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# Stand structure of a juvenile *Paulownia* Shan Tong plantation grown in the temperate dry climate zone in Hungary – A case study

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**Abstract:** In this paper, empirical relationships between diameter at breast height (*DBH*), crown diameter (*CD*), and stem number per hectare (*N*) were improved in a *Paulownia* Shan Tong plantation. Various functions of these variables were defined, focusing on growing space ($G_s$) and stem number per hectare. The linear crown index between *CD* and *DBH* seems to be particularly important in predicting stem number per hectare. Based on an analysis of the relationships, a *CD-DBH* ($R^2$ = 0.7254) and a *DBH-N* graphic model ($R^2$ = 0.7302) can be applied widely in plantation forestry. Under suitable site conditions, the investigated *Paulownia* hybrid can provide a higher increment in *DBH* than most of poplar hybrids at a certain age. The aim of this study was to explore the relationships between the $G_s$ based on *CD* and *DBH*. These types of investigations are of fundamental importance in terms of the growing technology of tree plantations.

**Keywords:** crown projection area; empress tree; growing space; stem number

These days, the cultivation of *Paulownia* primarily revolves around hybrid varieties that possess desirable traits, and these hybrids are predominantly propagated through *in vitro* techniques. Some well-known hybrids are the clones *in vitro* 112, Cotevisa 2, and Shan Tong. According to Jakubowski (2022), the growth results and the production capacities of the Central European countries are lower in comparison with the Southern European countries.

While natural species of *Paulownia* continue to be cultivated across Asia, reaching as far as Türkiye, their prominence is gradually being overshadowed by hybrid varieties. In certain countries, such as Bulgaria, hybrids have emerged as a significant alternative only after unsuccessful endeavours to grow pure species (Gyuleva 2008, 2010).

As reported by Jakubowski (2022), several studies of *Paulownia* hybrids have shown significant differences in the growth dynamics of individual clones in response to the local environmental and climatic conditions. The economically viable growing conditions for this timber were found in the Middle East and Southern Europe.

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The study of *Paulownia* cultivation in Central and Eastern Europe is still in its early stages, but preliminary results indicate lower production efficiency compared to Southern Europe. Factors such as shorter growing seasons, low temperatures, as well as spring and autumn frosts contribute to these challenges in the region (Jakubowski 2022).

Results published by Pástor et al. (2022) indicate that the hybrid Cotevisa 2 has considerable potential in timber production in the Danubian Lowland. After seven years of planting, the average diameter at breast height (*DBH*) and height (*h*) of the studied *P. cotevisa* plantation reached 21.5 cm and 11.2 m, respectively. *Paulownia* trees have a wide range of uses (Costea 2021), such as to improve degraded soils, utilise animal manure, and produce biomass or cellulose wood for paper production.

In a comparative biomass study conducted in Germany, *P. tomentosa* (12.7 t·ha$^{-1}$) produced more than *Salix viminalis* (8.2 t·ha$^{-1}$) on a short rotation coppice under non-irrigated conditions (Maier 2004).

Ptach et al. (2018) and Łangowski et al. (2019) found that *Paulownia* trees grown in Poland could be a valuable source of timber and biomass. Based on their results, irrigation had a significant effect on the stem diameter, the number of leaves, and the surface area. Jacek and Litwińczuk (2016) conducted a study to explore the feasibility of cultivating *Paulownia tomentosa* for biomass production in South-Eastern Poland with the conclusion that *Paulownia* plantations can be successfully established on sandy soils, provided that an irrigation system is available.

The cultivation of *Paulownia* in Hungary in the form of research plantations started only in the last decade, mainly to study its energetic properties (Vityi, Marosvölgyi 2014).

The properties of the wood of *Paulownia tomentosa* cultivated in Hungary do not show significant deviation in relation to those cultivated in other parts of the world. Based on the studies of Komán et al. (2017), its properties can be compared mainly with those of hybrid poplars, for example.

Forage studies on *Paulownia* leaves were reported by Bodnár et al. in 2014 and 2020. The *Paulownia* plantation established in Eastern Hungary in 2014 offers an innovative opportunity to analyse the growing space characteristics of this tree species and its hybrids.

**Growing characteristics of the *Paulownia* species.** There are nine species in the *Paulowniaceae* family, *P. albiphloea, P. australis, P. catalpifolia, P. elongata, P. fargesii, P. fortunei, P. kawakamii, and P. tomentosa* (Zhu et al. 1986; Jensen 2016). The best known of these is *P. tomentosa*, which appeared in Europe in the 1800s for horticultural purposes because of its interesting fruit and beautiful foliage. However, in recent years, its potential commercial role has been recognised.

The empress tree (*Paulownia tomentosa*) is a deciduous tree known for its exceptional growth rate. It is native to the subtropical regions of China, where annual rainfall typically ranges from 500 mm to 2 000 mm (Jay 1998). The empress tree is a majestic tree that can reach a height of 10 to 12 metres with a broad crown. Under favourable conditions, it can achieve an astonishing growth rate of 3 m·yr$^{-1}$ to 4 m·yr$^{-1}$. This species thrives in areas with plenty of sunlight and warmth. Its striking foliage consists of giant heart-shaped leaves up to 80 cm in length with a downy underside. The tree produces magnificent flowers that form intricate clusters of upright, purple inflorescences. It is also worth noting that the *Paulownia* is classified as a C4 plant (Woods 2008).

It has a deep root system (up to 8 m), the development of which is strongly influenced by the structure of the soil. Due to the high nutrient uptake capacity, *Paulownia* plantations have a significant impact on the microbial community of the soil in intensive agricultural systems (Lucas-Borja et al. 2011). One of the main concerns about the tree is its high water requirement, resulting in considerable impact on the local water resources (McKay 2011; García-Morote et al. 2014). However, the findings of Baier et al. (2021) suggest that *Paulownia* does not use significantly more water than other tree species regularly used in plantations in Central Asia.

The species is not very sensitive to soil type. However, soils with high clay content (30% or more) should be avoided (Barton et al. 2007). It does not tolerate acidic soils, pH should be between 5 and 8 (Zhu et al. 1986; El-Showk, El-Showk 2003). There are only a few studies focusing on the effects of soil management, both fertilisation and irrigation, on the biomass (above-ground dendromass), the soil structure and the soil microbial community in *Paulownia* plantations on semi-arid sites (e.g. Lucas-Borja et al. 2011; Madejón et al. 2016).

The *Paulownia* plantations are established at a specific density depending on the end-use. They are usually planted at a spacing of 2 m × 1.5 m to 4 m × 4 m. For biomass production, about 2 000–3 300 plants·ha$^{-1}$ are

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planted, while for timber production, far fewer are planted, about 550–750 trees·ha$^{-1}$ (Icka et al. 2016; Berdón Berdón et al. 2017). *Paulownia* hybrids are grown in short, 6–10-year cycles for their roundwood, but these cycles can be even shorter for biomass (Berdón Berdón et al. 2017). Nowadays, they are grown in plantations in many other places and have been crossed to produce some interspecific hybrids with even better growth dynamics. In this short communication, we report on the relationships between *CD-DBH* (*CD* – crown diameter) and *N-DBH* (*N* – stem number per hectare). Studies of this kind are essential in the field of plantation forestry.

## MATERIAL AND METHODS

The experimental site is located in Eastern Hungary (Monostorpályi, Hajdú-Bihar county) (47°37'96"N, 21°78'01"E), just at the edge of the cold and the warm temperate dry climate zones according to the classification of the Intergovernmental Panel on Climate Change (Hungarian Meteorological Service 2019). In 2022, the annual average temperature was 1.1 °C higher (12.1 °C) than the 30-year (1992–2021) average (11 °C). Furthermore, in 2022, the total annual precipitation (441 mm) was well below the 30-year average (537 mm). The meteorological data (annual average temperature and total annual precipitation) for the last 30 years (1992–2021) are shown in Figure 1 (based on the data of the nearest meteorological station, located in Debrecen). The forest climate type is forest-steppe, a free-draining site [according to the categories of the Hungarian climate classification, based on Járó (1972)]. The *Paulownia* plantation was established in 2014 in an area of 1.8 ha of sandy soil (humus content is less than 1%). The area was previously used for agricultural purposes. This is evidenced by the compacted soil layer at a depth of 40–50 cm. The plantation was planted with 1 580 seedlings, the planting area was 4 m × 4 m.

Simple random sampling was applied with regard to the diameter of the selected trees. The structure of the experimental plantation and the expected distribution of the trunk diameter did not make it reasonable to include a high number of samples.

The following structural factors of the plantation were assessed:

- to calculate the volume of stem wood [$v$ (m$^3$)] expressed in function of basal area [$ba$ (m$^2$); Szabó et al. 2022], see Equation (1)
- diameter at breast height [*DBH* (cm); Laar, Akça 2007; $n$ = 20 sample trees]
- crown diameter [*CD* (m)]: arithmetic average of four radius measurements ($n$ = 20 sample trees)
- crown projection area [*CPA* (m$^2$)], see Equation (2)
- stem number per hectare (*N*), see Equation (3)

$$v = 2.6846\ ba + 0.045 \tag{1}$$

$$CPA = CD^2 \frac{\pi}{4} \tag{2}$$

$$N = \frac{10\ 000}{CPA} \tag{3}$$

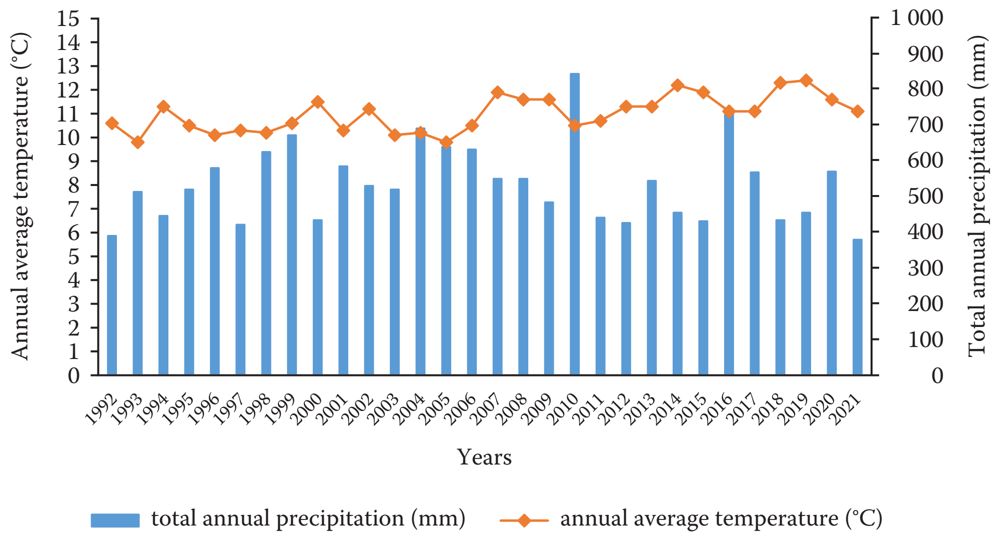


Figure 1. Annual sums of precipitation and averages of temperature (Debrecen, 1992–2021)

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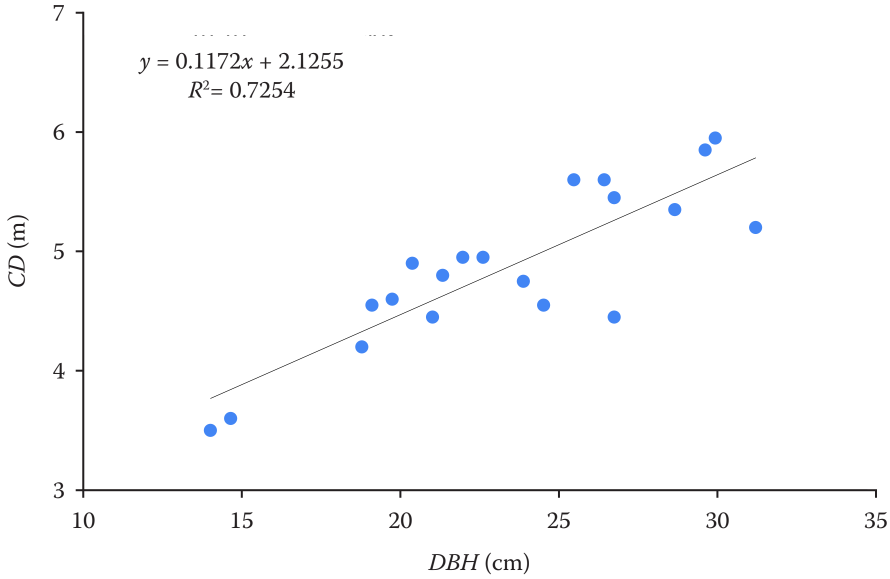


Figure 2. Linear regression of crown diameter (*CD*) on diameter of breast height (*DBH*) of sample trees ($n$ = 20)

## RESULTS AND DISCUSSION

We used linear regression to illustrate the relationship between *DBH* and *CD* with the consideration of the selected sample trees. The correlation ($R^2$ = 0.7254) suggests a high accuracy for predicting crown diameter (*CD*) from *DBH* (Figure 2).

The relationship between *DBH* and expected *N* can be seen in Figure 3.

The accuracy is also high ($R^2$ = 0.7302) which indicates the significant effect of stem number per hectare on *DBH*.

Table 1 contains the *DBH*, *CD*, *CPA*, and *N* values, based on Figure 1 and Figure 2.

The initial spacing chosen at planting, hence, the stand stocking density, has appreciable effects eventually on stand wood yields, the average diameter, and the average wood volume of trees in the stand. It also depends on the purpose for which a plantation is being grown. For example, in bioenergy plantations, the amount of wood produced is the main concern and the sizes of the individual trees are of little importance. However, in plantations being grown for high-quality sawn timber,

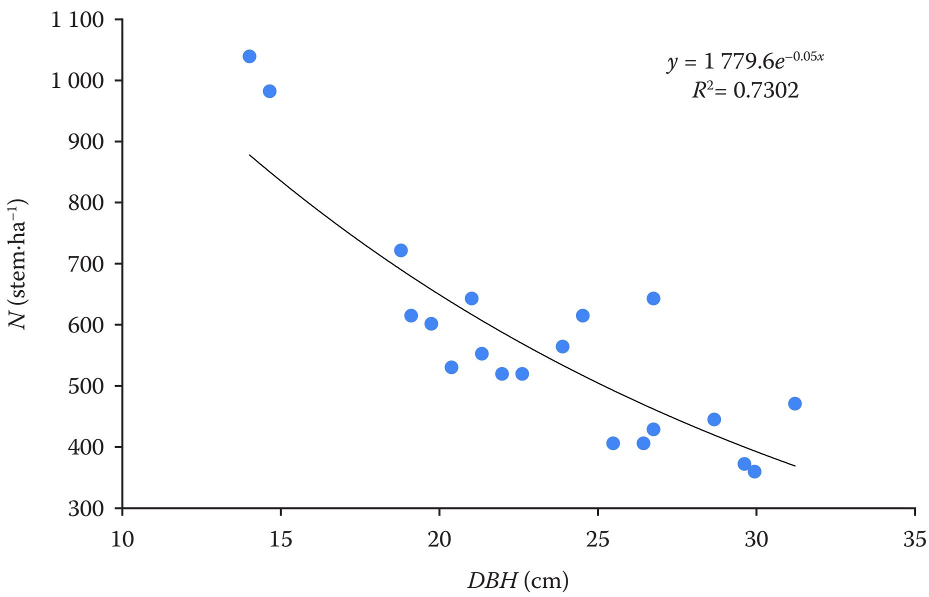


Figure 3. Exponential relationship of stem number per hectare (*N*) on diameter of breast height (*DBH*) of sample trees ($n$ = 20)

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large individual tree sizes are required to maximise the availability of large logs.

Considering the wood assortment requirements, the trees with a *DBH* of ≤ 18 cm are suitable for partly chips as well as fibrewood and pulpwood, while the trees with a *DBH* > 18 cm for sawlogs. The dividing line of stem number per hectare is 710. It should be noted that under the investigated site conditions, the *Paulownia* Shan Tong can provide a higher increment in *DBH* than most of hybrid poplars at a certain age (Sopp 1974).

Growing space and *N* are related terms, average growing space per tree is 10 000 per *N* in m$^2$. In the Hungarian plantation forestry, square and triangle initial spacings can be used. The following explanation is worth taking into consideration, see Equations (4–8).

– *CPA* in case of square spacing:

$$CPA = CD^2 \frac{\pi}{4} = 0.785\,CD^2 \tag{4}$$

Growing space ($G_s$) = $CD^2$

$$\frac{CPA}{G_s} = \frac{0.785\,CD^2}{CD^2} = 0.785 \tag{5}$$

Understocked area: 0.215

– *CPA* in case of triangle spacing:

$$CPA = CD^2 \frac{\pi}{4} = 0.785\,CD^2 \tag{6}$$

Growing space:

$$G_s = CD^2 \times \frac{1}{2} \times \sqrt{3} = 0.866\,CD^2 \tag{7}$$

$$\frac{CPA}{G_s} = \frac{0.785}{0.866} = 0.906 \tag{8}$$

Understocked area: 0.094

where:

*CD* – crown diameter;

*CPA* – crown projection area.

According to the above-mentioned demonstration, the triangle spacing provides better-growing space utilisation.

Table 1. Values of *DBH*, *CD*, *CPA*, and *N*

| *DBH* (cm) | *CD* (m) | *CPA* (m$^2$) | *N* (trees·ha$^{-1}$) |
|---|---|---|---|
| 14 | 3.8 | 11.14 | 898 |
| 15 | 3.9 | 11.85 | 844 |
| 16 | 4.0 | 12.57 | 795 |
| 17 | 4.1 | 13.32 | 751 |
| 18 | 4.2 | 14.09 | 710 |
| 19 | 4.4 | 14.88 | 672 |
| 20 | 4.5 | 15.69 | 637 |
| 21 | 4.6 | 16.52 | 605 |
| 22 | 4.7 | 17.38 | 575 |
| 23 | 4.8 | 18.26 | 548 |
| 24 | 4.9 | 19.15 | 522 |
| 25 | 5.1 | 20.07 | 498 |
| 26 | 5.2 | 21.01 | 476 |
| 27 | 5.3 | 21.98 | 455 |
| 28 | 5.4 | 22.96 | 435 |
| 29 | 5.5 | 23.97 | 417 |
| 30 | 5.6 | 25.00 | 400 |
| 31 | 5.8 | 26.05 | 384 |

*DBH* – diameter at breast height of sample trees; *CD* – crown diameter of sample trees; *CPA* – crown projection area of sample trees; *N* – stem number

## CONCLUSION

There are only a few studies dealing with the stand structure of *Paulownia* plantations. Even a case study can contribute to the available knowledge. Estimates of volume have not been addressed in this study. We did not consider it reasonable to evaluate yield data since the site-specific ecological factors and the growing technologies used in the studies are different.

The published relationships [*CD*→f(*DBH*) and *N*→f(*DBH*)] can be applied in an innovative way in creating *Paulownia* plantations, extending the growing space and planning the composition of the industrial wood mix. The need for more studies should be stressed, in particular with regard to the econometric analysis of *Paulownia* plantations. Indeed, the future/broader expansion of *Paulownia* plantations is under discussion in Hungary. The plantations established to date have been carried out on the basis of individual cost plans and therefore cannot be included in the so-called normal afforestation support scheme.

Furthermore, detailed and complex studies are needed to determine the site requirements of *Pau-*

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*lowinia* hybrids, with a special focus on the use of marginal (semi-arid, arid) sites for forestry (timber production). Similarly, the contribution of *Paulownia* plantations to sustainable biodiversity requires longer-term, systematic monitoring and analysis.

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