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Diameter growth performance of northern red oak (*Quercus rubra* L.) in northeastern Hungary

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Abstract: Northern red oak (*Quercus rubra* L.) is an important introduced tree species in Hungary, particularly in the Nyírség region. This study investigates its diameter growth (*DBH*) in six forest subcompartments, with stand ages ranging from 20 to 71 years. 5- and 25-year diameter increments were calculated. The distribution of diameter and diameter increment values was also determined. The results show significant growth across all sites. For example, quadratic mean diameter (*QMD*) increased from 16.4 cm to 30.4 cm over 25 years in the forest subcompartment Encsencs 12A, and from 20.3 cm to 38.4 cm in Ófehértó 2A. Five-year *DBH* increments ranged from 1.8 cm (± 0.8) in older stands to 4.2 cm (± 0.5) in younger or middle-aged stands. The findings confirm *Q. rubra*'s capacity for steady diameter growth in northeastern Hungary and contribute valuable growth data for future yield modelling and forest management strategies.

Keywords: increment; introduced tree species; plantation forestry; tree diameter; yield modelling

Northern red oak (*Quercus rubra* L. syn. *Q. borealis* F. Michx.) was introduced to Europe at the end of the 17th century. It was planted in parks and later used in afforestation and in plantations in most of the countries of the continent, except for Scandinavia. Its timber can be used for construction, for the interior of houses, veneer, lumber, firewood, etc. (Vansteenkiste et al. 2005). It could also play a role in agroforestry systems in the future (Nicolescu et al. 2018).

Today it is grown in about 350 000 ha in Europe, mostly in Ukraine, France, Germany, Poland and Hungary. It is tolerant to a wide range of climatic conditions, and it is well adapted to a temperate climate, which characterises Central Europe (Nicolescu et al. 2020). In 2025, it was named 'Tree of the Year' in Germany due to its ability to thrive in dry locations. It is forecast to become an important species in German forests (Kuratorium Baum des Jahres 2025).

Northern red oak favours deep, loose, moderately wet and acidic soils which do not contain calcium carbonate, with a minimum of moderate fertility (Miltner, Kupka 2016; Rédei 2018). It requires a moderately warm climate, it is more tolerant to biotic and abiotic stress (drought, storm

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damage) compared to other oak species, and it is less demanding in terms of soil water and nutrients (Kim et al. 1995). Compared to sessile oak (*Quercus petraea* L.), higher production has been reported under similar site conditions (Kupka et al. 2018; Štefančík, Pástor 2023). Its drought tolerance is confirmed by the fact that germination is still possible when the moisture content of the acorn falls between 18–20% as opposed to other oak species, which lose their ability to germinate at 25–28% (Nemky 1964). It is more resistant to sudden oak death (*Phytophthora ramorum* Werres, De Cock & Man in't Veld, 2001) than other oak species (Štefančík 2011). According to Paulin et al. (2020), North American red oaks are not suitable hosts for the oak lace bug (*Corythucha arcuata* Say, 1832). The species richness of herbivore insects on northern red oak is much smaller compared with pedunculate and sessile oak, which are domestic species in Hungary. (Csóka, Hirka 2001; Hirka, Csóka 2002; Sun et al. 2021). This is an appealing attribute to forest growers, but researchers draw attention to the fact that it could cause concerns to local biodiversity at large extent of northern red oak forest stands, since the decline of herbivore insect populations could consequently affect the population of other wildlife, such as birds and bats (Tallamy, Shropshire 2009; Tallamy, Shriver 2021).

There is no exact record of its first appearance in Hungary, whereas its application in afforestation was first mentioned by Fekete (1881). Today, northern red oak is present on 18 276 ha of land area in Hungary, and on 12 735 ha, the tree species covers over 70% of the stands. Its main growing area is the northeastern part of Hungary (mainly in the Nyírség region) (Figure 1), where about half of the stands of the country can be found (41 %, 5 258 ha) [Ministry of Agriculture (Hungary) 2024].

In this study, we present the diameter growth of northern red oak (*Quercus rubra* L.) stands at various ages in northeastern Hungary. Diameter growth plays a crucial role in determining yield. As relatively few studies have focused on the growth of northern red oak stands, the results presented here may contribute to bridging this research gap.

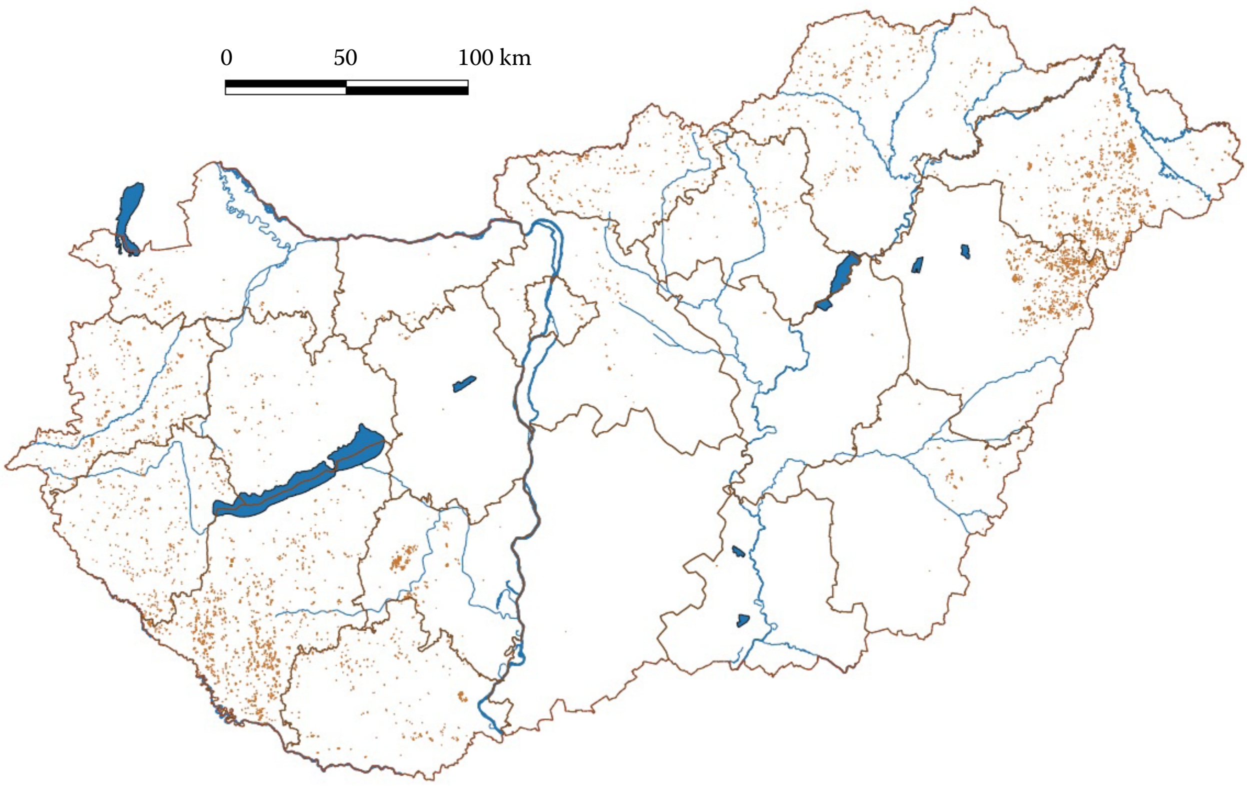

Figure 1. Distribution of northern red oak (*Quercus rubra* L.) in Hungary

Source: National Forest Inventory Database [Ministry of Agriculture (Hungary) 2024]

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MATERIAL AND METHODS

Study sites. The experimental sites are located in the Nyírség region, where the average mean temperature is 9.7 °C, which is below the country's average. Winter is boreal, summer is mild, and the region is prone to early and late frosts. The average annual precipitation is 579 mm, of which 360 mm falls in the vegetation period (April to September) (Führer 2017).

Based on the meteorological data of the past decades, the negative effects of local climate change are considerable (rising average mean temperature, uneven distribution of precipitation, decrease of precipitation in spring, extreme droughts) (Ábri et al. 2023).

The site is characterised by a 'Turkey oak – sessile oak' climate [(based on Hungarian site typology by Járó (1972)]. In this climate type, these two tree species either co-occur or alternate in characterising the site climate where beech (*Fagus sylvatica* L.) and hornbeam (*Carpinus betulus* L.) are absent. The annual average precipitation is around 600 mm, with approximately 195 mm during the main growing season. The annual mean temperature is nearly 10 °C, and during the critical months (July and August), it can reach up to 20 °C. This climate type occurs on approximately 30% of the Hungarian forested area, and it is projected to decrease in the future (Mátyás et al. 2018). The experimental stands are on humic sandy soil at a free-draining site [based on Hungarian site typology by Járó (1972)]. We investigated the growth of diameter (diameter at breast height, *DBH*) of northern red oak trees between the ages of 20–71 years in six forest subcompartments in Nyírség, Hungary, one of the main growing regions of the species in the country. The size of the sampling plots was 500 m^2, one plot in each subcompartment.

We recorded the *DBH* of individual trees in line with the international methodology (Burkhart et al. 2019). Five years later, we repeated the measurements and then we calculated the arithmetic mean of *DBH* and the *DBH* current annual increment. We returned to the experimental plots 25 years after the previous measurements, and we were able to collect data from the same sampling plots in three forest subcompartments (Encsencs 12A, Encsencs 11J and Ófehértó 2A), but we were unable to identify the exact individual trees. Moreover, selective thinning was carried out at age 49 (Encsencs 11J), age 37 (Encsencs 12A) and at age 44 (Ófehértó 2A). Hence, the stem number of experimental plots has decreased; therefore we applied the quadratic mean diameter (*QMD*) (Curtis, Marshall 2000). This is a standard method to define the average stand diameter. We also calculated *QMD* for the data we had collected 25 years before the last measurements to be able to compare it. The following Equation (1) was used:

$$\sqrt{\sum \frac{d_i^2}{n}} \quad (1)$$

where:

d_i – diameter at breast height of an individual tree;

n – total number of trees.

To define the arithmetic mean (± standard deviation) and *QMD* and to evaluate the results, we used IBM SPSS Statistics (Version 25.0, 2017) and MS Excel (Version 16.0, 2016) software.

The description of the stands (age, number of stems) of the studied stands can be found in Table 1.

Table 1. Age and stand density of the studied stands

Subcompartments	Age (years)	*n* (trees)	*N* (tree·ha^{-1})
Encsencs 12A	20–25	41	820
	50	16	320
Ófehértó 2A	22–27	34	680
	52	15	300
Encsencs 11J	38–43	30	600
	68	21	420
Encsencs 9M	47–52	16	320
Nyírvasvári 1M	60–65	12	240
Encsencs 9C	66–71	12	240

n – number of stems (experimental plot); *N* – number of trees per ha

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RESULTS

The diameter at breast height (*DBH*) of 41 sample trees was measured in the forest subcompartment Encsencs 12A. The average (arithmetic mean) diameter (± standard deviation) was 12.1 (± 1.8) cm at age 20, and 16.3 (± 2.0) cm at age 25. Shapiro-Wilk tests indicated that the *DBH* at the age of 25 followed a normal distribution ($P = 0.051$), whereas the *DBH* at the age of 20 did not ($P = 0.010$). The arithmetic mean of the diameter increment is 4.2 (± 0.5) cm. The 5-year *DBH* increment values also follow a normal distribution ($P = 0.389$) (Figure 2).

The quadratic mean diameter (*QMD*) calculated from the diameter values at age 50 ($n = 16$) is 30.4 cm. For comparison, the corresponding value 25 years earlier was 16.4 cm. In other words, the *QMD* of the studied stand increased by 14 cm over the period.

The arithmetic mean (± standard deviation) of the *DBH* values of 34 sample trees in the Ófehértó 2A forest plot was 17.8 (± 2.4) cm and 20.3 (± 3.0) cm at ages 22 and 27, respectively. Figure 3 shows the distributions of the diameter values.

The arithmetic mean (± standard deviation) of diameter increment (5-year *DBH* increment, age 22–27 years) values over 5 years was 2.5 (± 1.0) cm. The distribution of diameter increment data is shown in Figure 4.

At the age of 52 years, 15 trees remained in the sample plot due to various tending operations. The *QMD* was 38.4 cm, which is an outlier based on the relevant yield tables (Birck, Sopp 1974; Rédei et al. 2007). At the age of 27 years, this value was 20.3 cm; thus, the stand had a diameter increase of 18.1 cm over 25 years. All data follow normal distributions ($P > 0.05$).

The arithmetic means (± standard deviation) of *DBH* values for the 30 sample trees in the Encsencs forest plot 11J were 15.1 (± 2.6) cm and 19.1 (±2.8) cm at ages 38 and 43, respectively. The arithmetic mean of the 5-year diameter increment (*DBH*) values was 4.0 (± 0.5) cm (Figure 5). In this case, data also followed the normal distribution ($P > 0.05$).

At 68 years of age, the *QMD* values were calculated from 21 tree diameter data, and it was 29.6 cm, i.e. 10.3 cm more than the *QMD* at 43 years of age (19.3 cm).

The results for the other forest plots are presented without figures. The arithmetic means (± standard deviation) of *DBH* values in the subcompartment of Encsencs 9M were 26.5 (± 4.7) cm at age 47, and 30.7 (± 5.2) cm at age 52, based on the *DBH* measurements on 16 sample trees. The arithmetic mean (± standard deviation) of the 5-year diameter increments was 4.2 (± 0.6) cm.

The results of the *DBH* measurements on 12 sample trees in the Nyírvasvár 1M forest compartment

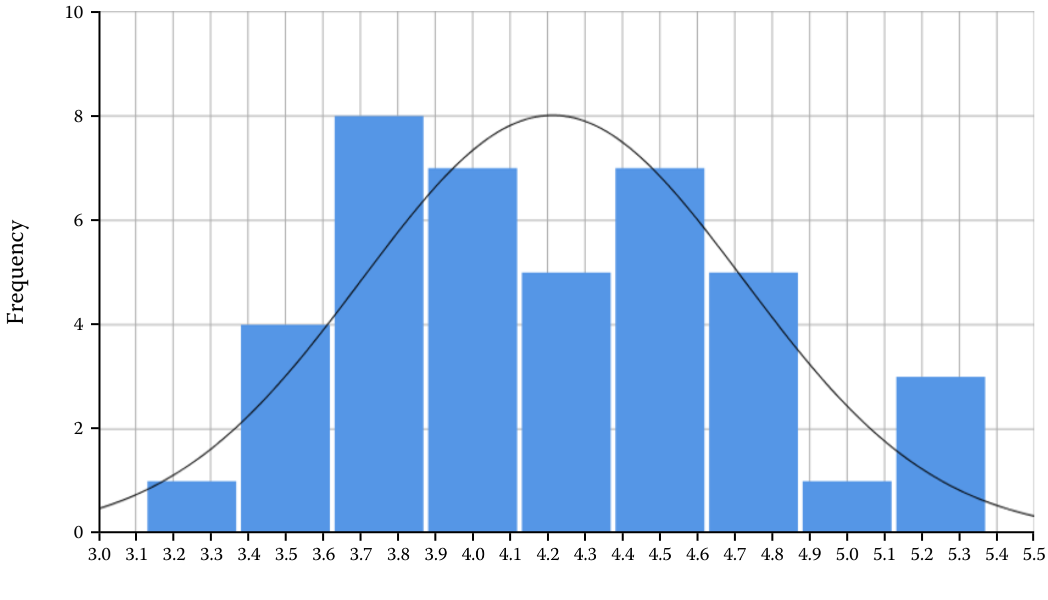

Figure 2. Distribution of the 5-year diameter increment, age 20–25 years (subcompartment Encsencs 12A)

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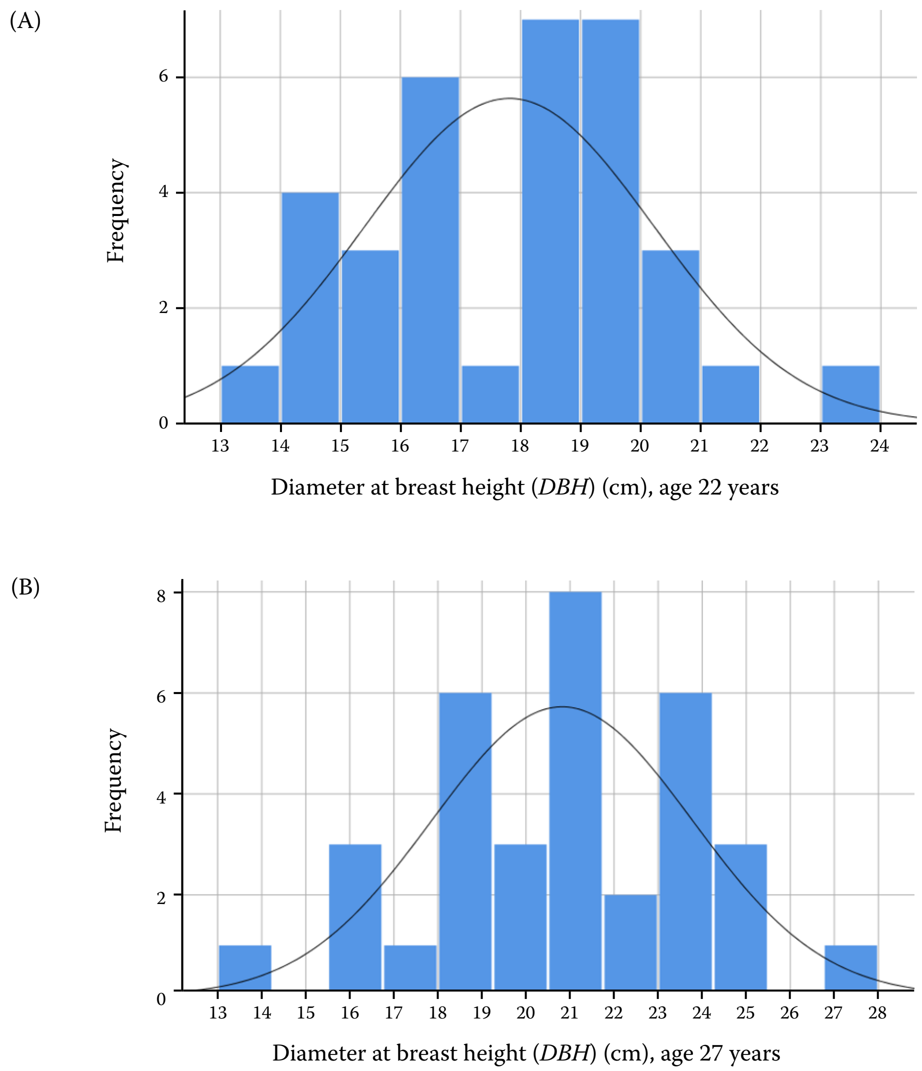

Figure 3. Distribution of the *DBH* values of northern red oak stands at the ages of (A) 22 years and (B) 27 years (subcompartment Ófehértó 2A)

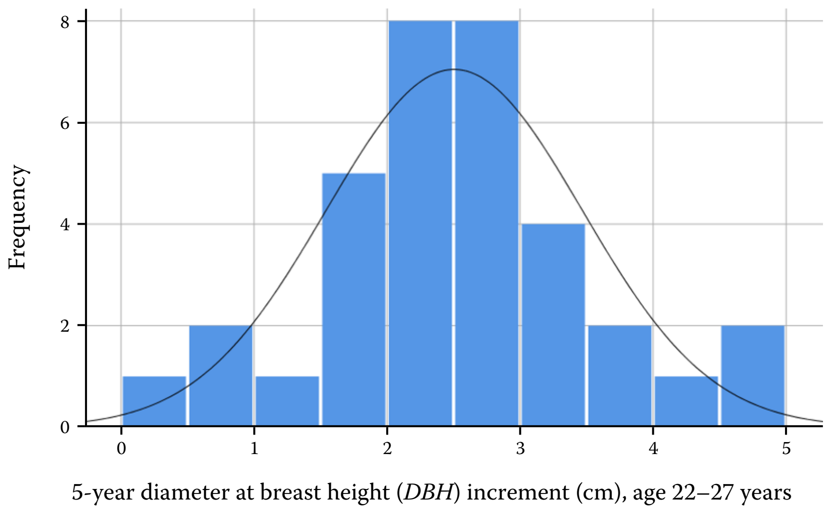

Figure 4. Distribution of the 5-year diameter increment, age 22–27 years (subcompartment Ófehértó 2A)

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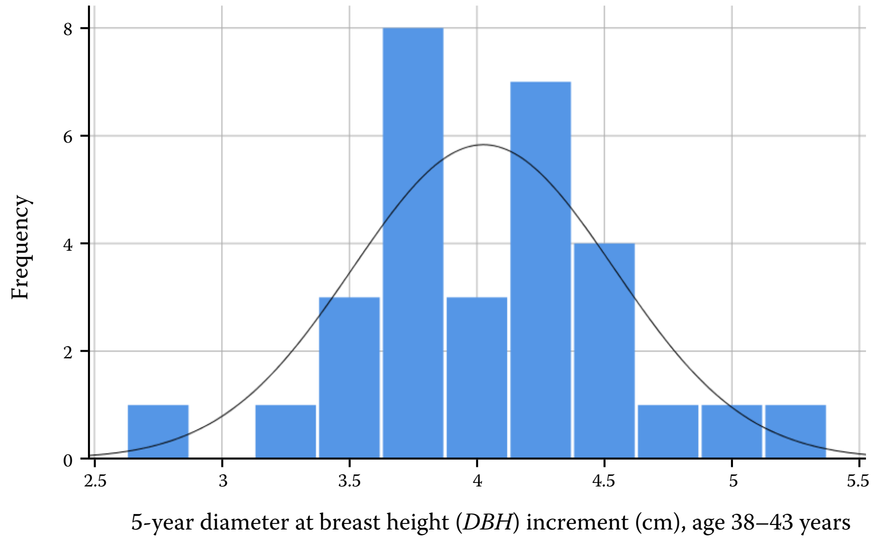

Figure 5. Distribution of the 5-year diameter increment, age 38–43 (subcompartment Encsencs 11J)

show that the arithmetic means (± standard deviation) of the *DBH* values were 40.2 (± 1.7) cm and 43.7 (± 2.1) cm at ages 59 and 64, respectively. The arithmetic mean of the 5-year diameter increment values was 3.5 (± 0.6) cm.

Based on the results of the diameter measurements of 12 sample trees (Encsencs 9C), the mean (± standard deviation) *DBH* was 33.1 (± 6.1) cm at age 66 and 34.9 (± 6.3) cm at age 71. The 5-year mean (± standard deviation) diameter increment was 1.8 (± 0.8) cm.

The data for the forest subcompartments described above follow a normal distribution ($P > 0.05$). The diameter and 5-year diameter increment values are summarised in Table 2. The *QMD* values and 25-year increments are summarised in Table 3.

Table 2. Arithmetic mean (± standard deviation) of the diameter and 5-year diameter increment values

Subcompartments	Age (years)	DBH_1 (cm)	DBH_2 (cm)	DBH_{inc} (cm)
Encsencs 12A	20–25	12.1 ± 1.8	16.3 ± 2.0	4.2 ± 0.5
Ófehértó 2A	22–27	17.8 ± 2.4	20.3 ± 3.0	2.5 ± 1.0
Encsencs 11J	38–43	15.1 ± 2.6	19.1 ± 2.8	4.0 ± 0.5
Encsencs 9M	47–52	26.5 ± 4.7	30.7 ± 5.2	4.2 ± 0.6
Nyírvasvári 1M	60–65	40.2 ± 1.7	43.7 ± 2.1	3.6 ± 0.6
Encsencs 9C	66–71	33.1 ± 6.0	34.9 ± 6.3	1.8 ± 0.8

DBH_1 – results of first diameter at breast height measurement; DBH_2 – results of second (5 years later) diameter at breast height measurement; DBH_{inc} – 5-year diameter at breast height increments

Table 3. *QMD* values and 25-year increments

Subcompartments	Age (years)	QMD_1 (cm)	QMD_2 (cm)	QMD_{inc} (cm)
Encsencs 12A	25–50	16.4	30.4	14.0
Ófehértó 2A	27–52	20.3	38.4	18.1
Encsencs 11J	43–68	19.3	29.6	10.3

QMD_1 – results of the first diameter at breast height measurement; QMD_2 – results of the second (25 years later) diameter at breast height measurement; QMD_{inc} – 25 years diameter at breast height increments

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DISCUSSION

Overall, it can be stated that the highest diameter increment occurred during the initial growth phase (age interval 20–25 years), reaching 4.2 ± 0.5 cm, while the lowest value was recorded in the oldest age class (66–71 years), at 1.8 ± 0.8 cm. The pronounced early growth is supported by the results of Sandi and Nicolescu (2011), who reported an annual average diameter increment of 0.50–0.63 cm at age 10. In contrast to the yield table data for the Nyírség region (Rédei et al. 2007), diameter increment did not decrease linearly. Notably, elevated diameter growth was observed in the 38–43, 47–52, and 59–64-year age intervals: 4.0 ± 0.5 cm, 4.2 ± 0.6 cm, and 3.6 ± 0.6 cm, respectively, corresponding to annual growth rates of 0.80, 0.84, and 0.72 $cm \cdot yr^{-1}$ based on 5-year averages. According to Dumitriu-Tătăranu (1984), the most intensive growth occurs between the ages of 20–40 years and 50–60 years, with annual increments of up to 1 cm, a trend also confirmed by Nicolescu et al. (2020). Our results are consistent with these findings, showing average annual diameter increments of 0.72–0.84 $cm \cdot yr^{-1}$ in the same age ranges.

The studied stands generally demonstrated good growth potential. According to the most recent diameter measurements, all stands exceeded the diameter values corresponding to yield class (YC) I, with the exception of the stand in the Encsencs 11J subcompartment, which lies between YC I and YC II. The stand in Ófehértó showed outstanding diameter values across all three measurement periods, significantly exceeding the age-specific reference values for YC I as reported in the regional yield table by Rédei et al. (2007).

Looking forward, Central European foresters and forest researchers must increasingly account for the adverse impacts of climate change, including the spread of drought-prone site conditions (Mátyás et al. 2018). Currently, *Q. rubra* in Hungary is primarily found on sites with sufficient water availability, mainly on humus-rich sandy soils and rusty brown forest soils. Approximately half of Hungary's northern red oak stands are located on such sites [Ministry of Agriculture (Hungary) 2024]. However, future shifts (due to local climate change) in site conditions may force the species to occupy more marginal habitats. Although *Q. rubra* is not currently among the main species recommended for afforestation on marginal sites, we find it relevant to note that yield expectations for such areas can be approximated using the parameters of yield classes YC V and VI in the regional yield table (Rédei et al. 2007). On these marginal sites, the expected total stand volume at final harvest age (70 years) is estimated at 142 $m^3 \cdot ha^{-1}$ for yield class VI and 189 $m^3 \cdot ha^{-1}$ for yield class V. Diameter growth is a key determinant of yield (total volume), accounting for approximately two-thirds of the final volume. At age 70, stand-level *DBH* values of 14.7–17.8 cm can be projected for stands belonging to yield classes V and VI, respectively (Rédei et al. 2007).

CONCLUSION

In forest management systems, increment data serve multiple functions, including the updating of compartment-level inventory data, growth projection modelling, and the increment-based adjustment of volumes scheduled for final cutting. Typically, forest management plans do not include data on height and diameter increment, as their field-based determination poses significant practical challenges. An additional complicating factor is the average-enhancing effect of tending operations (particularly noticeable in diameter growth), which can distort raw increment observations.

Given the logistical and methodological constraints of field-based increment analysis, such studies are most suitably conducted in high-value, near-cutting-age stands. These analyses can also contribute to the refinement of existing yield table data by providing empirical correction factors. Furthermore, increment studies provide essential insights into the biological and economic viability of extending the harvest rotation age of a given stand under site-specific conditions.

One of the foremost priorities of forestry science worldwide is the mitigation of the adverse effects of both global and local climate change. In this context, northern red oak (*Quercus rubra*) demonstrates considerable potential due to its favourable silvicultural and ecological characteristics. It enables efficient wood production even on nutrient-poor, acidic sandy soils. This capacity is substantiated by empirical data from the Nyírség region, where red oak stands classified to yield classes IV and V, according to the regionally developed yield table, have shown promising growth

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performance. Studying increment systematically requires long-term experiments, the maintenance of the designated parcels, and executing inventory and analyses of the forest stands at certain time intervals. Therefore, only a limited number of research institutions are capable of such activities due to their time, cost and labour-demanding nature.

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