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Comparison of the growth of royal paulownia strains (*Paulownia tomentosa* Steud.) suitable for biomass production under stressful conditions

Porównanie wzrostu klonów paulowni puszystej (*Paulownia tomentosa* Steud.) przydatnych do produkcji biomasy w warunkach stresowych

Abstract. The aim of the present study was to estimate the growth and winterhardiness of thirteen strains of royal paulownia in south-east Poland. Paulownia plants were grown under stressful conditions, such as poor soil, high density, no mineral fertilisation and no irrigation. However, intensive plant growth was confirmed in the first two years of vegetation. Among the studied strains, the 'LuP', 'LuD' and 'We' strains showed high growth intensity, high yield potential and the highest winter survival. They also had a significantly higher SPAD index than others. The selected strains were probably more tolerant of abiotic stress. Some specimens showed even stronger growth. The fast-growing selected paulownia strains could give an estimated 1.8 t ha^{-1} of fresh and 0.4 t ha^{-1} of dry shoot biomass. The leaves of paulownia plants are also a valuable source of biomass. Therefore, the aboveground biomass yield could be double that previously estimated.

Keywords: quotient method, short-rotation plantation, SPAD index, winterhardiness, woody biomass

INTRODUCTION

Royal paulownia (*Paulownia tomentosa* Steud.) is a deciduous tree native to China [Zhu et al. 1986, Woods 2008]. This species was introduced to North America, Australia and Western and Southern Europe [Essl 2007, Yadav et al. 2013]. Paulownia is one of the

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fastest-growing trees in the world [Icka et al. 2016]. In favourable conditions, the annual growth of paulownia plants can reach up to 5 m in length [Zhu et al. 1986].

Paulownia trees are widely used. The fast growth rate, high biomass production and resprouting potential make it a valuable plant in the energy industry. These plants have a higher biomass production than other woody crops used for energy purposes [López et al. 2012, Zuazo et al. 2013]. The annual biomass production can reach from 50 to 150 t ha^{-1} [Azzarello et al. 2012, López et al. 2012]. Under favourable conditions, 5–7-year-old plantation of 2000 trees per hectare can yield up to 150–300 tons of wood annually [Azzarello et al. 2012, Yadav et al. 2013]. Biomass from the paulownia plantation can be harvested in two- or three-year cycles for 20–25 years. After shoot harvest, plants are regenerated from the existing root systems and shoot remains without replanting [Danciu et al. 2016]. Thus, paulownia is a desirable species for biomass production in the world.

Paulownia wood can be used for making furniture, house construction, shipbuilding, farm implements, handicrafts, toys, packing boxes, musical instruments and the pulp and paper industry [Ayan et al. 2006, Akyildiz and Kol 2010]. Due to their high tolerance to heavy metals and fast growth rate, these plants are used for phytoremediation [Doumett et al. 2008, Stankovic et al. 2009, Wang et al. 2010]. Paulownia leaves are also used as green fertiliser or animal feed [Woźniak et al. 2018, Al-Sagheer et al. 2019]. The empress tree can also have medicinal, ornamental or beekeeping purposes [Zhu et al. 1986, Icka et al. 2016].

Recently, the 'Oxytree' (*P. fortunei* × *P. elongata*) and 'Shan Tong' (*P. tomentosa* × *P. fortunei*) hybrids have been widely cultivated in Poland [Lisowski and Porwisiak 2017, Lisowski and Porwisiak 2018, Liszewski and Bąbelewski 2018a, 2018b]. However, their cultivation may be risky as such genotypes are interspecific hybrids with *P. fortunei*. This species is not considered winter-hardy, as it tolerates temperatures as low as –10°C [Zhu et al. 1986]. It seems that *P. tomentosa* genotypes, the most winter-hardy species from the *Paulownia* genus, should be used first-line in Poland. Royal paulownia tolerates frost conditions below –20°C [Woods 2008].

Paulownia species are cultivated in the warmer parts of the world [Yadav et al. 2013]. Almost nothing is known about the possibility of their cultivation in regions with moderate and cold climate zones, such as Poland. Therefore, the aim of the present study was to estimate the growth and winterhardiness of thirteen strains of royal paulownia in the first two years of vegetation in Polish climatic conditions.

MATERIAL AND METHODS

The field experiment was established in south-eastern Poland, in Grochowe near Mielec (50°21'N 21°29'E) on sandy soil belonging to the VI quality class. The soil pH was acidic with medium phosphorus, low potassium and high magnesium content (tab. 1). The microelement content was generally low. Similarly, the content of organic matter and total nitrogen was also low. Temperature and precipitation data were from the Meteorological Station of the University of Rzeszów (tab. 2). In 2014 and 2015, the monthly temperatures were higher than the long-term average. However, in these years, the total precipitation was definitely below the long-term average. In particular, June and August 2015 were drier and warmer than in previous years.

Table 1. Soil chemical properties before the start of the experiment

pH_{KCl}	P_2O_5	K_2O	Mg	B	Mn	Cu	Zn	Fe	Nitrogen	Organic matter
	(mg·kg^{-1} of soil)			(mg·kg^{-1} of soil)					g·kg^{-1}	g·kg^{-1}
6.0	141	50	72	1.0	30.9	4.6	17.9	898	1.2	20.5

Table 2. Comparison of weather conditions in Rzeszów

Year	Month												Annual	Vegeta-tion
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		
temperature (°C)													average (°C)	
2014	0.5	3.3	6.8	10.1	14.2	16.3	20.1	18.0	15.3	9.7	6.6	1.8	10.2	17.4
2015	1.0	1.6	4.8	8.6	13.0	17.5	19.9	21.4	15.4	7.5	5.4	3.3	10.0	17.7
1981–2010	–2.3	–1.3	2.8	8.5	14.0	16.8	18.8	18.1	13.5	8.6	3.4	–1.0	8.4	16.2
precipitation (mm)													sum (mm)	
2014	19.7	16.9	37.8	29.9	92.2	48.1	57.1	46.8	32.2	24.0	9.2	12.5	426.1	275.2
2015	28.0	10.3	37.9	25.7	85.1	8.8	52.3	6.0	48.6	36.9	46.9	8.5	394.8	195.9
1981–2010	30.5	29.0	36.7	46.7	81.4	82.6	90.7	68.5	69.3	42.6	37.1	37.5	652.6	392.5

The studies were conducted on generatively propagated royal paulownia plants. Most of the strains came from seeds obtained from several-decade-old paulownia trees growing in botanical gardens, arboretums or private property in Poland (tab. 3). The three strains were of foreign origin. In June 2014, ten-week-old *Paulownia* seedlings with uniform growth were planted in the ground. These plants reached a height of approximately 15 cm. A randomized complete block design in four replications was established. Forty plants represented each strain. Paulownia plants were planted in double-row plots with a spacing of 0.75 m between rows and 3 m between bands. Each plant was spaced in a row 0.5 m apart. Thus, the plant density was approximately 10.000 plants ha^{-1}. The sewage sludge at 80 t ha^{-1} was used in the soil before planting the plants. The sludge sample had an alkaline pH, and contained approximately 58.8% organic matter, 5.9% total nitrogen, 1.3% ammonium nitrogen, 3.5% phosphorus, 3.8% calcium and 0.8% magnesium of dry matter and low heavy metal concentration. In 2015, no fertiliser was applied to the plants.

The biometric and physiological measurements were made in 2014–2015. In September, one fully expanded leaf from each plant was selected. The size of the leaf blade and petiole, and their fresh and dry mass, were determined. The relative chlorophyll content expressed in SPAD units was measured using a Chlorophyll Meter SPAD-502Plus. After the end of the vegetation period, the following biometric measurements, such as the length and base diameter of the strongest shoot, total length and number of shoots, were determined. After the winter period, the real winterhardiness of plants was assessed by determining the number of dead plants. The fresh and dry shoot mass was also determined.

Statistical analysis was performed using Statistica v.13.1. Collected data were subjected to an ANOVA, $LSD_{0.05}$ test. Ward's method and Euclidean distance were used to evaluate the similarity of the studied paulownia strains. All statistical tests were considered significant at the $p = 0.05$. Then, the best paulownia strains were selected using the quotient method according to Paszkowska and Mazurkiewicz [1967] and Kuraczyk et al. [2003]. This method divides the average value of a trait for a strain by the average value of this trait for all strains. The sum of the quotients determines the strain index.

Table 3. The origin of studied paulownia strains

Symbol	Locality	The origin of the seeds
Bd	Bydgoszcz, Poland	Plant Breeding and Acclimatization Institute in Radzików Bydgoszcz Research Center
Bg	Boguchwała, Poland	private property
Bl	Bolestraszyce, Poland	Arboretum in Bolestraszyce
Cr	Crimea	unknown
Kr	Kraków, Poland	Botanic Garden of the Jagiellonian University
LuB	Lublin, Poland	Botanic Garden of the University in Lublin
LuD	Lublin, Poland	Botanic Garden of the University in Lublin
LuP	Lublin, Poland	private property
Po	Poznań, Poland	Botanic Garden of the University in Poznań
Ru	Romania	University Campus in Oradea
Wa	Warszawa, Poland	Botanic Garden of the University of Warsaw
We	Hungary	unknown, Florpak seed company
Wr	Wrocław, Poland	Botanic Garden of the University of Wroclaw

RESULTS AND DISCUSSION

Paulownia is one of the fastest-growing trees in the world [Woods 2008, Icka et al. 2016]. However, information about the intensive growth of these plants comes mainly from warmer climate zones [e.g. Ulu et al. 2002, Bergmann 2003, Stankova et al. 2016]. There is limited information on the growth of royal paulownia in Polish climatic conditions. Nevertheless, preliminary observations and results on the growth of 'Shan Tong' and 'Oxytree' in western and central Poland are available. In Murowana Goślina near Poznań, the fertilised plants had an average of 0.7 m in height and 1.3 cm in diameter in the first year of vegetation [Smarul et al. 2018]. In turn, unfertilised plants were 0.5 m in height and 0.7 cm in diameter. Similarly, Kadlec et al. [2023] recorded a growth of paulownia by 0.5–0.8 m after the first year in the Czech Republic. In Poland, field experiments were also established in Łomża and Wrocław. The ‘Oxytree’ plants had an average of about 1 m in height and 2.8 cm in diameter after four months of vegetation [Lisowski and Porwisiak 2017, Liszewski and Bąbelewski 2018a]. However, the paulownia plants were grown in optimal conditions, such as lower density (625 plants ha^{-1}), mineral fertilization before sowing and top dressing, and irrigation during the vegetation period. The optimal conditions for the growth of paulownia plants are sandy soil, with a groundwater level below 1.5–2 m and pH 6.5–7.5. The optimal temperatures for maximum growth are 24–30°C and precipitation is 760 to 1200 mm annually [Woods 2008]. In our study, despite poor soil fertility and water scarcity, intensive growth of royal paulownia was also confirmed. After four months of vegetation, the average length of the strongest shoot surpassed 0.5 m, whereas the diameter of the shoot base was 1.7 cm. Significant differences were found among the studied paulownia strains (tab. 4). The ‘LuP’ and ‘We’ strains grew more intensively than the others. Their shoot length was close to 0.7 m, whereas the stem base diameter was almost 2 cm. The shoots of the strongest specimens were longer and thicker, exceeding 1.1 m in length and 2.5 cm in base diameter. In the year of planting, the plants generally exhibited strong apical dominance.

Table 4. Biometric properties of shoots of studied paulownia strains after the first year of vegetation

Strain	Length of the strongest shoot (m)		Total length of shoots per plant (m)		Number of shoots per plant		Diameter of shoot base (cm)	
	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max
Bd	0.47^{a}	0.67	0.53^{a}	1.01	1.2^{ab}	3.0	1.5^{a}	2.1
Bg	0.56^{cde}	0.85	0.67^{bc}	2.13	1.3^{b}	5.0	1.6^{ab}	2.3
Bl	0.54^{bcd}	0.87	0.58^{ab}	1.35	1.1^{ab}	3.0	1.6^{abc}	2.1
Cr	0.57^{de}	0.84	0.58^{ab}	0.84	1.0^{a}	2.0	1.8^{cd}	2.4
Kr	0.54^{bcd}	0.76	0.56^{a}	1.10	1.1^{a}	2.0	1.7^{bcd}	2.3
LuB	0.48^{ab}	0.75	0.67^{bc}	1.54	1.5^{c}	3.0	1.7^{bcd}	2.6
LuD	0.56^{cde}	0.81	0.63^{abc}	1.35	1.2^{ab}	4.0	1.8^{de}	2.7
LuP	0.63^{fg}	0.92	0.84^{d}	2.08	1.5^{c}	4.0	1.8^{de}	2.5
Po	0.57^{de}	0.81	0.58^{ab}	1.02	1.0^{a}	2.0	1.7^{bcd}	2.3
Ru	0.54^{cd}	0.80	0.58^{ab}	0.87	1.1^{ab}	3.0	1.7^{bcd}	2.2
Wa	0.61^{ef}	0.91	0.61^{abc}	0.91	1.0^{a}	1.0	1.8^{de}	2.4
We	0.67^{g}	1.16	0.70^{c}	1.34	1.1^{a}	2.0	1.9^{e}	2.5
Wr	0.50^{abc}	0.72	0.53^{a}	1.28	1.1^{ab}	3.0	1.7^{bc}	2.1
Mean	0.56	–	0.62	–	1.2	–	1.7	–

$\bar{x}$ – average forstrain; max – maximum value for specimens; different letters indicate significant differences among means at $p = 0.05$

Fig. 1. Differences in the growth of paulownia strains in the second year of vegetation (Grochowe in July 2015)

Summer 2015 was generally drier than average. June and August, which are most significant for paulownia growth, were extremely dry. After the second year of vegetation, the unfertilised plants had an average of 0.7 m in height and 1.5 cm in diameter. Among all tested strains, the 'LuP' and 'LuD' grew more intensively (tab. 5, fig. 1). The specimens of 'LuP' were almost 1.5 m in height and 3 cm in diameter. The total length of shoots per plant surpassed 4.6 m. Better results were obtained by Lisowski and Porwisiak [2018] and Liszewski and Bąbelewski [2018b] on the 'Oxytree' plantation. In Łomża, the two-year-old plants averaged 2.1 m in height and almost 6 cm in diameter. In Wrocław, the average height of the two-year-old plants was approximately 2.8 m, and their diameter was 5.9 cm. It is worth emphasising that these plants were grown under low plant density, irrigation and fertilisation.

Table 5. Biometric properties of shoots of studied paulownia strains after second year of vegetation

Strain	Length of the strongest shoot (m)		Total length of shoots per plant (m)		Number of shoots per plant		Diameter of shoot base (cm)	
	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max	$\bar{x}$	max
Bd	0.54^{a}	1.05	0.77^{a}	1.70	1.8^{a}	4.0	1.4^{a}	2.5
Bg	0.68^{bc}	1.08	1.04^{ab}	1.91	1.9^{ab}	3.0	1.5^{ab}	2.2
Bl	0.62^{ab}	1.12	0.90^{ab}	1.82	1.8^{a}	5.0	1.5^{a}	2.6
Cr	0.73^{bc}	1.11	1.57^{c}	3.74	2.7^{de}	5.0	1.6^{ab}	2.3
Kr	0.70^{bc}	1.07	1.11^{ab}	2.06	1.8^{a}	4.0	1.6^{ab}	2.2
LuB	0.69^{bc}	1.07	1.54^{c}	3.64	3.2^{e}	7.0	1.6^{ab}	2.4
LuD	0.79^{cd}	1.48	1.52^{c}	3.80	2.4^{bcd}	5.0	1.7^{b}	2.9
LuP	0.89^{d}	1.48	2.11^{d}	4.64	3.2^{e}	6.0	1.7^{b}	2.5
Po	0.70^{bc}	1.27	1.27^{bc}	2.58	2.2^{abcd}	4.0	1.5^{a}	2.7
Ru	0.64^{ab}	1.30	1.16^{ab}	3.25	2.1^{abc}	4.0	1.4^{a}	2.5
Wa	0.66^{ab}	1.43	1.22^{bc}	2.72	2.4^{cd}	6.0	1.5^{a}	2.8
We	0.69^{bc}	1.34	1.13^{ab}	3.47	2.4^{bcd}	5.0	1.5^{a}	2.4
Wr	0.68^{bc}	1.24	1.03^{ab}	2.16	1.8a	4.0	1.5^{ab}	2.6
Mean	0.70	–	1.29	–	2.3	–	1.5	–

$\bar{x}$ – average for strain; max – maximum value for specimens; different letters indicate significant differences among means at $p = 0.05$

According to López et al. [2012] and Zuazo et al. [2013], the paulownia plants have high biomass production. However, the information on paulownia biomass yield in regions with moderate and cold climate zones is limited. The poor soil site allowed the paulownia yield potential to be evaluated in areas of little use for food production. In our study, after the first year of vegetation, the average fresh stem mass was almost 0.1 kg, and the dry mass was approximately 0.03 kg. A density of 10.000 plants ha^{-1} could give an estimated 1.0 t ha^{-1} of fresh and 0.3 t ha^{-1} dry stem mass. However, some strains were more productive (tab. 6). The higher shoot yield might be obtained in cultivating the ‘LuP’ and ‘We’ strains of paulownia. The fast-growing selected paulownia strains could give an estimated 1.4 t ha^{-1} of fresh and 0.4 t ha^{-1} of dry shoot biomass after the first year of vegetation. It should be emphasised that the experiment aimed to select the strongest paulownia strains under extensive cultivation conditions, not to optimise plant yields. A similar biomass production was obtained in the following year (tab. 6). A significant effect of weather conditions was observed. In 2015, limited water availability had a direct impact on biomass production. The vegetation period was significantly dry. The ‘LuP’ strain produced the highest shoot yield among the studied strains. The predicted yield was approximately 1.8 t ha^{-1} fresh and 0.4 t ha^{-1} of dry shoot biomass after the second year of vegetation.

Table 6. The stem mass of the studied paulownia strains in the first two year of vegetation

Year	Strain													Mean
	Bd	Bg	Bl	Cr	Kr	LuB	LuD	LuP	Po	Ru	Wa	We	Wr	
Fresh mass of stem per plant (kg)														
2014	0.06	0.09	0.09	0.10	0.10	0.09	0.11	0.14	0.10	0.09	0.11	0.14	0.08	0.10
2015	0.08	0.09	0.10	0.11	0.11	0.12	0.14	0.18	0.09	0.09	0.10	0.15	0.09	0.11
Dry mass of stem per plant (kg)														
2014	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.03	0.04	0.02	0.03
2015	0.02	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.04	0.02	0.03
Dry mass content in the stem (%)														
2014	30.5	29.7	29.3	29.8	29.4	27.6	29.8	28.5	29.9	30.2	28.3	29.9	29.8	29.4
2015	27.8	34.5	32.0	32.7	27.4	28.0	20.5	23.9	36.4	31.1	30.0	26.9	22.5	28.7

In the literature, there is limited information about the winterhardiness of paulownia in Polish climatic conditions. In the *Paulownia* genus, the royal paulownia (*P. tomentosa*) is considered the most frost-resistant. It can withstand temperatures as low as below –20°C [Woods 2008]. However, according to Zhu et al. [1986], young trees are susceptible to frost damage. In our experiment, after the first winter period, the average number of dead plants was 19%. In the 2014/15 season, the lowest minimum air temperature was –20.6°C at the ground. Thus, the temperature falls outside this range for paulownia plants. However, significant differences were found among the studied strains (tab. 7). The two fast-growing strains (‘LuP’ and ‘We’) were more winter-hardy. The number of dead plants did not exceed 5%. The third fast-growing strain (‘LuD’) was characterised by slightly lower winterhardiness. The number of dead plants did not exceed 8%. Moderate winter survival was observed in the ‘Ru’, ‘LuB’, ‘Wr’ and ‘Bg’ strains. However, the ‘Po’, ‘Bd’ and ‘Bl’ strains were the least winter-hardy. The number of dead plants was almost 40%. The problem with the winter hardiness of paulownia plants in the Czech Republic was also highlighted by Kadlec et al. [2023].

Table 7. Winter survival of studied paulownia strains after 2014/15 season

Strain	Number of dead plants (%)
Bd	35.0
Bg	17.5
Bl	37.5
Cr	20.0
Kr	27.5
LuB	15.0
LuD	7.5
LuP	2.5
Po	35.0
Ru	10.0
Wa	22.5
We	5.0
Wr	15.0
Mean	19.2

The juvenile paulownia plants have large leaves (fig. 2). They can reach up to 80 cm in width [El-Showk and El-Showk 2003]. In the first year of vegetation, the average leaf blade length reached 25 cm, whereas the leaf blade width was 30 cm. The smaller leaves are likely a result of high plant density and inadequate irrigation. Generally, the 'LuP' and 'We' strains had significantly larger leaves than others (tab. 8). Moreover, the maximal leaf blade length and width of the strongest specimens were almost 45 cm and surpassed 53 cm, respectively. The leaves had relatively long petioles, with a length close to 20 cm and a diameter of 1 cm. However, the petiole size of the strongest specimens was significantly larger. The leaf petioles were almost 40 cm in length and 2 cm in diameter. For all strains, the average fresh and dry leaf mass was 18 g and 5 g, respectively. The leaves of the 'We' strain were heavier than the others (tab. 9). The leaves of paulownia plants are also a valuable source of biomass. The mass of all leaves per plant is slightly heavier than the mass of stems [Liszewski and Bąbelewski 2018b]. Therefore, the aboveground biomass yield can be doubled compared to the previously estimated value.

Fig. 2. Royal paulownia in the second year of vegetation (Grochowe in June and July 2015)

In the second year of vegetation, the paulownia plant had slightly smaller leaves than the previous year (tab. 8). This was probably due to low precipitation during the vegetation period. The average leaf blade reached 15 cm in length and 20 cm in width. Among the studied strains, 'LuP' had significantly larger leaves (tab. 8). Moreover, the leaves of 'LuD' and 'LuP' strains were heavier than the others (tab. 9).

The basic physiological measurements of paulownia leaves were made. Significant differences among strains in the case of relative chlorophyll content were found (tab. 10). Generally, the 'LuP' and 'LuD' strains have the highest SPAD values. However, the third

Table 8. Biometric properties of leaves of studied paulownia strains after the first two year of vegetation

Strain	Length of leaf blade (cm)		Width of leaf blade (cm)		Length of the leaf petiole (cm)		Diameter of the leaf petiole (cm)	
	2014	2015	2014	2015	2014	2015	2014	2015
Bd	22.1^{a}	13.3^{a}	26.4^{a}	16.0^{a}	15.6^{a}	9.0^{a}	0.9^{a}	6.6^{a}
Bg	23.6^{ab}	14.8^{ab}	28.0^{ab}	19.2^{bc}	19.2^{bcd}	12.3^{b}	1.0^{bc}	8.0^{bcd}
Bl	24.5^{bc}	13.7^{a}	30.3^{bcd}	18.1^{ab}	19.6^{bcde}	11.0^{ab}	1.1^{bcde}	7.2^{ab}
Cr	25.0^{bcd}	14.5^{ab}	31.0^{de}	18.9^{abc}	20.9^{def}	12.0^{b}	1.1^{bcde}	7.4^{abc}
Kr	24.6^{bc}	14.2^{ab}	30.2^{bcd}	18.2^{ab}	19.8^{cde}	10.9^{ab}	1.1^{bcde}	7.6^{abc}
LuB	24.7^{bc}	14.5^{ab}	29.5^{bcd}	19.0^{bc}	21.3^{ef}	12.5^{b}	1.1^{cde}	7.9^{bcd}
LuD	23.7^{ab}	15.9^{b}	30.2^{bcd}	21.3^{c}	22.4^{fg}	15.2^{c}	1.2^{de}	8.7^{d}
LuP	26.6^{de}	19.2^{c}	33.3^{ef}	24.4^{d}	24.4^{gh}	16.1^{c}	1.1^{bcd}	8.3^{cd}
Po	23.4^{ab}	14.8^{ab}	29.3^{bcd}	18.9^{abc}	18.2^{bc}	11.2^{ab}	1.0^{b}	7.3^{ab}
Ru	24.4^{bc}	14.8^{ab}	30.6^{cd}	19.4^{bc}	18.6^{bc}	12.2^{b}	1.1^{bc}	7.8^{bcd}
Wa	25.6^{cd}	13.7^{a}	31.4^{def}	18.1^{ab}	19.4^{bcde}	10.6^{ab}	1.1^{bcde}	7.1^{ab}
We	27.4^{e}	14.7^{ab}	33.5^{f}	18.5^{ab}	24.8^{h}	12.4^{b}	1.2^{e}	7.3^{ab}
Wr	23.3^{ab}	14.5^{ab}	28.4^{abc}	18.9^{abc}	17.7^{b}	11.7^{b}	1.0^{b}	7.8^{bcd}
Mean	24.5	15.0	30.1	19.3	20.1	12.3	1.1	7.7

Different letters indicate significant differences among means at $p = 0.05$

Table 9. The leaf mass of the studied paulownia strains in the first two years of vegetation

Year	Strain													Mean
	Bd	Bg	Bl	Cr	Kr	LuB	LuD	LuP	Po	Ru	Wa	We	Wr	
Fresh mass of leaves (g)														
2014	15.2	15.9	19.4	18.6	20.0	17.2	18.0	18.2	17.8	18.3	19.1	21.8	16.9	18.2
2015	5.3	7.7	7.5	8.0	7.3	7.8	10.6	10.6	7.1	7.8	6.9	8.3	8.2	7.9
Dry mass of leaves (g)														
2014	4.2	4.2	5.5	5.1	5.4	5.5	5.4	5.3	5.1	4.8	4.9	6.3	4.6	5.1
2015	1.2	1.7	1.7	1.4	1.2	1.8	2.4	2.4	1.6	1.8	1.5	1.9	1.6	1.7
Dry mass content in the leaves (%)														
2014	28.7	27.3	28.0	27.3	26.0	30.7	30.7	28.7	28.0	27.7	26.3	28.7	28.0	28.2
2015	26.7	22.6	23.0	18.3	19.7	22.9	23.2	22.8	26.8	23.2	22.0	23.3	19.7	22.6

Table 10. Relative chlorophyll content of studied paulownia strains in the first two years of vegetation

Strain	2014	2015
Bd	42.2[ab]	34.4[ab]
Bg	41.4[ab]	32.8[a]
Bl	40.3[ab]	35.7[ab]
Cr	44.2[b]	35.5[ab]
Kr	39.0[a]	34.3[ab]
LuB	43.5[b]	33.4[a]
LuD	44.2[b]	36.5[b]
LuP	44.2[b]	36.3[b]
Po	42.7[ab]	34.6[ab]
Ru	42.5[ab]	34.9[ab]
Wa	40.6[ab]	34.6[ab]
We	39.3[a]	34.5[ab]
Wr	42.3[ab]	34.0[ab]
Mean	42.0	34.7

Table 11. Evaluation of paulownia strains using the quotient method after the first year of vegetation

Strain	Strain index								
	length of the strongest shoot	total length of shoots	number of shoots	diameter of shoot base	fresh mass of stem	dry mass of stem	SPAD index	winter plant survival	sum
Bd	0.85	0.86	1.03	0.88	0.64	0.66	1.00	0.80	6.72
Bg	1.00	1.08	1.09	0.93	0.88	0.90	0.99	1.02	7.90
Bl	0.97	0.94	0.95	0.95	0.86	0.85	0.96	0.77	7.25
Cr	1.02	0.93	0.88	1.03	1.04	1.05	1.05	0.99	7.99
Kr	0.98	0.91	0.90	1.01	0.98	0.97	0.93	0.90	7.57
LuB	0.87	1.08	1.29	0.98	0.87	0.82	1.03	1.05	7.99
LuD	1.01	1.01	1.01	1.06	1.06	1.07	1.05	1.15	8.42
LuP	1.13	1.36	1.30	1.05	1.36	1.32	1.05	1.21	9.79
Po	1.02	0.93	0.88	0.98	1.04	1.06	1.02	0.80	7.74
Ru	0.98	0.93	0.97	0.98	0.92	0.94	1.01	1.11	7.84
Wa	1.09	0.98	0.86	1.06	1.13	1.09	0.97	0.96	8.13
We	1.21	1.13	0.90	1.12	1.44	1.46	0.93	1.18	9.37
Wr	0.90	0.85	0.93	0.96	0.79	0.80	1.01	1.05	7.29
Mean	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

strongest strain (‘We’) was characterised by a slightly lower value for this parameter. In the second year, lower SPAD values were observed, probably due to unfavourable weather conditions during the growing season.

The most productive and winter-hardy paulownia strains were selected using the quotient method. In the two-year study, the highest total index was determined for the ‘LuP’ strain (tab. 11, 12). The plants of this strain were characterised by the most intensive growth, high yield and high winter hardiness. A relatively high index was also determined for the ‘We’ and ‘LuD’ strains.

Table 12. Evaluation of paulownia strains using the quotient method after the second year of vegetation

Strain	Strain index								
	length of the strongest shoot	total length of shoots	number of hoots	diameter of shoot base	fresh mass of stem	dry mass of stem	SPAD index	winter plant survival	sum
Bd	0.85	0.86	1.03	0.88	0.73	0.67	0.99	0.80	6.80
Bg	1.00	1.08	1.09	0.93	0.82	1.00	0.94	1.02	7.89
Bl	0.97	0.94	0.95	0.95	0.91	1.00	1.03	0.77	7.51
Cr	1.02	0.93	0.88	1.03	1.00	1.33	1.02	0.99	8.20
Kr	0.98	0.91	0.90	1.01	1.00	1.00	0.99	0.90	7.68
LuB	0.87	1.08	1.29	0.98	1.09	1.00	0.96	1.05	8.32
LuD	1.01	1.01	1.01	1.06	1.27	1.00	1.05	1.15	8.56
LuP	1.13	1.36	1.30	1.05	1.64	1.33	1.04	1.21	10.06
Po	1.02	0.93	0.88	0.98	0.82	1.00	1.00	0.80	7.43
Ru	0.98	0.93	0.97	0.98	0.82	1.00	1.00	1.11	7.80
Wa	1.09	0.98	0.86	1.06	0.91	1.00	1.00	0.96	7.85
We	1.21	1.13	0.90	1.12	1.36	1.33	0.99	1.18	9.23
Wr	0.90	0.85	0.93	0.96	0.82	0.67	0.98	1.05	7.16
Mean	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

Based on the cluster analysis, paulownia strains were divided into several groups. In 2014, the ‘LuP’ and ‘We’ strains were separated from the others (fig. 3). Generally, these strains were fast-growing, high biomass-yielding and better winter-hardy with higher values of physiological parameters. Thus, selecting valuable paulownia genotypes that are well-adapted to Polish climatic conditions should be possible. The other groups were more complex and consisted of weaker strains (fig. 3). In 2015, the ‘LuP’, ‘LuD’, ‘LuB’ and ‘Cr’ strains stood out.

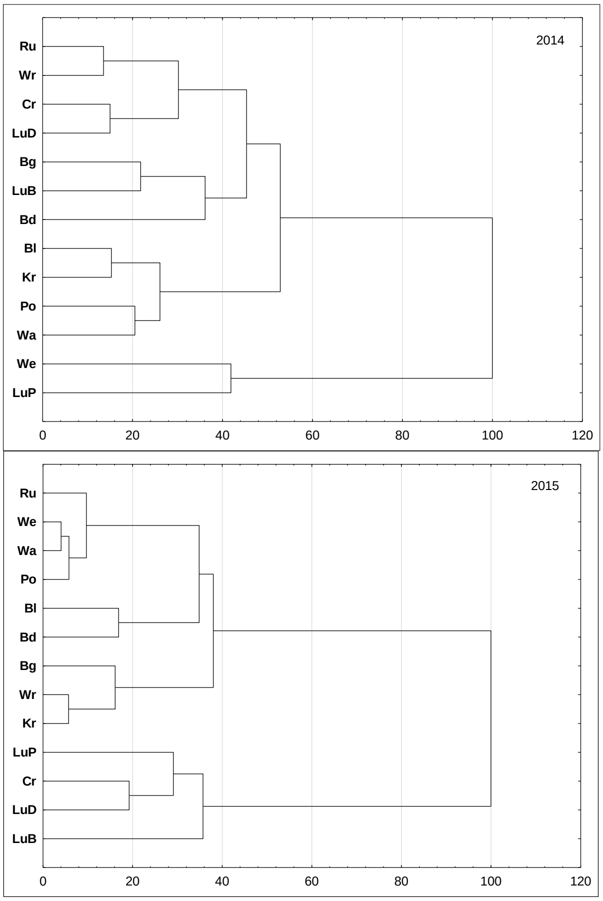

Fig. 3. Similarity of the studied paulownia strains in first two years of vegetation (the following traits were used for agglomeration length and diameter of the strongest shoot, total length and number of shoots, the fresh and dry mass of shoots, SPAD index and winter plant survival)

CONCLUSIONS

Intensive growth and relatively high biomass yield of paulownia plants were confirmed. It is worth emphasising that these plants were grown on poor soil, in high density, with no mineral fertilisation or irrigation. Significant differences were found among studied paulownia strains in growth strength, biomass yield, winter hardiness and the physiological condition. Thus, the ‘LuP’ strain is most promising for cultivation on poor soil. The fast-growing paulownia ‘LuP’ strain could give an estimated 1.8 t ha^{-1} of fresh stem biomass after the second year of vegetation. However, in optimal growing conditions, a higher yield can be expected. The leaves of paulownia plants are also a valuable source of biomass. Therefore, the aboveground biomass yield can even be doubled than previously estimated. It may be concluded that the ‘LuD’ and ‘We’ strains should also be recommended for cultivation in moderate climate zones. The fast-growing strains were more winter-hardy than others. They were also characterised by a significantly higher SPAD index. It could therefore be argued that the selected strains were more tolerant to abiotic stress.

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