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Analyses of periodic annual increment by diameter and volume in differently aged black locust (*Robinia pseudoacacia* L.) stands: Case study

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Abstract: Black locust is one of the most commonly planted exotic tree species in the world. It has a crucial role in mitigating the negative effects of climate change. Its increment analyses have a key role in forest planning. Increment is added to the wood stock of the forest over and over again, and only this continuous replenishment makes the sustainable forest management possible. This study presents the results of the analysis of periodic annual increment (*PAI*) by diameter (*dbh*) and volume (*v*) of two differently aged black locust (*Robinia pseudoacacia* L.) stands, growing under similar ecological conditions. The main correlations are as follows: PAI_{dbh} and diameter at breast height: r = 0.601 and 0.704 (P = 0.01); PAI_v and mean tree volume (v): r = 0.721 and 0.849 (P = 0.01). The presented correlations clearly demonstrate the importance of individual differentiation within a stand.

Keywords: black locust management; growth; *PAI*

The tree stand is a complex organic unit made up of a multitude of individual trees. It therefore goes without saying that there must be a strong correlation between the growth and development of the stand and individual trees (Van Laar, Akça 2007; Avery, Burkhart 2015). The only way to quantify changes is to make the stand itself the object of our observation. However, general statistical rules are derived from a larger number of increment analyses with individual trees.

The increment analyses help to improve the quality of forest management in the following main

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aspects: providing a feedback on the correctness of pest management; serving as a predictive tool for future planning and management; having the knowledge of increment, suitable silvicultural and management practices can be applied; deciding the length of rotation; useful tool for yield regulation (Assmann 1961; Clutter et al. 1983; Rédei et al. 2012).

The three conventional indicators of increment are as follows: periodic annual increment (PAI), current annual increment (CAI) and mean annual increment (MAI). PAI is the change in the size of the tree between the beginning and ending of a growth period, divided by the number of years that was designated as the growing period. CAI is the increment over a period of one year at any stage in the tree history. It varies from year to year being affected by ecological factors, site conditions and treatment. For this reason, it is a common practice to express the increment as a mean over the period of a year, called the periodic annual increment. The PAI is a more realistic indicator of the capacity of a tree (or a stand) of a certain age or size to grow. Increment data must be related to tree age or size. The data are meaningless otherwise (Van Laar, Akça 2007; Avery, Burkhart 2015).

Black locust (*Robinia pseudoacacia* L.) is one of the most commonly planted broadleaved introduced tree species, used for forestry and wood production in Europe (Nicolescu et al. 2018, 2020). Soon after its introduction into Europe it also started to be used for amelioration, reclamation of disturbed sites (DeGomez, Wagner 2001; Quinkenstein et al. 2012; Enescu, Danescu 2013; Lange et al. 2022), leaf forage (Zhang et al. 2012; Nicolescu et al. 2020), biomass production (Grünewald et al. 2009; Böhm et al. 2011; Rédei et al. 2011; Manzone et al. 2015; Lange et al. 2022), honey production and shading (Keresztesi 1988). Moreover, the tree is suitable for planting in urban or industrial areas due to its tolerance to air pollution, drought, toxic, salty or nutrient-poor soils. It is also to be considered as a significant tree species in mitigating the negative effects of global and local climate change on the environment including forest management (Rédei et al. 2013; Mantovani et al. 2014; Moser et al. 2016, 2018; Keserü et al. 2021; Ábri et al. 2022). The ecological risks of black locust are well-known, and many studies have been published on this subject (Vítková, Kolbek 2010, Vítková et al. 2015, 2017; Sádlo et al. 2017). However, if the relevant cultivation technology is followed, the invasive characteristics of *Robinia pseudoacacia* can be significantly reduced (Rédei 1984; Rédei et al. 2017; Nicolescu et al. 2020).

In Hungary, black locust is also one of the most important stand-forming forest tree species, covering approximately 24% of the forest land and providing 25% of the annual timber supply (FAO 2020). In spite of this fact, there are only few national and international research results on the increment analyses of diameter and volume in black locust stands. Systematic increment and yield studies allow a better understanding of the impact of tending cuttings on increment (growth and yield) and a more precise determination of their intervals. Growth studies can also help in the selection of tree species, as they can be used to analyse the effects closely related to changes in site conditions (climate change). The aim of this study is to present case studies of the growth (increment) conditions of black locust, which is an important tree species in many countries and which plays a key role in mitigating the negative effects of local and global climate change, thus the presented results and relationships are crucial for predicting its yield. Furthermore, such analyses are also important from an economic aspect. Our paper aims to contribute to this subject in informative and innovative ways.

MATERIAL AND METHODS

Study site. Our experimental plots (500 m^2 per plot) are located in the Nyírség region, north-eastern Hungary. In this area the annual average temperature is 10.4 °C and the total annual precipitation is 527.4 mm (HMS 2022). One of the plots is in subcompartment Nyírbátor 27A (47°50'19''N, 22°11'47''E), and the other is in Nyírbátor 28A (47°50'10''N, 22°11'51''E). The site type [according to Járó and Lengyel (1988)] of the subcompartments is as follows: hornbeam-oak forest climate, free-draining site, 'kovárvány' brown forest soil type. The depth of the soil is medium deep and the soil texture is sand (Nyírbátor 27A). The site type of Nyírbátor 28A subcompartment is almost the same, but the soil type is humic sandy soil. The selected stands have a normal stand structure. There were three tending cuttings performed at the age of 7, 13 and 20 years [according to Rédei (1984)].

Assessed parameters. We carried out two full inventories in the stands. The first at the age of 21 (Nyírbátor 28A) and 23 years (Nyírbátor 27A), and

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the second one was at the ages of 25 (Nyírbátor 28A) and 27 years. During the full inventories, for each tree (N = 34 in the plot of Nyírbátor 28A subcompartment and N = 31 in the plot of Nyírbátor 27A) diameter at breast height (*dbh*) and height (*h*) were measured according to the relevant international forest measurement methods (Van Laar, Akça 2007). We used Vertex IV forestry hypsometer (Haglöf, Sweden) for the height measuring. The basal area (*ba*) was calculated using Equation (1) and the stem volume (mean tree volume; *v*) of each tree was calculated using Equation (2), a volume function based on the volume table for black locust (Sopp, Kolozs 2013).

$$ba = \frac{dbh^2 \times \pi}{4} \quad (1)$$

where:
ba – basal area of a single tree (m²);
dbh – diameter at breast height of a single tree (cm).

$$v = 10^{-8} \times dbh^2 \times h \times \left(\frac{h}{h-1.3}\right)^4 \times \times \left(-0.6326 \times dbh \times h + 20.23 \times dbh + 3\,034\right) \quad (2)$$

where:
v – stem volume (m³);
dbh – diameter at breast height of a single tree (cm);
h – tree height of a single tree (m).

We also calculated these parameters at the stand level. The height of the stands (*H*) was determined by Lorey's formula (Lorey 1878). In the case of the diameter of the stands (*DBH*) we used quadratic mean diameter (Van Laar, Akça 2007). The growing spaces per tree were measured by Equation (3). The most important key characteristics of the stands are listed in Table 1.

$$Gs = \frac{N}{10\,000} \quad (3)$$

where:
Gs – growing space (m²);
N – number of stems (stems·ha⁻¹).

In forestry, periodic annual increment (*PAI*) is the change in the size of a tree between the beginning and ending of a growth period, divided by the number of years that was designated as the growing period (Avery, Burkhart 2015):

$$PAI = \frac{Y_2 - Y_1}{T_2 - T_1} \quad (4)$$

where:
PAI – periodic annual increment;
Y_1; Y_2 – the yield (*DBH*, volume, etc.) at times 1 and 2;
T_1 – the year starting the growth period;
T_2 – the end year of the growth period.

Statistical analyses. We compared PAI_{dbh}, PAI_v, *dbh*, *h* and *v* values using Pearson's correlation (*r*) and linear regression analyses. The results are shown in matrix tables and in scatter plots. Statistical evaluations were performed by Microsoft Excel (Version 2016, 2016) (for linear regression lines, determination of the R^2 values) and IBM SPSS (Version 25, 2017) software packages (for Pearson's correlation).

RESULTS

A matrix of correlation coefficients for PAI_{dbh} and PAI_v as a function of diameter at breast height (*dbh*), tree height (*h*) and stem volume is provided for both experimental sites. Tables 2 and 3 show the results of Pearson's correlation of the data from

Table 1. Key characteristics of the stands (subcompartments Nyírbátor 27A and Nyírbátor 28A)

Subcompartment	Age (years)	*H* (m)	*DBH* (cm)	*BA* (m²·ha⁻¹)	*V* (m³·ha⁻¹)	*N* (stem·ha⁻¹)	*v* (m³)	*DBH*/*H* (%)	*Gs* (m²)
Nyírbátor 28A	21	20.1	18.23	17.99	210.44	680	0.3095	90	14.71
	25	20.8	20.72	23.23	254.43		0.3742	100	
Nyírbátor 27A	23	20.6	20.07	19.87	246.43	620	0.3975	97	16.13
	27	21.0	22.45	24.87	298.19		0.4810	107	

H – Lorey's height; *DBH* – diameter of the stand; *BA* – basal area of the stand; *V* – volume; *N* – number of stems; *v* – stem volume; *DBH*/*H* – stability index; *Gs* – growing space

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Table 2. Pearson correlation matrix (Nyírbátor 28A)

Variables	*dbh*	*h*	*v*	PAI_{dbh}	PAI_v
dbh	–	0.920*	0.980*	0.601*	0.702*
h	0.920*	–	0.853*	0.543*	0.633*
v	0.980*	0.853*	–	0.609*	0.721*
PAI_{dbh}	0.601*	0.543*	0.609*	–	0.966*
PAI_v	0.702*	0.633*	0.721*	0.966*	–

*correlation is significant at the 0.01 level (2-tailed); *dbh* – diameter at breast height; *h* – tree height; *v* – mean tree volume; PAI_{dbh} – periodic annual increment in diameter; PAI_v – periodic annual increment in volume

subcompartments (Nyírbátor 28A, Nyírbátor 27A). As evident from Table 2, the highest correlation coefficient $r = 0.980$ ($P = 0.01$) was found between *dbh* and volume. This is followed by PAI_{dbh} and PAI_v ($r = 0.966$), *dbh* and *h* ($r = 0.920$), and *h* and *v* ($r = 0.853$). The Pearson's r in the case of PAI_{dbh} and *dbh* is $r = 0.601$, and *v* and PAI_v $r = 0.721$.

In Nyírbátor 27A (Table 3) we have got similar results like in Table 2: we found strong correlations between the studied parameters. The main correlations are as follows. PAI_{dbh} and *dbh*: $r = 0.704$ ($P = 0.01$); PAI_v and *v*: $r = 0.849$ ($P = 0.01$).

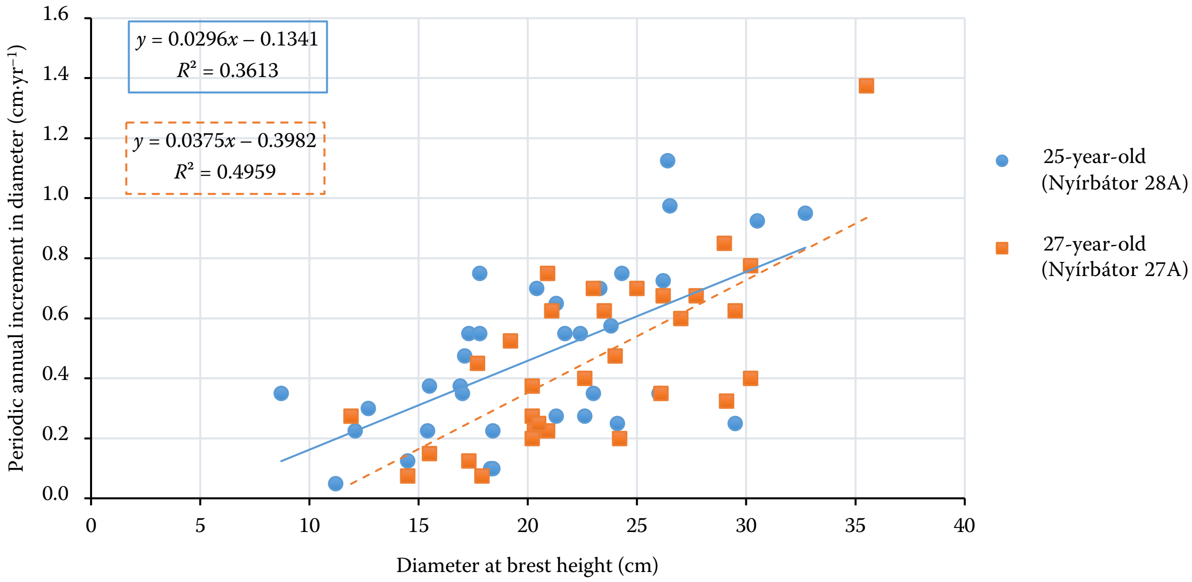

Figure 1. Linear regression between periodic annual increment in diameter (PAI_{dbh}) and diameter at breast height (*dbh*)

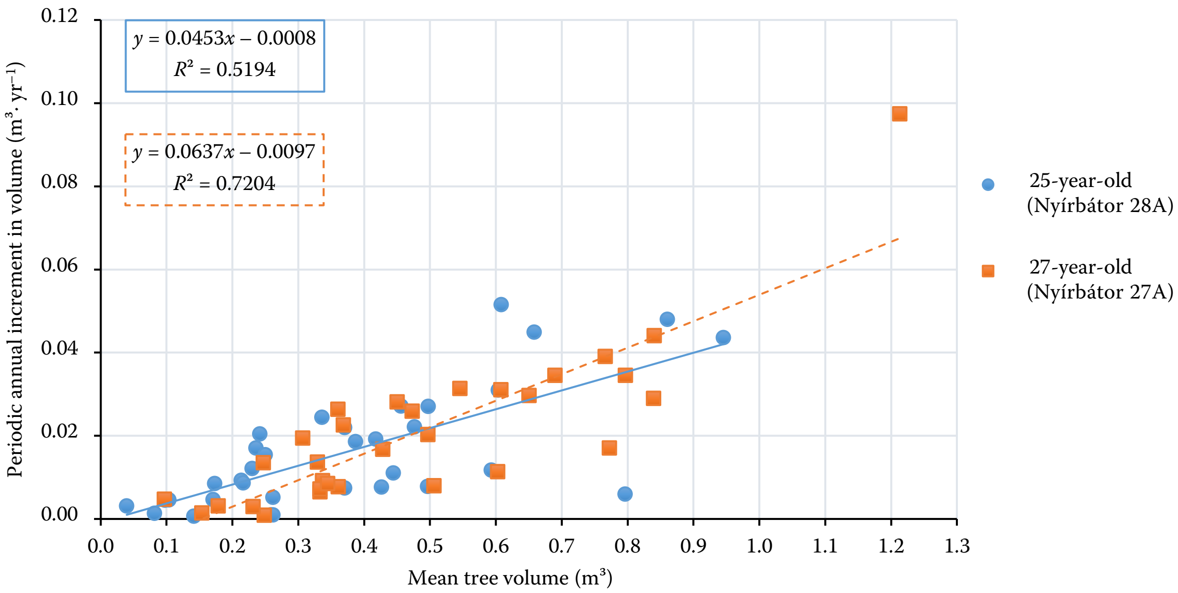

Figure 2. Linear regression between periodic annual increment in volume (PAI_v) and mean tree volume (*v*)

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Table 3. Pearson correlation matrix (Nyírbátor 27A)

Variables	*dbh*	*h*	*v*	PAI_{dbh}	PAI_v
dbh	–	0.980*	0.984*	0.704*	0.797*
h	0.980*	–	0.938*	0.685*	0.747*
v	0.984*	0.938*	–	0.730*	0.849*
PAI_{dbh}	0.704*	0.685*	0.730*	–	0.944*
PAI_v	0.797*	0.747*	0.849*	0.944*	–

*correlation is significant at the 0.01 level (2-tailed); *dbh* – diameter at breast height; *h* – tree height; *v* – mean tree volume; PAI_{dbh} – periodic annual increment in diameter; PAI_v – periodic annual increment in volume

Figure 1 provides with a linear regression the relationship between PAI_{dbh} and *dbh* in two differently aged (25-year-old stand in Nyírbátor 28A subcompartment and 27-year-old stand in Nyírbátor 27A subcompartment) black locust stands. The coefficients of determination are R^2 = 0.3613 and R^2 = 0.4959. These R^2 values are acceptable.

Next, linear regression equations were developed to study the relationship between PAI_v and *v*. The results are shown in Figure 2: R^2 = 0.5194 (in Nyírbátor 28A subcompartment) and R^2 = 0.7204 (in Nyírbátor 27A subcompartment).

DISCUSSION

The growth pattern, and consequently the set of increments, is greatly affected by age, site, tree species and stand structure (Silva et al. 1996; da Silva et al. 2002; Seo et al. 2014; Nicolescu et al. 2020). The increment is also affected to a large extent by the frequency, type and intensity of tending cuttings (clearings, thinnings) carried out in the stand (Bradley 1963; Harrison et al. 1986; Schuler et al. 2017). Differences in growth within stands have a significant effect on diameter at breast height and volume, among others. All of these can be verified numerically in this study (see *R* values in the presented matrix tables).

The study focused on the diameter and volume increment of a black locust stand (age 10–27 years, yield class II) has shown that in comparison with the *PAI* in *dbh* values of trees in height class I, trees in height class II have reached 83.3%, while in class III only 43.9%. The same relations of 59.0% and 24.5% for volume were found. The mean values of the whole stand were close to those of height class II. According to the distribution of the *PAI* in volume between 10 and 27 years of age, 50% of the values were between 2.00 and 13.88 dm^3, 73% were between 2.00 and 19.82 dm^3, and 96% were between 2.00 and 37.64 dm^3. The range of 13.88–19.82 dm^3 had the highest occurrence (24.5%) (Rédei, Ábri 2021).

An important field of the practical use of increment values is the definition of the profitability of timber production. An econometric study of Hungarian black locust stands shows that at the total growing stock value of 6 $m^3 \cdot yr^{-1} \cdot ha^{-1}$, the management is still profitable (Rédei et al. 2012).

Increment data also play a great role in determining the final cutting age, which assumes the highest yield in plantation forestry. In the black locust management, it is obvious to grow until approximately the age of maximum MAI or until the time of some other measures of economic maturity and then clear-felling the whole crop. This ensures high productivity and it is simple to carry out. Felling an even-aged stand at the age when maximum MAI is attained is analogous to harvesting a natural forest at the late pioneer stage of succession when the mean annual net primary production is at its highest. Since monocultures predominate in simple plantation forestry, the species chosen to grow in them are of paramount importance (Savill et al. 1997).

CONCLUSION

However, it should be noted that the authoritative international studies on growth, increment and primary wood production are relatively limited in their coverage of "growth theory", with a more in-depth examination of the factors that affect growth. One reason for this may be that the relevant research work focuses mainly on modelling the growth of tree stands, with little emphasis on studying the relationships between the factors that affect the growth.

This paper has shown the significant correlations of the main stand structural factors (diameter at breast height and stem volume) between periodic annual increments by diameter and stem volume. By comparing the two figures, Figure 2 provides a more reliable correlation, not only for the study of the given stand structure, but also for practical silviculture. A large amount of data is needed to obtain tabularly summarized, mathematically modellable results. However, the partial results highlight the importance of the research related to the increment and the fact that the stand improvement can affect this characteristic.

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