# RESPONSE OF BLACK ALDER (*Alnus glutinosa* (L.) GAERTN.) TO SELECTIVE THINNING OF VARIOUS INTENSITIES: A HALF-CENTURY STUDY IN NORTHEASTERN SLOVENIA

## ODZIV CRNE JOHE (*Alnus glutinosa* (L.) Gaertn.) NA RAZLIČITE INTENZITETE SELEKTIVNE PRORJEDE: PEDESETGODIŠNJA ISTRAŽIVANJA U SJEVEROISTOČNOJ SLOVENIJI

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## SUMMARY

Pure black alder stands are specific and require adapted silvicultural models. To determine the best intensity of selective thinning in such stands, research plots were established in Polanski Log in 1967. Three thinning intensities were selected: control, moderate and high. These stands are presently in a mature phase. In 1967, 1973, 1979, 1983, 1993, 1998 and 2018 diameter at breast height was measured and social status, vitality, tendency, silvicultural role, crown length and overall quality were estimated. The differences in black alder responses to thinning intensities were analysed and the results were compared with recommendations for selective high thinning and newer crop tree situational thinning models. Diameter increments were lower than expected regardless of thinning intensity. In moderately thinned plots and control plots diameter increment was the same (0.33 cm/year); high intensity thinning plots showed higher increment (0.37 cm/year). Dominant trees had slightly higher increment regardless of thinning model. Compared to thinning models with a lower number of crop trees, density and basal area of studied stands were significantly higher and diameter increments lower. We attribute the small diameter increments and small differences among thinning models to insufficient intensity and partially to inconsistent thinning. The results indicate that thinning must be of higher intensity and the largest-diameter trees which display the best vigour, quality, tendency, and which have well formed, long crowns, must be promoted from the beginning.

**KEY WORDS:** black alder (*Alnus glutinosa* (L.) Gaertn.), thinning, diameter increment, traditional selection model, situational thinning model

## INTRODUCTION
## UVOD

In central Europe the selective thinning is a widespread practice for tending young and mature forest stands. With it, crop trees in regular spacing across the whole stand are favoured with removal of competing inferior trees. The density of crop tree decreases with age and their grid may adapt with each new entry (Schädelin, 1934). Conventional black alder thinning models were based on long rotations, sometimes longer than 100 years, which accelerated root rot formation (Claessens et al., 2010). Authors of traditio-

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**Table 1:** Principal guidelines of different thinning models
Tablica 1: Osnovne smjernice različitih modela prorjeđivanja

| | Source<br>*Izvor* | Final no. of crop trees /ha<br>*Konačni broj stabala/ha* | First thinning<br>*Prva prorjeda* | Rotation (years)<br>*Ophodnja (godine)* | Target diameter (cm)<br>*Ciljani promjer (cm)* |
|---|---|---|---|---|---|
| Traditional models with selection thinning<br>*Tradicionalni modeli sa selektivnim prorjeđivanjem* | Nemesszeghy (1986)<br>Rauš (1975) | 300–350, 160 selected trees/*odabranih stabala* | Year 8–10/<br>*8.-10. godina* | 50–60 | |
| | Mlinšek (1961) | | Year 10/<br>*10. godina* | | |
| | Kecman (1999) | | Year 6–7/<br>*6.-7. godina* | | |
| Newer models with fewer selected trees<br>*Noviji modeli s manjim brojem odabranih stabala* | Fennessy (2004) | 100–120 | At 6–7 m of branch free stem/*uzgojeno 6–7 m čistog stabla* | | |
| | Claessens (2004),<br>Claessens et al. (2010) | 70–100 | Year 10, 6 m of branch free stem/10 godini, *uzgojeno 6 m čistog stabla* | 50–70 | 50–60 |
| | Lockow (2003) | 117 | | 60–80 | |

nal black alder thinning models in Slovenia (Mlinšek, 1961; Nemesszeghy, 1986; Kecman; 1999) advocated shorter rotations, 50–60 years (Table 1). Subsequent studies found that thinning promotes too many crop trees, which requires a significant investment of effort and reduces collective stand stability (Spiecker and Spiecker, 1988; Schütz, J.-Ph., 1996; Arnič et al., 2018). Therefore, they started to develop crop tree situational thinning, which involves one-off selection of a smaller number of trees – which must be the most vigorous and best-quality trees – and final or semifinal spacing of crop trees (Ammann, 2013). Crop tree situational thinning focuses on favouring part of tree population with the highest quality potential; in other segments it is restricted to ensuring stand stability (Roženbergar et al., 2008; Arnič et al., 2018). Development of this thinning method started in the 1990s (Claessens et al., 2010) but it was not yet been tested for black alder stands in Slovenia.

Authors of thinning models with fewer selected trees (Table 1) recommend similar rotations as authors of traditional models, but with less frequent measures (Lockow, 2003; Immler, 2004; Claessens, 2004; Fennessy, 2004; Claessens et al., 2010), and lower densities (70-120 trees / ha) whereas Nemesszeghy (1986) and Rauš (1975) recommend a final density of 250-350 trees / ha, of which 160 are selected trees / ha. Most authors of traditional selection thinning models and models with a smaller number of selected trees advocate early thinning of alder stands, to be conducted no later than year 10 or at 6 metres of branch free stem (Table 1).

In Slovenia, the stands of pure black alder are mostly located in the Pannonian region, where they form larger forest complexes in Murska Šuma, Črni Log and Polanski Log (Brus, 2015). Polanski Log and Črni Log were studied in the past by Mlinšek (1961) and Nemesszeghy (1986), who contributed to a transition from coppicing to high forest with regular thinning and the production of better-quality

wood with larger diameter. Stand regeneration with coppicing was efficient, but the management method promoted irregular stem growth and accelerated root rot infection. After the Second World War it also turned out that black alder forest can represent an important input for the wood industry, and in recent years demand for high-quality black alder wood has been growing (Utschig, 2003). It is therefore important to develop optimal thinning models for managing such stands.

In 1967 sample plots were established in Polanski Log to monitor two different intensities (moderate and high intensity) of selection thinning compared to a control (no thinning). At present, the stands on these plots are mature and suitable for analysis. This study therefore analysed the development of densities, growing stock, basal area and diameter increments to determine the outcomes of different thinning intensities. We wanted to determine which method is best for pure black alder stands and the scope of differences between tended and untended plots. The results were compared with recommendations and findings of authors of traditional thinning models, and thinning models based on a smaller number of crop trees and less frequent intervention.

## STUDY AREA AND METHODS
## PODRUČJE ISTRAŽIVANJA I METODE

### Study area – *Područje istraživanja*

Floodplain forests of black alder (*Alnus glutinosa* (L.) Gaertn.) account for just 0.4% (approx. 4708 ha) of total forest area in Slovenia (Čater et al., 2001). The largest black alder areas are found in Russia, Belarus and Ukraine (Pernar et al., 2012, quoted from Zalesov, 2008). The study was conducted in Prekmurje, Slovenia's north-eastern most region (Figure 1). Adjacent to Mala Polana is the Polanski Log forest, which forms a 1,100-hectare complex of lowland floodplain pure black alder forest.
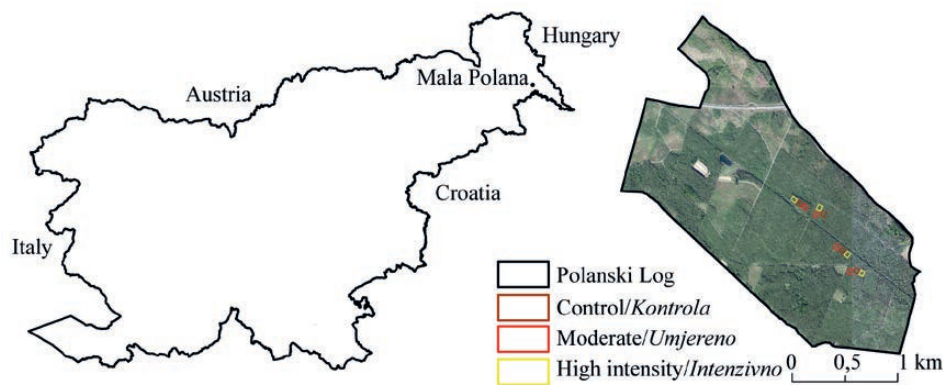
**Figure 1:** Location of  Polanski Log on Slovenia map (left) and locations of sample plots in Polanski Log (right)
Slika 1: Lokacija Polanskog Loga na karti Slovenije (lijevo) i lokacije pokusnih ploha u Polanskom logu (desno)

The altitude of study plots is approx. 163–165 metres above sea level. Although the terrain is typical lowland with small differences in altitude, such small, barely perceptible differences in altitude have a decisive impact on which species will thrive there (Nemesszeghy, 1986). The Polanski Log developed on gley soils on substrate of Holocene alluvial deposits of loam and clay (Lovrenčak, 1991). In gley soils groundwater is somewhere between 0–80 cm from surface all year, only in summer does the soil dry slightly (Nemesszeghy, 1986; Rauš, 1975). In depressions the groundwater comes to the surface, where it is stagnant or slow-flowing and where it remains longer than in slightly elevated areas (Wraber, 1951). These depressions are ideal black alder growing sites (Mlinšek, 1961; Vukelić and Rauš, 1998). Prekmurje has a sub-Pannonian climate with hot summers and cold winters. Mean annual temperature for 1963–2017 from the nearest meteorological station (Lendava, 190 m a.s.l.) was 10.5 °C, mean annual precipitation for the same period was 797.4 mm (ARSO METEO, 2018). Although precipitation is relatively low, 61% falls during vegetation period, which is favourable for forest vegetation (Nemesszeghy, 1986).

Sample plots were established at four locations. Each plot was divided into three 0.20 ha (40 x 50 m) fields representing different treatments: control, moderate thinning, high intensity thinning. The fields were separated by a 20 m buffer zone. In moderately thinned fields the strongest competitors of selected trees and some dominant trees of low quality were removed. In high intensity thinning fields all competitors and advanced regeneration of poor quality were removed (Kecman, 1999). As well-established, the thinning intensity decreased with the developmental stage of stands. For example, the thinning intensity of 40-year-old stands relative to the growing stock was approximately 13% and 20%, respectively.

Below is a brief description of each plot. Plot 4 is the oldest plot with trees aged 100–105 years. It was included in the experiment in 1967. In the subsequent years moderate and

high intensity thinning fields were carried out three times (Table 2). After 1986 there were no more measures on this plot because the area on which the plot is located was designated a protected forest. After change of ownership it was changed to its present status of forest reserve in which logging is banned.

Plot 5 was formed in 1970 with the planting of two-year saplings with a density of 10,000 saplings/ha (Table 2). The trees are presently about 50 years old. Until age 12, when the first thinning was performed in the thinned fields, ground vegetation was cleared and removed. At stand age 18 the second and final thinning was conducted.

Plot 11 was established with planting of 10,000 saplings/ha in 1963 (Table 2). First thinning was conducted at stand age 16 in the moderately thinned field and stand age 12 in the high intensity thinning field. Subsequent thinning in both fields was conducted at stand ages 38, 51 and 57. The final thinning was also conducted in the control field, just before the final measurement in 2018.

Trees on plot 12 are currently 66–72 years old, at the start of the experiment they were approximately 17 years old. Since then three thinnings were conducted in moderate and high intensity thinning fields (Table 2). There were no measures in the last 30 years.
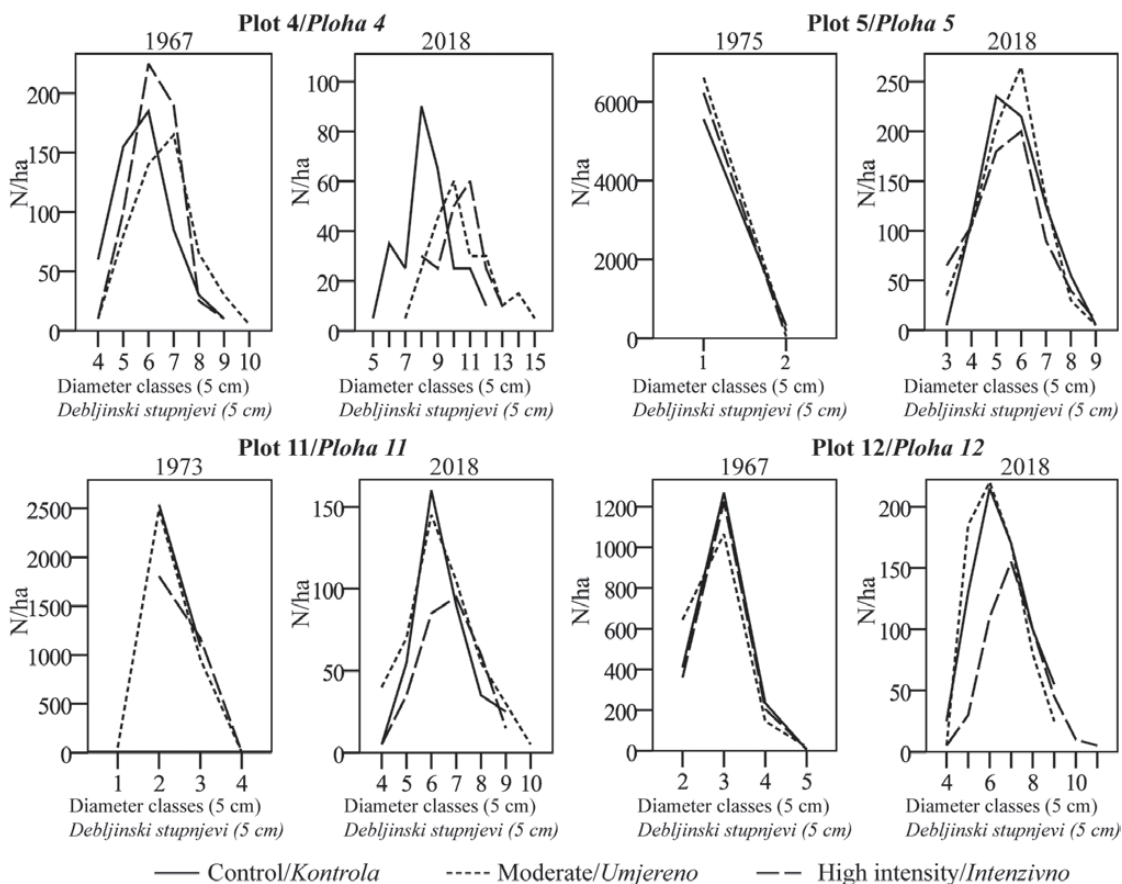
## METHODS
## METODE

All trees in the fields were numbered and at each measurement their diameter at breast height (dbh) was measured using a diameter tape. Seven measurements were conducted on the plots (1967, 1973, 1979, 1983, 1993, 1998, 2018), except on plot 5, where five measurements were conducted (1975, 1980, 1993, 1998, 2018). Using IUFRO classification (Ouellet and Zarnovican, 1988), the trees were classified at measurement by social position, development class, evolutive trend, silvicultural role, crown length and

**Table 2:** Silvicultural measures on plots by treatment
Tablica 2: Šumskouzgojni postupci po plohama i tretiranju

| | Treatment/*Tretiranje* | | |
|---|---|---|---|
| | Control<br>*Kontrola* | Moderate<br>*Umjereno* | High intensity<br>*Intenzivno* |
| Plot 4<br>*Ploha 4* | No measures<br>*Bez intervencije* | Thinning at stand age 52, 58 and 65 years<br>*Prorjeda u dobi od 52, 58 i 65 godina* | |
| | From stand age approx. 70 part of protected forest, eventually forest reserve (no measures)<br>*Od približno 70. godine starosti sastojine ploha je uključena u šumski rezervat, kasnije ekološka stanica, bez intervencije* | | |
| Plot 5<br>*Ploha 5* | Planting in 1970, 10,000 saplings/ha<br>*1970. godine posađeno je 10.000 sadnica/ha* | | |
| | No measures<br>*Bez intervencije* | Thinning at stand age 12 and 18<br>*Prorjeda u dobi od 12 i 18 godina* | |
| Plot 11<br>*Ploha 11* | Planting in 1963, 10,000 saplings/ha<br>*1963. godine posađeno je 10.000 sadnica/ha* | | |
| | Thinning at age 57<br>*Prorjeda u dobi od 57 godina* | Thinning at stand age 16, 38, 51 and 57/*Prorjeda u dobi od 16, 38, 51 i 57 godina* | Thinning at stand age 12, 38, 51 and 57/*Prorjeda u dobi od 12, 38, 51 i 57 godina* |
| Plot 12<br>*Ploha 12* | No measures<br>*Bez intervencije* | Thinning at stand age 18, 29 and 39<br>*Prorjeda u dobi od 18, 29 i 39 godina* | |

quality (Table 3). In 2018, we also measured the height of ten trees in upper stratum on each plot. Height was measured using Haglöf Vertex IV instrument.

The collected data was processed using IBM SPSS Statistics 22.0 and R Version 3.5.2 (R Core Team, 2018). Results were presented separately for all living trees and for dominant



**Figure 2:** Diameter structure by plot and method at first and last measurement
Slika 2: Debljinska struktura po plohama i metodama rada pri prvom i posljednjem mjerenju

**Table 3:** Classification of trees in plots
Tablica 3: Razvrstavanje stabala na plohama

| | |
|---|---|
| Social position *Pripadnost etaži* | 1 – upper stratum (up to 1/3 of upper tree height)/*gornji sloj (do 1/3 gornje visine stabla),* + predominant/*predominantna,* ° dominant/*dominantna,* – co-dominant trees/*kodominantna stabla,* 2 – middle stratum (from 1/3 to 2/3 of upper tree height)/*srednji sloj (od 1/3 do 2/3 gornje visine stabla),* 3 – lower stratum (under 1/3 of upper tree height)/*donji sloj (ispod 1/3 gornje visine stabla* |
| Development class *Vitalnost* | 1 – great vigour and responsiveness capacity of individual/*velika vitalnost i sposobnost reakcije pojedinca,* 2 – moderate vigour and responsiveness capacity of individual/*umjerena vitalnost i sposobnost reakcije pojedinca,* 3 – poor vigour and responsiveness capacity of individual/*loša vitalnost i sposobnost reakcije pojedinca* |
| Evolutive trend *Uzgojna perspektiva* | 1 – sociologically progressive tree (noticeable tendency to dominate)/*sociološki progresivno stablo (primjetna tendencija za dominacijom),* 2 – sociologically stable trees (noticeable keeping up with surrounding individuals)/*sociološki stabilna stabla (primjetno da budu ukorak s okolnim pojedincima),* 3 – sociologically regressive (noticeable regression compared to surrounding individuals)/*sociološka regresivna stabla (vidljiva regresija u odnosu na okolne pojedince)* |
| Silvicultural role *Uzgojna uloga* | 4 – crop (superior) trees/*odabrana stabla* 5 – indifferent trees/*indiferentna stabla* 6 – competitors/*konkurentna stabla* |
| Crown length *Duljina krošnje* | 4 – long crown (> 1/2 of total tree height)/*duga krošnja (> 1/2 ukupne visine stabla)* 5 – average crown (from 1/2 to 1/4 of total tree height)/*srednja krošnja (od 1/2 do 1/4 ukupne visine stabla)* 6 – short crown (< 1/4 of total tree height)/*kratka krošnja (<1/4 ukupne visine stabla)* |
| Quality *Kvaliteta* | 1– trees without defects, with all characteristics to develop into logs of high standard/*stabla bez pogreška, sa svim karakteristikama da se razviju u trupce visokog standarda,* 2 – trees that cannot be classified as highest quality; defects may affect log formation in the lower third to a smaller degree or can be predicted to disappear/*stabla koja se ne mogu svrstati u najkvalitetnije; nedostaci mogu u manjoj mjeri utjecati na stvaranje trupaca u donjoj trećini ili se može predvidjeti da će nestati,* 3 – other trees/*ostala stabla* |

trees, classified as the 100 largest-dbh crop trees per hectare. To compare the diameter structure, we classified trees into diameter classes (5 cm): 1 (0–4.9 cm), 2 (5–9,9 cm), 3 (10–14,9 cm), 4 (15–19,9 cm), 5 (20–24,9 cm), 6 (25–29,9 cm), 7 (30–34,9 cm), 8 (35–39,9 cm), 9 (40–44,9 cm), 10 (45–49,9 cm), 11 (50–54,9 cm), 12 (55–59,9 cm), 13 (60–64,9 cm), 14 (65–69,9) and 15 (70–74,5 cm). The growing stock was calculated using modified French tables for even-aged stands (Schaeffer tariffs) as usual in Slovenia (Kotar, 2007). We adopted the tariff class from the Slovenian Forest Service. Diameter increment was calculated based on the difference between the first and last diameter measurement. Diameter increment was modelled with linear mixed-effects model (LMM) where three repetitions (i.e. plots) were considered as random factors. Final model was selected following a top-down approach (Zuur et al., 2009). For model diagnostics of all model types, we examined confidence intervals of parameters and analysed sets of graphical summaries proposed by Robinson and Hamann (2011).

## RESULTS
REZULTATI

By design the plots were of different ages at the start of the experiment, which made it possible to analyse the development of pure black alder stands from stand initiation to over 100 years of age. In Polanski Log black alder stands are regenerated by planting; study plots 5 and 11 had 10,000 saplings/ha planted (Figure 3). The first data on diameter structure (Figure 2) is available several years after planting. At stand age of approximately 7 years, most trees on plot 5 were in diameter class 1 irrespective of the thinning model.

For plot 11 the first data on diameter structure is available at stand age approximately 13 years. At that point the majority of trees were in diameter class 2 and 3, with negligent differences among thinning models. The next diameter structure data is available for plot 12 at stand age 17. Irrespective of the thinning model, trees in diameter classes 2, 3 and 4 dominated. Between stand age 10 and 20, densities on plots were between 1,500–2,985 trees/ha in high intensity thinning fields and 1,920–3,630 in control fields (Figure 3). In the same period growing stock was 54–177 m³/ha in high intensity thinning fields and higher in control fields, 109–213 m³/ha (Figure 4). Basal area at this stand age was 12–22 m²/ha in high intensity thinning fields and 18–26 m²/ha in control fields (Figure 5).

Until approximately stand age 30, densities dropped to 625–1,235 trees/ha in high intensity thinning fields and 1,305–1,890 trees/ha in control fields (Figure 3). Growing stock increased to 194–356 m³/ha in high intensity thinning fields and 294–438 m³/ha in control fields (Figure 4). Basal area
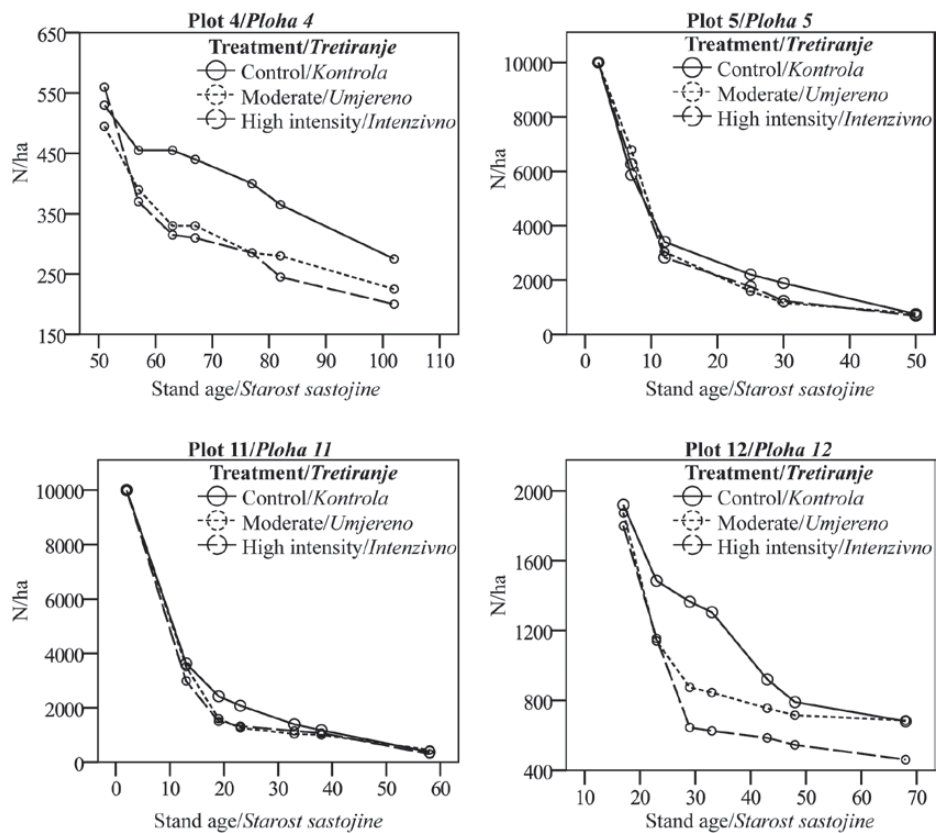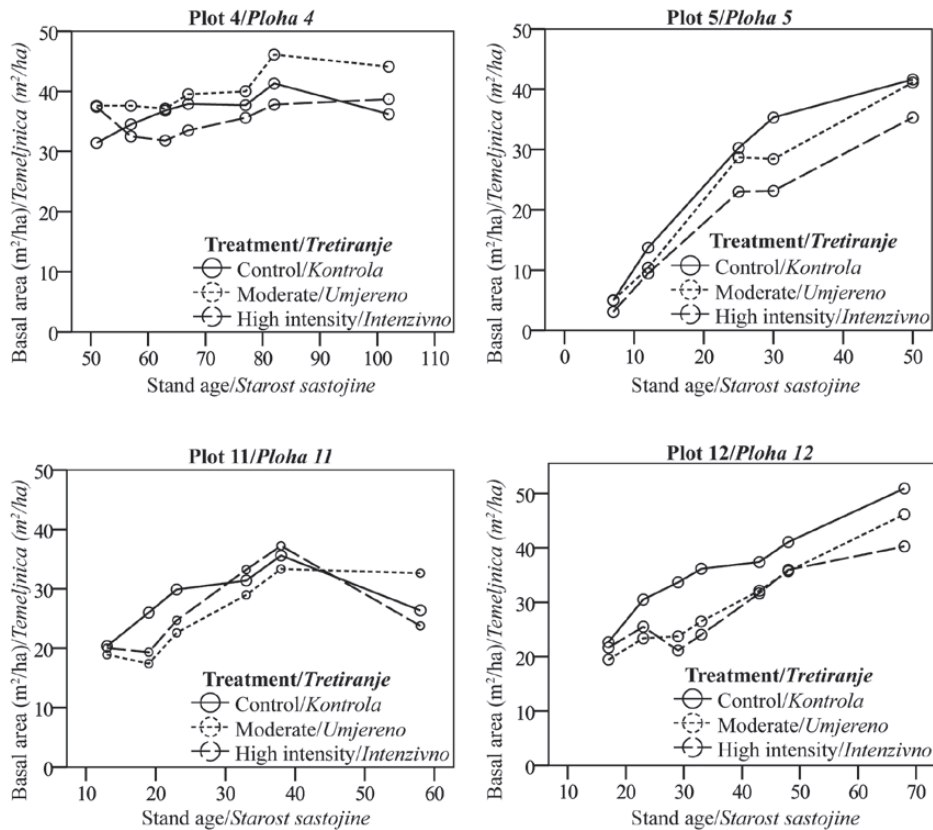
**Figure 3:** Change in number of trees over time by plot and thinning intensities
Slika 3: Promjene u broju stabala prema starosti sastojine na plohama s obzirom na intenzitet prorjeda
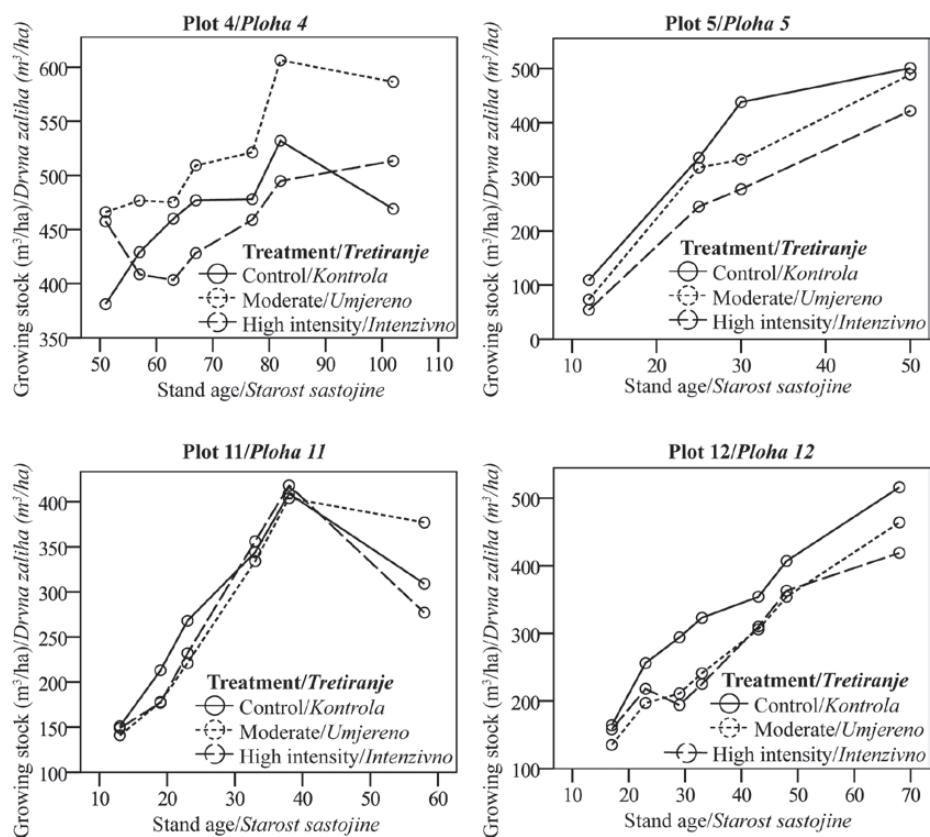


**Figure 4:** Development of growing stock over time by plot and thinning intensities
Slika 4: Razvoj drvne zalihe prema starosti sastojine na plohama s obzirom na intenzitet prorjeda

**Figure 5:** Development of basal area over time by plot and thinning intensities
Slika 5: Razvoj temeljnice prema starosti sastojine na plohama s obzirom na intenzitet prorjeda

rose as well, to 21–34 m²/ha in high intensity thinning fields and 34–42 m²/ha in control fields (Figure 5).

At the end of rotation, at stand age 50–70, densities in high intensity thinning fields were 295–690 trees/ha (Figure 3); in control fields they were 370–790 trees/ha. At the end of the rotation densities were very similar in control fields and moderately thinned fields, but always lowest in high intensity thinning fields. Growing stock at the end of rotation was 277–458 m³/ha in high intensity thinning fields and higher in control fields, 309–516 m³/ha (Figure 4). The

highest growing stock was recorded on plot 4, where it exceeded 600 m³/ha in a moderately thinned field at stand age approximately 80 years. Between first measurement and the measurement in 2018, growing stock increased the least in high intensity thinning fields regardless of plot. Between stand ages 50 and 70 basal area was even higher 23–41 m²/ha in high intensity thinning fields and 26–51 m²/ha in control fields.

Development of pure black alder stands throughout the rotation period can be monitored at plot 4. We found that
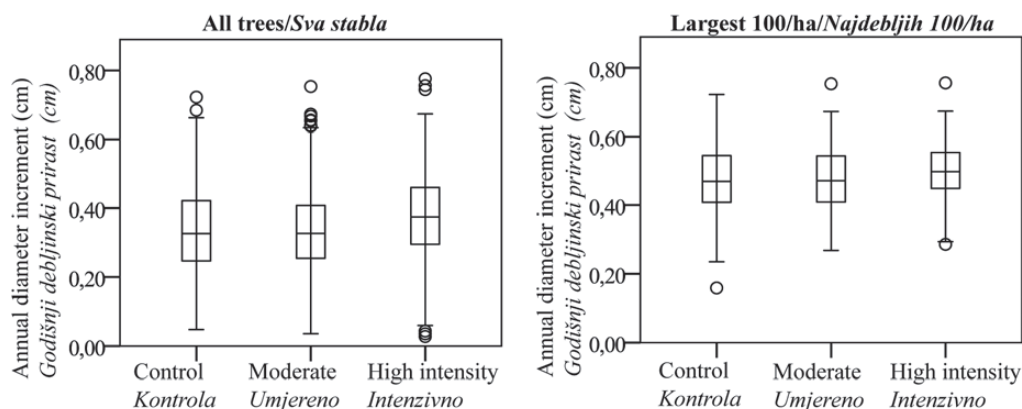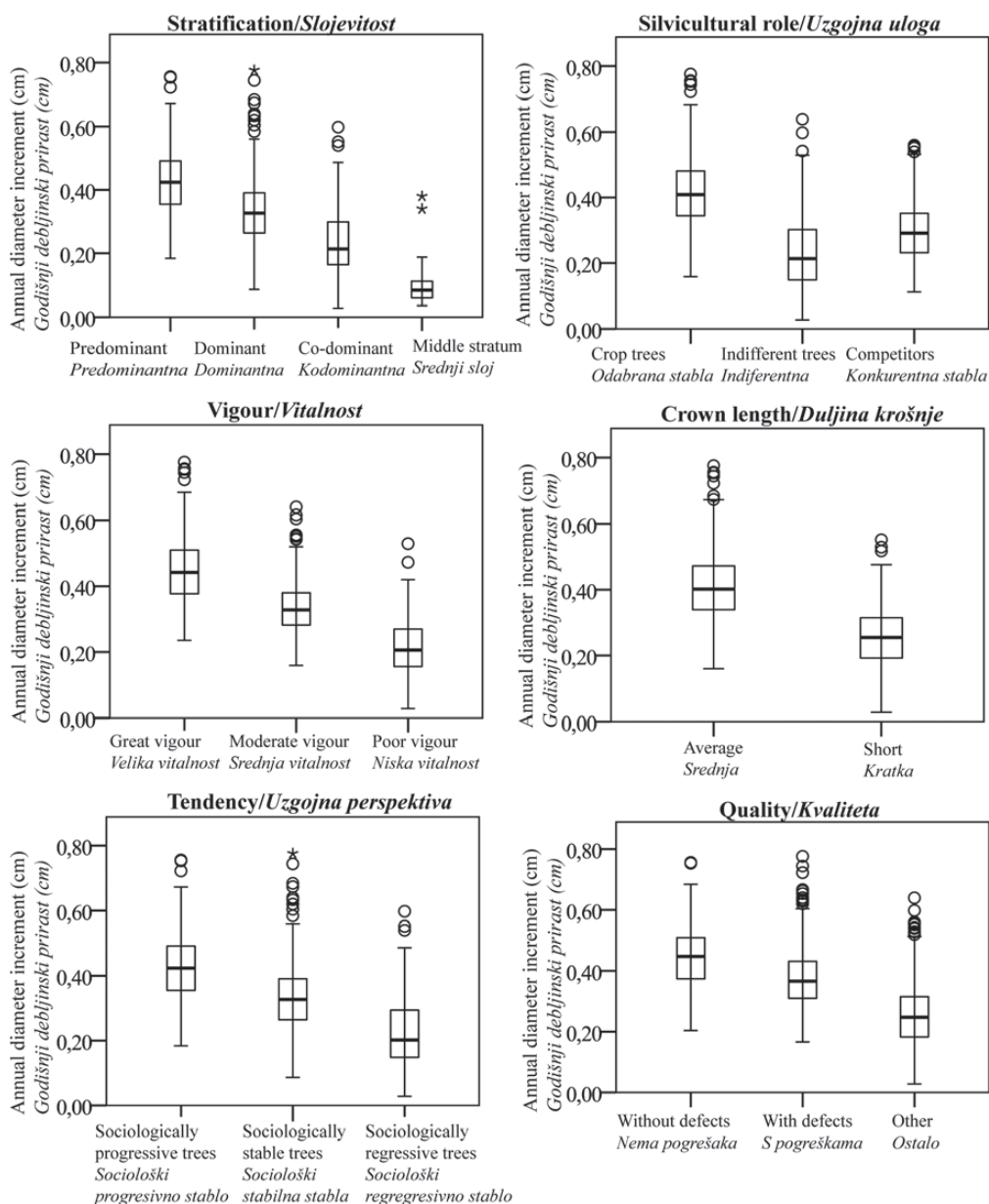


**Figure 6:** Annual diameter increment by tending model for all trees (left) and the 100 trees/ha with largest dbh (right) (circles=outliers)
Slika 6: Godišnji debljinski prirast prema metodama rada za sva stabla (lijevo) i najdeblja 100 stabla/ha (desno) (krugovi=outlier)

growing stock and basal area started to decline or stagnate after the stand was approximately 80 years old (Figures 4 and 5). At the start of monitoring of plot 4, at stand age approximately 51, most of the trees in moderately and high intensity thinning fields were in diameter class 6 and 7 (Figure 2). The control field has a slightly higher proportion of trees in diameter classes 4 and 5 compared to the thinning fields; 51 years later, the control field still had a noticeably higher proportion of trees in lower diameter classes. Regardless of thinning model, most trees gained 3–4 diameter classes. On other plots trees gained 3–4 diameter classes as well, despite lower age.

Annual diameter increment of trees in control fields and moderately thinned fields was practically the same, averaging 0.33 cm/year. In high intensity thinning fields it was slightly higher, on average 0.37 cm/year (Figure 6). Using statistical analysis, we determined statistically significant differences among thinning models ($\chi^2$ = 29.540; p < 0.001). There were statistically significant differences in annual diameter increments between high intensity and moderate intensity thinning fields ($\chi^2$ = 120.744; p < 0.001) and between high intensity thinning and control fields ($\chi^2$ = -119.383; p < 0.001). There were no statistically significant differences between moderately thinned and control fields



**Figure 7:** Impact of stratum, vigour, tendency, silvicultural role, crown length and quality on annual diameter increment (circles=outliers, stars=extreme outliers)
Slika 7: Utjecaj slojevitosti, vitalnosti, uzgojne perspektive, uzgojne uloge stabla, duljine krošnje i kvalitete na godišnji debljinski prirast (krugovi= outlier, zvijezde=ekstremni outlier)
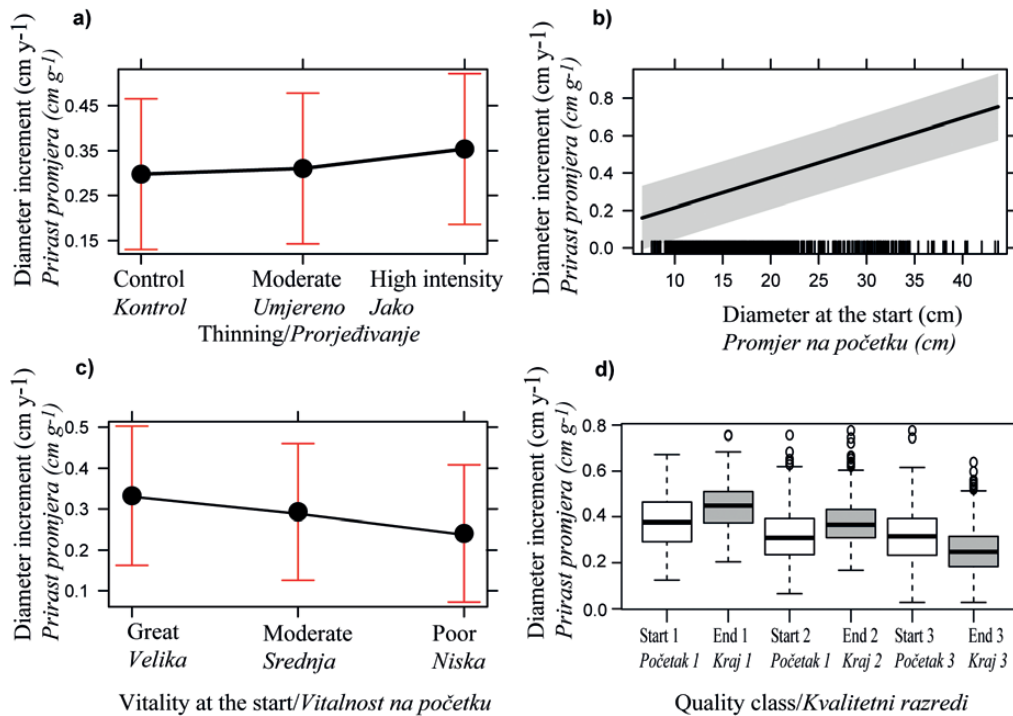
**Figure 8:** Results from linear mixed-effects models (a, b, c). Predicted diameter increment with 95% confidence intervals (grey area or error bars) as a function of (a) thinning type, (b) diameter at the start of experiment and (c) vitality class at the start of experiment. (d) Measured diameter increment as a function of trunk quality classes at the start and at the end of experiment (N = 1178).

Slika 8: Rezultati linearnih modela miješanih efekata (a, b, c). Predviđeni porast promjera s intervalima pouzdanosti od 95% (siva površina ili trake pogrešaka) kao funkcija (a) vrste prorjeđivanja, (b) promjera na početku pokusa i (c) razreda vitalnosti na početku pokusa. (d) Izmjereno povećanje promjera kao funkcija klase kvalitete stabla na početku i na kraju pokusa (N = 1178).

($\chi^2$ =1.361; p = 0.954). In 2018 the mean tree heights per treatment were 31.0, 31.6 and 30.9 m in control, moderate, and high thinning intensity, respectively and were not statistically significant ($\chi^2$ = 0.117; p = 0.943).

Average annual diameter increment was highest for predominant trees (n=391), 0.43 cm/year (Figure 7), slightly lower for dominant trees (n=555), 0.33 cm/year, and even lower for co-dominant trees (n=207), 0.24 cm/year and trees in the middle stratum (n=25), 0.11 cm/year ($\chi^2$ = 410.056; p < 0.001). The most vigorous trees (n=408) added 0.45 cm/year on average (Figure 7), moderately vigorous trees (n=463) 0.12 cm/year less than the most vigorous trees, and the least vigorous trees had diameter increment of only 0.21 cm/year ($\chi^2$ = 649.661; p < 0.001). Sociologically progressive trees (n=391) on average grew faster (0.43 cm/year) than sociologically stable trees (n=555), which averaged 0.33 cm/year (Figure 7) and sociologically regressive trees (n=232), which grew 0.22 cm/year ($\chi^2$ = 401,944; p < 0,001).

Crop trees (n=572) had higher average annual diameter increment than competitors (n=396) and indifferent trees (n=210), 0.42 cm/year (Figure 7). Competitors grew 0.12 cm/year slower and indifferent trees 0.19 cm/year slower than crop trees ($\chi^2$ = 448.172; p < 0.001). Trees with average crown length (n=669) grew on average 0.41 cm/year (Fi-

gure 7), while trees with short crowns (n=508) grew 0.25 cm/year ($\chi^2$ = 497.668; p < 0.001). The results are similar for quality (Figure 7): the highest quality (n=195) trees grew fastest, 0.45 cm/year, while those of slightly lower quality (n=539) grew 0.38 cm/year and trees of the lowest quality (n=444) 0.26 cm/year ($\chi^2$ = 405,379; p < 0,001).

Among the largest 100 crop trees/ha the differences in annual diameter increments varied little by thinning model as well (Figure 6). The largest crop trees in control fields grew slowest, 0.46 cm/year on average, followed by trees in moderately thinned fields, which averaged 0.48 cm/year. The largest crop trees in high intensity thinning fields grew fastest, 0.50 cm/year. We did not detect statistically significant differences in annual diameter increments among thinning intensities ($\chi^2$ = 4.720; p = 0.094). But there were statistically significant differences in annual diameter increment by vigour ($\chi^2$ = 33.586; p < 0.001), crown length ($\chi^2$ = 12.081; p < 0.01) and quality ($\chi^2$ =7.709; p < 0.05). We did not however detect statistically significant differences in annual diameter increment by stratum ($\chi^2$ = 3.360; p = 0.186) and evolutive trend - tendency ($\chi^2$ = 3.360; p = 0.186).

For the 100 largest-dbh crop trees it was determined that there are no statistically significant differences among thinning models in stratification ($\chi^2$ = 8.084; p = 0,089), vigour ($\chi^2$ = 3.354; p = 0.500), tendency ($\chi^2$ = 8.084; p = 0.089),

crown length ($\chi^2 = 0.209$; $p = 0.901$) and quality ($\chi^2 = 7.328$; $p = 0.120$). Regardless of thinning model, the majority of these trees were in the predominant layer (73%), highly vigorous (85%), sociologically progressive trees (73%) with average crown length (46%) or slightly lower quality (51%).

The regression model predicted that diameter increment increased with thinning intensity ($p < 0.001$), diameter at the start of the experiment ($p < 0.001$) and with vitality classes at the start of the experiment ($p < 0.001$). The effects of the thinning intensity and vitality were weaker than that of the initial diameter (Figure 8). The effect of thinning was also reflected by the higher proportion of good and medium quality trees between the beginning of the experiment and year 2018 (49% vs. 62%). The differences in the diameter increment between the three trunk quality classes also increased (Figure 8d).

## DISCUSSION
RASPRAVA

The densities, growing stock and basal area determined in this study are in line with the findings and recommendations of Nemesszeghy (1986) and Mlinšek (1961), who developed a traditional selection model for black alder thinning. As expected, the results correspond to a lesser extend to recommendations of more contemporary models with a lower number of selected trees and less frequent intervention. Some authors of these models recommend basal area values after second or third thinning of 15 m²/ha (Claessens, 2004) and decrease of densities until stand age 20–30 years to 200–300 trees/ha (Claessens et al., 2010) or selection of 300 trees/ha by stand age 18 (Immler, 2004). On our plots, such densities were not even achieved at the end of rotation, which Nemesszeghy (1986) recommends be at stand age of 50–60 years (Table 1).

Statistical model used in the study (LMM) proved thinning intensity, diameter at the start of the experiment and vitality class at the start of the experiment as the most important factors affecting the diameter increment. In all cases the relation was positive. Trees in moderately thinned fields and control fields had average annual diameter growth increment of 0.33 cm/year, while trees in high intensity thinning fields averaged 0.37 cm/year. The selected 100 largest-dbh trees grew faster, as expected. In control fields their annual diameter increment was 0.46 cm/year, in moderately thinned fields it was 0.02 cm/year higher, and in high intensity thinning fields it averaged 0.50 cm/year. Malus (2012) recorded similar annual diameter increment (0.34 cm) with dendrochronological analysis of cut trees in Polanski Log. Claessens et al. (2010) report than in the best growing sites, such as Slovenia, north Germany and south France, black alder can reach a dbh of 40–50 cm in 40–65 years. This means that annual diameter increment should

be at least 0.6 cm or even in excess of 1 cm. The trees in our plots did not even achieve the annual diameter increment values that Claessens et al. (2002) measured for dominant trees at the end of rotation on less productive sites in Belgium. There, dominant trees in non-thinned stands grew 0.4 cm/year and trees without competition 0.7 cm/year.

This shows that annual diameter increment of dominant trees in our plots was at least 0.5 cm lower than expected for black alder on such sites. At the same time, the differences among thinning models in this study were small, which may indicate that predominant black alders are characterised by a similar diameter increment for extended periods regardless of thinning measures. Favourable social differentiation and small differences in growth patterns of predominant crop trees was also indicated for spruce, beech, ash and maple by Ammann (2004). We also determined that there were no significant differences among thinning models in terms of stratification, vigour, tendency, crown length and quality of dominant trees, whereby it is necessary to account for inadequate consistency of measures in thinning fields: from two to a maximum of four thinnings were conducted, whereas Nemesszeghy (1986) and Kecman (1999) recommend from five to seven throughout the rotation period. Still, such intervention frequency may not be justifiable in today's economic terms.

Excluding plot 4, where intervention started at a significantly higher age, the first thinning on our plots was conducted later, at stand ages 12-18. Subsequent thinning was conducted at very different ages (Table 2) and even less in line with the recommendations of authors of traditional thinning models (Mlinšek, 1961; Nemesszeghy, 1986; Kecman, 1999).

It is also notable than in recent years thinning has not been conducted systematically, as labour costs rose and wood prices fell (Roženbergar et al., 2008; Arnič et al., 2018). The thinning delay was partially influenced also by the change of ownership. In spite of all, the thinning performed exemplifies a representative situation from the past practice of thinning of lowland forests. In the future it seems worthwhile to check the appropriateness of crop tree situational thinning models for black alder in Slovenia.

We also attribute the low annual diameter increment to excessive densities, short crowns and developed epicormic sprouts. As many as 43% of trees in the plots had short crowns and there were no trees with long crowns at all. There was also a high share (38%) of trees of the lowest quality with developed epicormic sprouts. There may also be other reasons not dealt with in this study. Malus (2012) for example found that above-average irradiation and above-average water levels reduced diameter increment of black alder. Hydrological improvements may theoretically affect growth as well, but Levanič (1993) ruled that out in Polanski Log.

This study shows that thinning on plots was not intense enough and, to a certain extent, not consistent enough. In the case of delayed start of thinning, as in our experiment, two to four moderate (removal of strongest competitors) or high intensity (removal of all competitors) thinning are not enough to achieve satisfactory diameter increments. Differences in annual diameter increments among thinning intensities were not large, but it has nevertheless been shown that regular thinning of high intensity must be carried out and trees with highest dbh with the best vigour, quality, tendency and with a long, well-formed crown must be promoted. Traditional selection thinning should result in better growth, but also improved overall quality of the stand, to some extent, showed also from our results. If the cost of traditional selection thinning is too high, we recommend trying crop tree situational thinning, which also has a beneficial effect on collective stand stability.

## CONCLUSION
## ZAKLJUČAK

This study suggests that thinnings in black alder stands should be carried out at an early stage. It is a light-demanding species that quickly loses its ability to respond to silvicultural measures. However, care should also be taken to ensure that the natural branch shedding process in the lower part of the trunk is not interrupted. The most vital trees should be selected and favoured and the intensity of thinning should be significantly higher than in this study, e.g. up to 30% of the basal area. This study suggests that the implementation of long-term silvicultural experiments could be challenging, both due to knowledge progress and socio-economic changes. However, the results of such studies provide direct insights into stand development and the tree response to silvicultural measures and should therefore be actively pursued now more than ever.

## ACKNOWLEDGEMENT
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## SAŽETAK

Područje poplavnih šuma crne johe (Alnus glutinosa (L.) Gaertn.) u Sloveniji čini samo 0,4 % (približno 4708 ha) ukupne površine šumskog zemljišta (Čater i sur., 2001.). Veći kompleks takvih sastojina u Sloveniji su Črni i Polanski Log, a istraživanje je provedeno na području potonjeg (slika 1). Kako čiste sastojine johe odlikuju brojne specifičnosti, potrebno im je prilagoditi šumskouzgojne postupke.

Da bi se utvrdio odgovarajući intenzitet prorjede takvih sastojina, 1967. godine u Polanskom Logu postavljene su pokusne plohe. Od tada do 2018. godine na plohama je izvršeno pet do sedam mjerenja. Sva stabla na plohama su bila obrojčana. Izvršeno je mjerenje prsnih promjera i procjena sljedećih elemenata na stablima: pripadnost etaži, vitalnost, uzgojna perspektiva, uzgojna uloga, duljina krošnje i kvaliteta (tablica 3). Svaka ploha bila je podijeljena u tri polja (40 x 50 m) s različitim metodama rada: bez intervencije, umjereno i intenzivno prorjeđivanje. Uzgojni postupci koji su poduzeti tijekom praćenja pokusa prikazani su u tablici 2. Danas su te sastojine u zreloj fazi razvoja, stoga smo u ovom radu analizirali reakcije crne johe na različite intenzitete prorjeđivanja i dobivene rezultate usporedili s preporukama autora tradicionalnih uzgojnih modela i modela koji se temelje na situacijskoj njezi šuma.

Ustanovili smo da se na plohama s intenzivnim prorjeđivanjem gustoća sastojine koja je u dobi između 50 i 70 godina i na kraju je ophodnje kreće od 295 do 690 kom/ha (slika 3), dok se na plohama bez intervencije ova vrijednost kreće u rasponu od 370 do 790 kom/ha. Drvne zalihe u istom su se razdoblju kretale u rasponu od 277 do 458 m³/ha na plohama s intenzivnim prorjeđivanjem, dok su na plohama bez intervencije bile veće, u rasponu od 309 do 516 m³/ha (slika 4). U to su se doba temeljnice nalazile u rasponu između 23 i 41 m²/ha na plohama s intenzivnim prorjeđivanjem, a na plohama bez intervencije u rasponu od 26 do čak 51 m²/ha (slika 5). Tijekom cijelog razdoblja praćenja ploha, stabla su, bez obzira na metodu rada, narasla za tri do četiri debljinska stupnja (slika 2). Na plohama s umjerenim prorjeđivanjem i onima bez intervencije, debljinski prirast stabala bio je skoro jednak (0,33 cm godišnje) (slika 6). Statistički je značajan veći debljinski prirast stabala na plohama s jako intenzivnim prorjeđivanjem (0,37 cm godišnje). Debljinski prirast dominantnih stabala bio je nešto veći, od 0,46 cm godišnje na plohama bez intervencije do 0,50 cm godišnje na plohama s jako intenzivnim prorjeđivanjem, ali statistički značajne razlike između metoda rada nisu utvrđene (slika 6). Međutim, otkrili smo da kod dominantnih stabala ne postoje statistički značajne razlike s obzirom na njihovu slojevitost, vitalnost, tendenciju, dužinu krošnje i kvalitete s obzirom na korištenu metodu rada.

U usporedbi s uzgojnim modelima koji su se koristili za manji broj odabranih stabala, gustoća i temeljnica ispitivanih sastojina je znatno veća, a debljinski prirast manji. Autori tradicionalnih i modela s manjim brojem odabranih stabala zagovaraju rano prorjeđivanje takvih sastojina (tablica 1). Veće razlike nastaju u konačnom broju stabala po hektaru i u intenzitetu intervencije. Razlog malog debljinskog prirasta i razlike između metoda rada na našim plohama pripisali smo nedovoljnom intenzitetu i djelomično nedosljednoj provedbi postupka prorjeđivanja. Ipak, ukazala se potreba za intenzivnim prorjeđivanjem i pospješivanjem rasta stabala najvećeg prsnog promjera, vitalnosti i tendencije, lijepo oblikovane i duge krošnje (slika 7, slika 8).

**KLJUČNE RIJEČI:** crna joha (*Alnus glutinosa* (L.) Gaertn.), prorjeđivanje, godišnji debljinski prirast, tradicionalni model sa selektivnim prorjeđivanjem, situacijski model prorjeđivanja