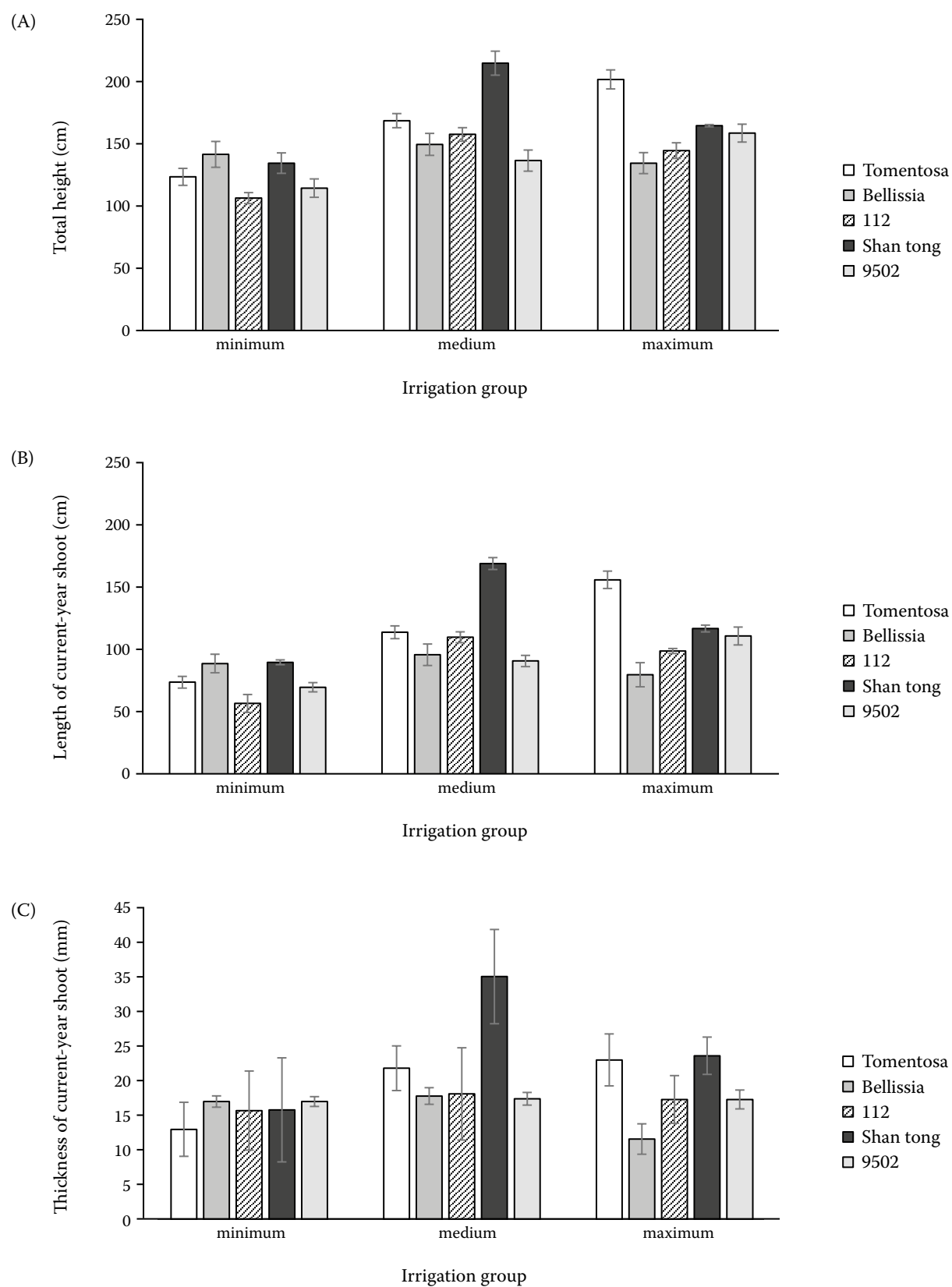


Figure 1. Mean values of (A) the total height, (B) the length of the current-year shoot, and (C) the thickness of the current-year shoot according to species and irrigation group

Whiskers – standard deviation

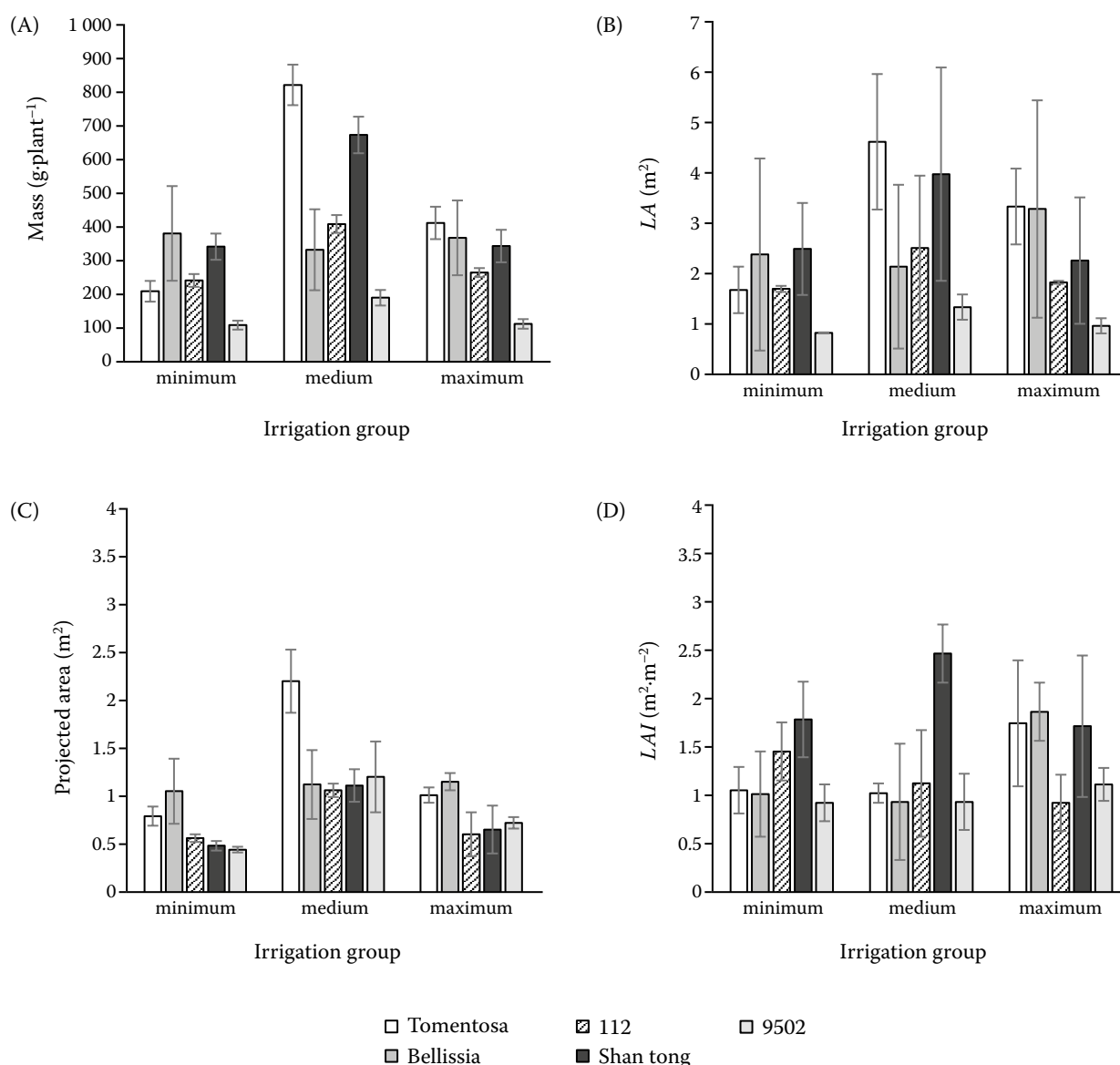


Figure 2. Mean values of (A) the leaf biomass, (B) the leaf area (LA), (C) the projected area of the crown, and (D) the leaf area index (LAI) according to species and irrigation group

Whiskers – standard deviation

DISCUSSION

The information and knowledge about the individual species of *Paulownia* spp., especially the artificially created hybrids, that should be available is very limited (Kumar et al. 1999; Guo-qiang et al. 2001). Internet shops often sell several hybrids together, without specifying which kinds they are, or they merely specify what purpose these plants serve best (e.g. saw-timber, biomass), what maximal thickness or volume they reach after how many years and what temperature range they can survive. Unfortunately,

ly, there is no specification regarding the optimal amount of water these plants should receive and the length of the growing season, or any technical reports containing the place of origin, the climatic and soil conditions and the necessary silvicultural measures. Most authors of scientific articles only describe the genus or hybrid in question, merely as a cross between two named species (Lv et al. 2024; Rodríguez-Rebelo et al. 2024; Xu et al. 2024; Zhang et al. 2024), which could lead to people mistaking one hybrid for another, e.g. the cross between *P. elongata* and *P. fortunei* can be called 'P. Clon in vitro 112[®]' (More-

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no et al. 2017), 'P. Cotevisa 2[®]' (iPaulownia 2022) or even 'P. Bellissia[®]' (BIO TREE 2022), where each name is a registered trademark. All this (above) is why we were unable to find the optimal amount of water to provide the individual species with and, subsequently, to be able to perform a comparison with our results.

We found no significant differences in the total heights and lengths of the current-year shoots among the species that had received the minimum amount of water. These results correspond with the results of Ayan et al. (2006), who had investigated the influence of the amount of water on the growth of several species and did not reveal any differences among them, either. On the other hand, we found differences in the heights and lengths of the current-year shoots of the species when we used a greater amount of water. With medium watering, P. Shan Tong grew the tallest of all species/hybrids, and with maximum watering, it was *P. tomentosa*. These results correspond to those of Ptach et al. (2017), who explained that a greater amount of water helps the plants to grow taller. Also, the growth trend of P. Hybrid 9502 shows the same results as those stated by Ptach et al. (2017). We achieved the tallest plants with maximum watering; however, the total heights and lengths of the current-year shoots of P. Hybrid 9502 were ca. 1/3 shorter than those of *P. tomentosa*. The growth trends of P. Clon *in vitro* 112[®] and P. Bellissia[®] were similar to those of P. Shan Tong; however, the total heights and lengths of the current-year shoots of these plants (i.e. P. Clon *in vitro* 112[®] and P. Bellissia[®]) were ca. 1/3 shorter than those of P. Shan Tong. The different reaction of *P. tomentosa* and P. Hybrid 9502 to P. Shan Tong, P. Clon *in vitro* 112[®] and P. Bellissia[®] may have been due to the different amount of water necessary for optimal growth and their sensitivity to waterlogging. *P. tomentosa* naturally occurs in places with precipitation from 500 mm to 1 500 mm (Zhao-Hua et al. 1986). This species may grow according to the rule: the more water, the greater the growth. P. Hybrid 9502 may have a similar rule. On the other hand, P. Clon *in vitro* 112[®] needs 750 mm (UCLM 2013) or 800 mm of precipitation annually (Jabłoński 2016). When this hybrid occurs in conditions with such precipitation, it should grow best. This amount of water corresponds to our medium watering. P. Shan Tong and P. Bellissia[®] may need a similar amount of water. Moreover, some of these five species/hybrids may

be affected by waterlogging. Jazirehi and Rostaghi (2003) classified Paulownia as a plant demanding moisture, but our results show that not all species of Paulownia respond equally to soil moisture. P. Shan Tong might be more intolerant to soil waterlogging, which occurred due to the large amount of water supplied in the case of maximum watering. This could correspond to the study conducted by Barickman et al. (2019), who state that excessive water slows the growth down. The same trend (as was in the case of P. Shan Tong) was observed with P. Clon *in vitro* 112[®] and P. Bellissia[®].

The radial growth of each newly formed terminal shoot was measured 10 cm from the stem. Unlike the observations of Ayan et al. (2006), we did not find any differences among the species – only in the case of minimum watering, because when we applied medium and maximum watering, we found differences which do not correspond to their results. The response of the shoot's radial growth to the medium and higher amount of water supplied varies, depending on the species/hybrid. The plants of *P. tomentosa* and P. Shan Tong were thicker than others in these irrigation groups. We expected the plants of individual species to react similarly to the amount of irrigation and, with an increase in the amount of water, their thickness to increase. The same is described by Ptach et al. (2017), who used P. Shan Tong, where they applied two types of watering, which was confirmed only in the radial growth of the shoots of *P. tomentosa*. This may be due to the fact that *P. tomentosa* naturally occurs in places with precipitation from 500 mm to 1 500 mm (Zhao-Hua et al. 1986). The thickness (as well as the height) of this species can increase according to the statement: the more water, the greater the growth. This species manifests the same trend in the radial growth of the stem and the height. P. Shan Tong is a hybrid of *P. tomentosa* and *P. fortunei*, which naturally occur in places with precipitation of 500–1 500 mm and 1 200–2 500 mm, respectively (Zhao-Hua et al. 1986), therefore we expected the growth trend to be similar to that of *P. tomentosa* or *P. fortunei*. However, the plants of P. Shan Tong had the thickest shoots when we applied medium watering, which can partially correspond with the results of Ptach et al. (2017). This trend was the same as that of the height. Therefore, we assumed that P. Shan Tong is intolerant to intense waterlogging, which occurred due to the great amount of water

supplied, thus reducing the height and thickness increment. On the other hand, *P. Clon in vitro* 112[®], *P. Hybrid* 9502 and *P. Bellissia*[®] had similar radial growth when we applied all three types of watering. This trend is similar to that in the study by Rad and Mirkala (2015), where they did not record any differences between the radial growth of the plants growing with a different amount of water.

The leaf area and the leaf biomass showed similar trends. According to Ptach et al. (2017), the more the plants were watered, the greater the leaf area and amount of biomass. Our results, similarly, show that the amount of the leaf biomass and leaf area were usually the smallest with the minimum amount of water. A study conducted on *Pinus ponderosa* Douglas ex C. Lawson (Maherali, DeLucia 2001) conveys similar results. These studies, however, examined the effect of only two types of watering on the leaf biomass.

Our results indicate that the greatest amount of leaf biomass and leaf area was gained with medium watering. On the one hand, little water could bring about a drop in the level of cytokinin and auxin and, subsequently, lead to limited growth (Seeley 1990). On the other hand, a large amount of water could cause waterlogging, which also slows down growth (Barickman et al. 2019). Our results show that *P. tomentosa* and *P. Shan Tong* gave the most leaf biomass and leaf area with medium watering, whereas the plants of *P. Hybrid* 9502 had the smallest amount of biomass and leaf area in all types of watering.

We did not find differences in the *LAI* within each species after the three different types of watering, which does not correspond to the results of, for example, Devakumar et al. (1999), who investigated the effect of water supply on *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg. They found that the differences in the *LAI* between the non-irrigated and the irrigated plants were almost 50%. We found differences in the *LAI* only among certain species receiving the same amount of water. With the minimum water, we found a difference between *P. Shan Tong* and *P. Hybrid* 9502 (i.e. between the highest and lowest *LAI*, respectively). In this case, the difference in *LAI* was evident due to the amount of the leaf biomass and leaf area because the plants of *P. Hybrid* 9502 had a fraction of the leaf biomass of *P. Shan Tong*, but the projection areas of their crowns were similar. There was a difference between *P. Bellissia*[®] and *P. Clon in vitro* 112[®] (i.e. between the highest and lowest

value of *LAI*, respectively, under maximum watering). A comparison of the individual parameters indicated that the projection area of the crown of *P. Clon in vitro* 112[®] was almost 50% smaller than that of *P. Bellissia*[®]; *P. Clon in vitro* 112[®] was taller, and its leaf area was also smaller. This means that *P. Clon in vitro* 112[®] was taller (with fewer leaves that were closer to the stem) than *P. Bellissia*[®], whose leaves were more spread out. In the case of *P. Bellissia*[®], there may have been changes in the distribution of the biomass (Lei et al. 2006), where it is the roots and leaves that grow first and then all the other parts (Zhang et al. 2004; Duan et al. 2005). With the medium amount of water, *P. Shan Tong* had the highest *LAI* value. There were differences in the *LAI* between *P. Shan Tong* and *P. Clon in vitro* 112[®], *P. Hybrid* 9502 and *P. Bellissia*[®], due to the greater amount of leaf biomass and larger leaf area in *P. Shan Tong* plants, compared to those of the above-mentioned species (whereas the projected area of the crowns was similar). In contrast, the difference between *P. Shan Tong* and *P. tomentosa* was probably in the distribution of their crowns because the amount of the leaf biomass and size of leaf area of these species were similar, but the projected area of the crown of *P. tomentosa* was nearly 100% larger, compared to that of *P. Shan Tong*.

CONCLUSION

There is no recommended amount for optimal irrigation or precipitation for any hybrid of Paulownia (except for *P. Clon in vitro* 112[®]). We assumed that the same rule applies to all species of Paulownia: the more water supplied, the more intense the growth. However, our results concluded that Paulownia species have various responses to the amount of water supplied.

In terms of growth characteristics in an area with a mean temperature of around 8 °C and a mean relative air humidity of around 70% in the growing season, it seems that:

- Precipitation of 50 mm per month (in the growing season) is insufficient for optimal growth in the first years after planting for all species/hybrids because, under this amount of water, the values of the measured parameters of these species/hybrids were the smallest of all.
- Precipitation of 100 mm per month is the most suitable for the best growth of *P. Shan Tong*,

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which grew more than 160 cm per year under this amount of water. Moreover, this hybrid should not be planted in an area with high groundwater levels or near watercourses, because it seems to lose growth potential when it is waterlogged.

- Precipitation of 150 mm (more water was not tested) per month is most suitable for the best growth of *P. tomentosa*, which reached an annual height increment of almost 160 cm.
- Precipitation of 50 mm, 100 mm or even 150 mm per month is insufficient for good growth of *P. Hybrid 9502*, *P. Bellissia*® and *P. Clon in vitro 112*®, where all three reached heights of only approx. 100 cm.

When plantations of *P. tomentosa* and *P. Shan Tong* are established in areas with insufficient precipitation (see above), the plants need supplementary irrigation until they produce a rich and deep root system via which they can draw groundwater from the soil. On the other hand, *P. Hybrid 9502*, *P. Bellissia*® and *P. Clon in vitro 112*® reached very low values, compared to those of *P. tomentosa* and *P. Shan Tong*, and it would therefore be useful to find out if they need even more water for good growth, or they will simply never achieve their potential.

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