INITIAL PLANTING DENSITY EXPERIMENTS OF NARROW-LEAVED ASH IN TURKEY: TEN-YEAR RESULTS

POKUSI S POČETNOM GUSTOĆOM SADNJE POLJSKOG JASENA U TURSKOJ: DESETOGODIŠNJI REZULTATI

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SUMARY

Narrow-leaved ash (*Fraxinus angustifolia* subsp. *oxycarpa* Vahl.) is a source of valuable wood in Europe and plantations produce high yields in Turkey. Initial planting density plays an important role in plantation silviculture and affects the growth and quality of trees as well as establishment costs. This study aimed to determine the ten-year effects of initial planting density on tree growth and quality of narrow-leaved ash. In 2004, three replications of four initial planting densities (1111, 1667, 2500 and 3333 stem ha^{-1}) were established in a randomized block design in Adapazarı, Turkey. After ten growing seasons, no mortality was seen in all of four planting densities. The initial planting density had no effect on mean stem diameter; however, with the initial planting density increase from 1111 to 3333 stem ha^{-1}, mean tree height was significantly increased and live crown ratio decreased. The H/D ratios at planting densities of 2500 and 3333 stem ha^{-1} were 21% higher than at lower planting densities. Aboveground dry biomass increased with increasing initial planting density at the stand level, although individual tree sizes were similar. In general, tree form and branch characteristics were improved when initial planting density was increased. Results suggest that on lowland sites where intensive weed competition occurs, higher initial planting density at 2500–3333 stems ha^{-1} is recommended for narrow-leaved ash plantations.

KEY WORDS: Growth, *Fraxinus angustifolia*, initial spacing, stocking, tree quality, Turkey

INTRODUCTION
UVOD

Narrow-leaved ash is found naturally in southern Europe, the Balkans, the Caucasus, Iran and North Africa (Boshier et al. 2005). The narrow-leaved ash has a wide natural distribution in different regions of Turkey at altitudes from sea level to 2200 m a.s.l. (Yaltırık 1978) and is particularly dominant in the bottomland forests of the northern coastal region of the country (Çiçek and Yilmaz 2002a; Boshier et al. 2005).

In general, in forest areas in the lowlands, this species is subject to marginal growing conditions such as floodplain (Drvodelić et al. 2016), poor drainage and heavy-textured soil (Pliura 1999). In addition, until full canopy closure occurs, seedlings in these bottomlands have competition from very dense, tall (1.5–2.0 m) weeds (Çiçek et al. 2007). It is

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reported that some ash species (*F. excelsior* and *F. angustifolia*) are very sensitive to weed competition (Evans 1997; Kerr 2003; Boshier et al. 2005; Çiçek et al. 2010). Nevertheless, narrow-leaved ash exhibits the ability for fast growth, and the mean annual increment of stem wood over bark in Turkey can reach about 23 m³ ha⁻¹ and 15 m³ ha⁻¹ in plantations and natural stands, respectively (Kapucu et al. 1999).

In Turkey, almost all of the natural narrow-leaved ash dominated bottomland forests have been converted to pure narrow-leaved ash plantations over the last 60 years. The conversion is concentrated in the Adapazarı region, where the largest forests of this species are found (Çiçek 2004). Due to intensive weed competition, planting is preferred for the regeneration of the narrow-leaved ash stands and establishment of new narrow-leaved ash plantations in Turkey. The demand for large-diameter narrow-leaved ash sawlogs and veneer logs (ø: 40–60 cm) is high and thus, it is important to ensure optimal planting density in these plantations. Initial planting density is the most essential factor in determining the stocking, tree growth and quality, rotation periods, and management costs of a plantation establishment (Boydak 1992; Savill et al. 1997).

In Europe, the trend to use spacing of 3.0×3.0 m in broad-leaved species has been reportedly increasing recently; however, in plantations of trees like ash, oak and beech, a planting density of at least 2500 stems per hectare is recommended in order to produce high-quality logs (Kerr 1995; Evans 1997; Boshier et al. 2005; Kuehne et al. 2013). During the artificial regeneration of narrow-leaved ash stands or the establishment of new narrow-leaved ash plantations in the bottomlands in Turkey, spacings of 3.0×2.0 m and 3.0×2.5 m (1667-1333 stem ha⁻¹) were used until 1980. In the 1980's, spacings of 3.7×3.7 m – 4.0×4.0 m (730 – 625 stem ha⁻¹) and in the 1990's and 2000's spacings of 4.0×2.0 m (1250 stem ha⁻¹) were used. As a result of this wide spacing, thick branches, knots, and trunks with low stem quality were formed. The narrow-leaved ash plantations established before 1980 produced better quality trees than the plantations established in later years (Çiçek and Yilmaz 2002b; Çiçek 2004).

In recent years, an initial planting density of 1111 stem ha⁻¹ (3.0×3.0 m) has frequently been used in narrow-leaved ash plantations. Due to the low quality of the trees in existing narrow-leaved ash plantations and also due to the conditions of the growing environment (heavy weed competition), it is very important in silvicultural practice to determine the appropriate initial planting density of narrow-leaved ash. To this purpose, in Akyazı-Adapazarı, a region in Turkey where narrow-leaved ash plantations are widespread, a long-term initial planting density trial was established in December 2004 with four different initial planting densities which included 1111, 1667, 2500 and

3333 stem ha⁻¹ (Çicek et al. 2010). In this study, the ten-year results of this research were evaluated and the effects of initial planting density on the growth and quality parameters (tree shape, branch characteristic) of narrow-leaved ash trees were investigated.

MATERIAL AND METHODS
MATERIJALI I METODE

Study site – *Područje istraživanja*

The study site was established in the bottomlands of the Akyazı-Adapazarı region (40° 48' N, 30° 33"E, 25 m) in Turkey. This was the site of a natural stand dominated by Narrow-leaved ash along with some other important broad-leaved tree species (*Ulmus laevis*, *Ulmus minor*, *Quercus robur*, *Acer campestre*). However, the older natural stand had undergone clear-cut logging at the end of summer 2004 and the stumps were uprooted in the fall of 2004. After the stumps and slash were disposed of, the area was first ripped (60–80 cm soil depth) and then disked (20–30 cm soil depth) to aerate the soil.

The site has a deep alluvial soil and because of the heavy-textured soil the drainage is very poor. The soil pH varies at 7.5–7.9 and the Ah horizon is very thin due to rapid decomposition. According to the Adapazarı meteorological station, the average annual precipitation is 846 mm and the average annual temperature is 14.3 °C. A water deficit is observed in the area during the summer period, while in some years the standing water level on the site may rise above ground level throughout November–March, depending on the seasonal rainfall (Çicek et al. 2010).

Experimental Design and Initial Planting Density – *Dizajn pokusa i početna gustoća sadnje*

In December 2004, the experimental site (4.50 ha) was established in a randomized block design with three replications. The size of the experimental plots was 55 m × 66 m (3630 m²) (Figure 1) and four different initial planting densities were used (Table 1). The 1+0-year-old bare-rooted (65–75 cm in height) narrow-leaved ash seedlings were produced in the Hendek nursery and planted in December 2004. Hand hoeing and disking were carried out around the seedlings for three years following the planting. In the first two years, 1-2% of the two-year narrow-leaved ash seedlings in the field had been damaged by animal browsing or frost (Çicek et al. 2010). These seedlings were stumped back to 8 cm above the root collar at the end of the second year. In May of the third year, singling was carried out on the stumped-back plants, leaving a healthy, straight stem. Two years after the stumping back, no difference was observed in height and diameter between the stumped and the non-stumped seedlings (Çicek and Tilki 2007).
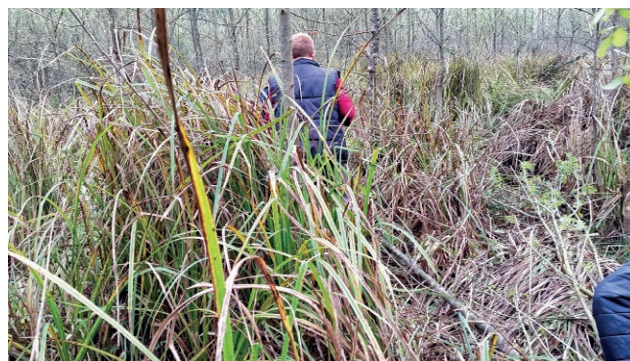
Figure 1. A view from the initial planting density of 3333 (left) and 1111 (right) tree per hectare at the narrow-leaved ash experimental site in 2015. Since the canopy cover was not fully closed in the 1111 tree per hectare initial planting density, weeds under the lover planting density seem to be taller and thicker than with the higher planting density.
Slika 1. Pogled na početnu gustoću sadnje 3333 (lijevo) i 1111 (desno) stabala po hektaru na pokusnoj plohi poljskog jasena 2015. godine. Pošto sklop krošanja nije bio u potpunosti zatvoren pri početnoj gustoći sadnje od 1111 stabala po hektaru, korov U slučaju niske gustoće sadnje izgleda viši i deblji nego kod visoke gustoće sadnje.

Data Collection and Calculations – *Prikupljanje podataka i izračuni*

In 2015, ten years after planting, data were collected in sampling quadrats of 20 × 20 m (44–130 trees) at the center of each experimental plot. Diameter at breast height (DBH), tree height, height to lowest dead and lowest live branch and maximum diameter of live and dead branches were measured, after which the height/DBH ratio (H/D), live crown ratio, stem volume, form quotients and aboveground dry biomass were calculated.

The DBH of all trees was measured with a tree caliper in the sampling quadrats of the plots. Tree height, height to lowest dead branch and lowest live branch were measured using a combination of a laser rangefinder and a clinometer. Maximum diameters of live and dead branches were measured with a digital caliper on the five thickest tree branches. The H/D ratio was determined by dividing the height of the tree by the DBH. The live crown ratio for each tree was determined by the ratio of live crown length to the total tree height.

In addition, 16 trees representing the diameter class (0–3.9 cm, 4–7.9 cm, 8–11.9 cm, 12–15.9 cm) in each plot were cut down (48 trees for each planting density) for determination of stem volume and aboveground dry biomass. After the branches were stripped from the stem, diameters were measured at the heights of 0.30 m, 1.30 m, 3.30 m, 5.30 m… using calipers, and the stem volume with bark of each tree was calculated using the Smalian formula. The billet volumes were calculated by the cylinder and the end parts by the cone formula (Kalıpsız 1999). Double-bark thicknesses of each of the cut trees were also measured.

Form quotients of the trees were determined using the following formula (Assmann 1970; Kalıpsız 1999):

$$ q = \frac{d_{3.30}}{d_{1.3}} ; \frac{d_{5.30}}{d_{1.3}} ; ...; \frac{d_n}{d_{1.3}} $$

where, q is the form quotient, $d_{1.30}$ the diameter at breast height (cm), and $d_{3.30}$ and $d_{5.30}$ the tree diameters (cm) at 3.30, 5.30 m… of tree total height.

In order to determine the aboveground biomass of each felled tree, branches were weighed after removal from the stem. In addition, two branch samples (10 cm-long) were taken from the lower and upper parts of the length to the crown and these were also weighed. The stem was then divided into three equal parts and weighed. A 5-cm-thick stem section was taken from the middle of each piece and weighed. Branch and stem samples were dried in the oven at 105 ºC for 48 h, and weighed on 0.01 g precision scales. The stem and branch dry biomass of each tree was determined using these dry weights (Saraçoğlu 1998). Leaf biomass was not calculated because biomass measurements were carried out during the leafless period. Therefore, aboveground dry biomass was calculated from total stem and branch dry biomass.

Volume and aboveground dry biomass equations for individual trees depending on the DBH were obtained by regression analysis for all initial planting densities (Table 2). These selected models were used to estimate the volume and dry biomass of the remainder of the trees.

Table 1. Initial planting density used in the narrow-leaved ash trial in Adapazari, Turkey
Tablica 1. Početna gustoća sadnje u pokusu s poljskim jasenom u Adapazari, Turska

Initial planting density Početna gustoća sadnje (stem ha-1) (deblo ha-1)	Initial spacing Početni razmak (m × m)	Growing space Prostor rasta (m2 tree-1) (m2 stablo -1)
1111	3.0 × 3.0	9.0
1667	3.0 × 2.0	6.0
2500	2.5 × 1.6	4.0
3333	2.5 × 1.2	3.0

Statistical Analysis – *Statistička analiza*

Analysis of variance (ANOVA) was performed to determine the effects of initial planting density on mean diameter, tree height, H/D ratio, live crown ratio, form quotient, stem volume, branch and stem dry biomass, total aboveground dry biomass, maximum diameter of live and dead branches, and height to lowest live and dead branches according to the randomized block design with three replications (P <0.05). Normality distribution was tested and controlled for all variables before ANOVA was performed. Treatment means were separated by Duncan's New Multiple Range Test (P <0.05). When choosing the best volume and dry biomass regression models (Loetsch et al. 1973), the criterion of having the largest adjusted-R-squared values (R^2) was taken into account along with the lowest standard error. The statistical analyses were performed via SPSS 21.0 for Windows software (IBM SPSS Inc.).

RESULTS
REZULTATI

Mortality – *Mortalitet*

Ten years after planting, tree mortality had not occurred in any of the initial planting density treatment plots.

Tree Growth – *Rast stabla*

The initial planting density had no significant effect on the mean diameter, and the mean diameter for all planting densities was approximately 7.0 cm (P >0.05). The mean DBH values according to initial planting densities are given in Table 3. Mean tree height increased with increasing initial planting density. The mean tree height in the initial planting density of 3333 stem ha^{-1} was 9.6 m, 25% higher than in the planting densities of 1111 and 1667 stem ha^{-1} (Table 3).

Table 2. Equations of stem volume and aboveground dry biomass depending on the DBH, according to initial planting density.
Tablica 2. Jednadžbe volumena debla i nadzemne suhe biomase ovisno o prsnom promjeru vezano za početnu gustoću sadnje

| Initial planting density (stem ha^{-1}) Početna gustoća sadnje (deblo ha^{-1})	Diameter range (min-max) Promjer (min-max)	Models Modeli	R^2	P
Stem volume (V) Volumen debla (V)				
1111	5.0-9.5		0.915	<0.001
1667	4.0-12.3		0.890	<0.001
2500	3.6-8.0		0.870	<0.001
3333	5.0-11.0		0.926	<0.001
Aboveground dry biomass (AB) Nadzemna suha biomasa (AB)				
1111	5.0-9.5		0.784	<0.001
1667	4.0-12.3		0.857	<0.001
2500	3.6-8.0		0.864	<0.001
3333	5.0-11.0		0.620	<0.001

In models: V is the volume with bark (m^3), DBH is the diameter at breast height (cm), and AB is the aboveground dry biomass (kg).
U modelima: V je volumen s korom (m^3), DBH je promjer na prsnoj visini (cm), a AB je nadzemna suha biomasa (kg)

Table 3. Effects of initial planting density on stem diameter, tree height, ratio of height-diameter, live crown ratio, volume and form quotients (q) of narrow-leaved ash trees after 10-year growth
Tablica 3. Utjecaj početne gustoće sadnje na promjer debla, visinu stabla, omjer između visine i promjera, omjer žive krošnje, koeficijenti volumena i oblika (q) na stablima poljskog jasena nakon 10-godišnjeg rasta

Initial planting density (stem ha^{-1}) Početna gustoća sadnje (stabala ha^{-1})	Diameter Promjer cm	Height Visina m	Height/ DBH Visina/Prsni promjer m cm^{-1}	Live crown ratio Omjer žive krošnje	Volume Volumen dm^3	$q_{3.30}$	$q_{5.30}$	$d_{5.30}/d_{3.30}$
1111	7.03 (0.32) a*	7.68 (0.21) a	1.10 (0.04) a	0.75 (0.01) c	19.27 (3.01) a	0.69 (0.02) a	0.51 (0.02) a	0.75 (0.04) a
1667	7.10 (1.33) a	7.60 (0.88) a	1.08 (0.08) a	0.73 (0.03) c	17.93 (9.32) a	0.66 (0.05) a	0.40 (0.13) a	0.59 (0.16) a
2500	6.90 (0.01) a	8.89 (0.13) ab	1.29 (0.02) b	0.63 (0.01) b	21.47 (2.20) a	0.68 (0.05) a	0.47 (0.08) a	0.68 (0.06) a
3333	7.16 (0.18) a	9.59 (0.94) b	1.34 (0.11) b	0.57 (0.03) a	20.12 (1.95) a	0.77 (0.03) b	0.60 (0.04) a	0.77 (0.03) a
P-value	0.972	0.028	0.008	<0.0001	0.8790	0.0246	0.0826	0.1745

*Values shown with the same letter in the column are statistically similar (P <0.05). The standard deviation is indicated in parentheses.
Vrijednosti prikazane s istim slovom u stupcu su statistički slične (P <0.05). Standardno odstupanje je naznačeno u zagradama.
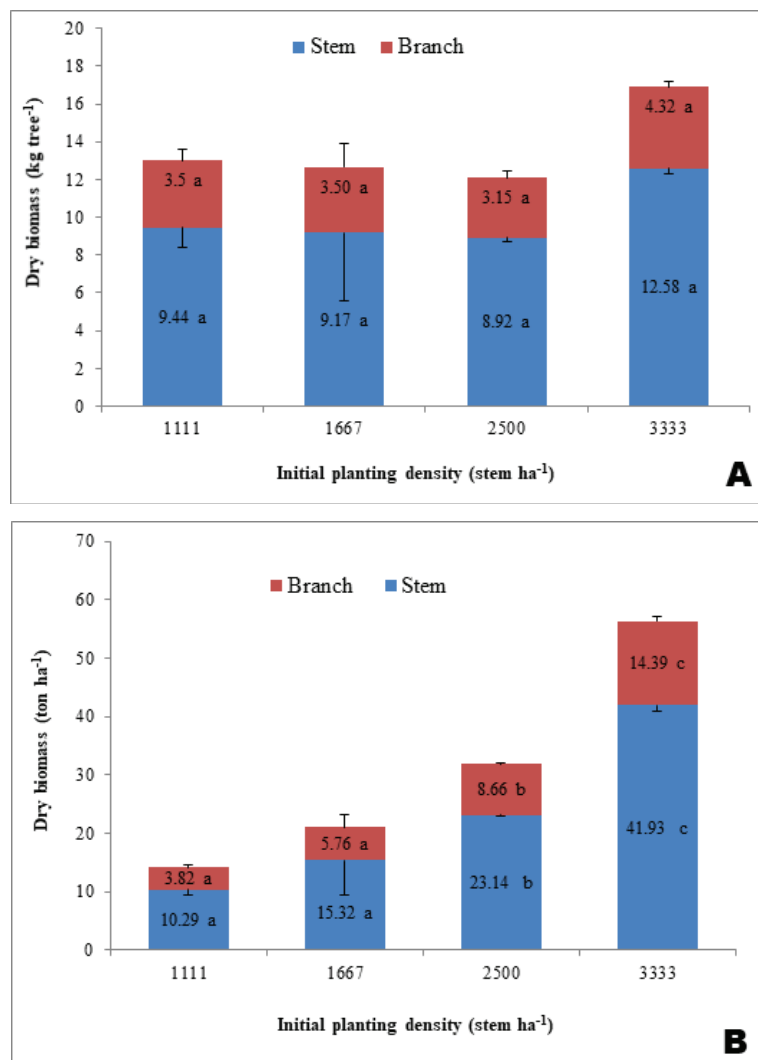
Figure 2. Effect of initial planting density on stem and branch biomass level of individual tree (A) and stand (B). The averages shown with the same letter in the colors in the graph are similar ($P < 0.05$). The error bars indicate one standard deviation.

Slika 2. Utjecaj početne gustoće sadnje na razinu biomase debla i grana pojedinog stabla (A) i sastojine (B). Prosjeci prikazani s istim slovom u bojama na grafikonu su slični ($P < 0.05$). Stupci s pogreškama prikazuju jedno standardno odstupanje.

In the initial planting densities of 1111 and 1667 stem ha⁻¹, although it did not differ statistically, the mean tree height (7.6 m) was 16.4% lower than in the planting density of 2500 stem ha⁻¹. In the experiment, the height varied between 4.5 m and 12.2 m, regardless of the planting density.

Volume regression models for individual trees depending on the DBH were developed for each initial planting density and are given in Table 2. Initial planting density did not affect the stem volume of individual trees, and the mean stem volume in all planting densities was 19.7 dm³ (Table 3).

Mean stem, branch and total aboveground dry biomass of individual trees were 10.3, 3.63 and 13.7 kg, respectively, and these were not affected by the initial planting density ($P > 0.05$; Figure 2A). Stem dry biomass constituted approximately 73% of the aboveground dry biomass and this ratio wasn't different in all seedling densities. Furthermore, the ratio of branch dry biomass to stem dry biomass was wasn't different statistically (0.36) in all planting densities ($P > 0.05$; Figure 2A).

Stem, branch and aboveground dry biomass at stand level were significantly affected by initial planting density ($P < 0.05$; Figure 2B). Stand level aboveground dry biomass in the 1111 and 1667 stem ha⁻¹ density treatments were not different statistically and lower than in the higher initial planting densities. The highest stand level aboveground dry biomass occurred in the highest initial planting density (3333 stem ha⁻¹). Although there was a threefold difference between the number of seedlings planted per hectare in the highest and lowest initial planting densities, this difference was approximately four times for stand level dry biomass. The ratio of stem-aboveground dry biomass at stand level at the density of 3333 stem ha⁻¹ (0.74) was higher than at the other initial planting densitys (0.72) ($P < 0.05$; Figure 2B).

Table 4. Effect of initial planting density on branch characteristics in narrow-leaved ash plantation
Tablica 4. Utjecaj početne gustoće sadnje na karakteristike grana na plantažama poljskog jasena

Initial planting density (stem ha⁻¹) Početna gustoća sadnje (stabala ha⁻¹)	Height to lowest live branch (m) Visina do najniže žive grane (m)	Mean maximum diameter of live branches (mm) Srednji maksimalni promjer živih grana (mm)	Height to lowest dead branch (m) Visina do najniže mrtve grane (m)	Mean maximum diameter of dead branches (mm) Srednji maksimalni promjer mrtvih grana (mm)	Branch/ stem dry biomass Suha biomasa grana/ debla
1111	1.95 (0.13) a*	14.75 (1.59) a	-	-	0.37 (0.03) a
1667	2.10 (0.10) a	19.36 (0.32) b	1.23 (0.11) a	15.44 (0.39) a	0.39 (0.03) a
2500	3.29 (0.07) b	14.88 (0.33) a	2.51 (0.27) b	13.42 (3.12) a	0.35 (0.03) a
3333	4.14 (0.42) c	18.22 (1.59) b	2.3 (0.21) b	15.69 (2.45) a	0.34 (0.01) a
P-value	<0.0001	0.006	0.002	0.291	0.202

*Values shown with the same letter in the column are statistically similar ($P < 0.05$). The standard deviation is indicated in parentheses.

Vrijednosti prikazane s istim slovom u stupcu su statistički slične ($P < 0.05$). Standardno odstupanje je naznačeno u zagradama.

Tree shape – *Oblik stabla*

The H/D ratios were not statistically different at the initial planting densities of 1111 and 1667 stem ha⁻¹, and lower than the other initial seedling densities (Table 4). The H/D ratios at initial planting densities of 3333 and 2500 stem ha⁻¹ were 1.32 m cm⁻¹, 21% higher than at other initial planting densities.

Although the live crown ratio decreased with an increase in initial planting densities from 1111 to 3333 stem ha⁻¹, the difference between the spacing of 1111 and 1667 stem ha⁻¹ was not significant (Table 3).

There weren't significant differences among the $q_{3.30}$ of trees at initial planting densities of 1111, 1667 and 2500 stem ha⁻¹, and they were lower than that at the planting density of 3333 stem ha⁻¹. The $q_{5.50}$ and the $d_{5.5}/d_{3.30}$ ratios of trees at all initial planting densities were not statistically different (Table 3).

Branch characteristics – *Karakteristike grana*

Since self-pruning had not yet begun in the initial planting density of 1111 stem ha⁻¹, there were no dead branches on the stems. The heights of the lowest dead branch of trees in the 2500 and 3333 stem ha⁻¹ planting densities weren't statistically different, and approximately 80% higher than that of the 1667 stem ha⁻¹. There was no difference between the mean maximum diameter of dead branches in any of the initial planting densities except for the 1111 stem ha⁻¹ density ($P > 0.05$, Table 4).

Height to the lowest live branch increased with increasing initial planting density, but wasn't different for the 1111 and 1667 stem ha⁻¹ planting densities ($P > 0.05$). The height to the lowest live branch in the highest initial planting density was approximately 2.1 m greater compared to the planting densities of 1111 and 1667 stem ha⁻¹. Mean maximum diameters of the live branches in the initial planting densities of 3333 and 1667 stem ha⁻¹ were not different statistically, and 27% higher than in the other densities ($P < 0.05$)

DISCUSSION
RASPRAVA

Mortality – *Mortalitet*

No mortality was observed in any of the initial planting density plots, especially despite intraspecific competition in the higher initial planting densities. Although the light demand of narrow-leaved ash is high (Boshier et al. 2005), it can be noted that its tolerance to intraspecific competition is also high. In other studies, it has been reported that common ash (*Fraxinus excelsior*) can survive under low light conditions for a long time compared to intolerant trees such as oak (Kerr 1995; Kerr and Cahalan 2004; Kuehne et al. 2013).

Tree growth – *Rast stabla*

In plantation forestry, the planting density significantly affects the growth and quality of trees (Smith et al. 1997) as competition for light, nutrients and water is intensified among the trees due to their increasing number (Savill et al. 1997). Accordingly, a tendency toward decreased tree diameter is expected as the planting density increases (Huang et al. 1999; Neilsen and Gerrand 1999; Kerr 2003; Mehari and Habte 2006; Alcorn et al. 2007; Benomar et al. 2012; Kuehne et al. 2013; Andrzejczyk et al. 2015). However, in this study, the initial spacing did not affect the mean diameter reached at the end of ten years. According to the results of the first three years of this study, there was no statistical difference between the spacing treatments in terms of mean diameter, but the mean diameter in the weed controlled plots was higher than that in the control plot (Çicek et al. 2010). Kerr (2003) stated that the mean tree diameter decreased as the initial spacing increased in a five-year-old common ash plantation which was not under weed control.

Height growth in plantations may vary depending on the tree species and the size of the growing space tested (Benomar et al. 2012). In broadleaved trees, with increased grow-

ing space between the trees, the height of the trees may increase (Kerr 2003; Pinkard and Neilsen 2003; Alcorn et al. 2007; Kuehne et al. 2013) or remain unchanged (Mehari and Habte 2006; Andrzejczyk et al. 2015). As height growth plays an important role in light competition, trees tend to allocate photosynthetic production to height growth before that of diameter (Lanner 1985; Smith et al. 1997). In the present study, the tree height was greater in the two higher initial planting densities (3333 and 2500 stem ha^{-1}), which exhibited a closed canopy (Table 3). With the higher planting density, the intraspecific competition for light may have led to increases in height growth. Furthermore, the closed canopy formed in these higher initial planting densities along with the consequent lower weed competition could have increased the height growth. According to the three-year results of this study, it was found that the weed control had increased the diameter and height growth during the period when the canopy had not yet closed (Çicek et al. 2010). Moreover, the height and diameter growth was similarly increased with weed control in common ash plantation sites (Culleton and Bulfin 1992). Kuehne et al. (2013) emphasized that tree height tended to increase with increased planting density in a 24-year-old common ash plantation which had undergone regular weed control. Because these ash species (*Fraxinus excelsior* and *Fraxinus angustifolia*) are very sensitive to weed competition, this may have been the cause of the differing results (Evans 1997; Kerr 2003; Boshier et al. 2005; Çicek et al. 2010). Çicek et al. (2007) stated that the weed height was found to be 1.5–2.0 m and consequently, there was excessive weed competition in these sites. In this study, although the density and height of the weedy vegetation under the canopy could not be measured, it may be said that the density of weeds in the plots with lower planting densities (1111 and 1667 stem ha^{-1}) was greater than in the plots with higher planting densities (Figure 1). Kerr (2003) attributed the decrease of the mean diameter with increased spacing to weed competition.

The stem volume and aboveground biomass of individual trees were similar in all initial planting densities, as was the mean diameter (Table 3). On the contrary, it has been reported that with increased initial planting density, the stem volume of individual trees increased due to their diameter increase (Huang et al. 1999; Kerr 2003; Pinkard and Neilsen 2003).

In initial planting density with a high number of trees, the stand levels of aboveground biomass were higher. The stocking in the widest initial planting density plot was three times that in the narrowest initial planting density plot. However, the difference in the stem volume was 3.5 times greater and the stand level of the aboveground biomass was four times greater (Table 3). Similarly, in several studies, higher aboveground biomass levels were determined in the stands with higher initial planting densities (Neilsen and Gerrand 1999; Pinkard and Neilsen 2003; Guner et al. 2010).

Tree shape – *Oblik stabla*

The H/D ratio is seen as an important indicator of the stem shape, especially for the bottom billet (Muhairwe 1999). An H/D ratio of 1.30 m cm^{-1} is critical for the stability of individual young broadleaved trees (Mosandl et al. 1991; Kuehne et al. 2013). A number of trees at the initial planting density of 3333 stem ha^{-1} exceeded this ratio, while trees in the other initial planting densities were below the ratio. However, as the age of the stand increases, a decrease in the H/D ratio is expected, and older trees at the planting density of 3333 stem ha^{-1} may fall below this H/D ratio. These results showed that the trees at planting densities of 3333 and 2500 stem ha^{-1} had acceptable tree stability and cylindrical stems.

The live crown ratio tended to decrease with narrower initial planting density. A similar result was also reported in an initial spacing trial of common ash (Kuehne et al. 2013). The live crown ratio in all spacing treatments was over 57%. This value was higher than the value recommended for the quality of future common ash stands, which is at least one third (Kerr 1995) or half (Kuehne et al. 2013) of the live crown height of the clear bole. Although the live crown ratio was high in the trees in the lower planting density plots, their branches could be thin, exhibit weak survival rates and provide little contribution to their crowns.

The $q_{3.30}$ of trees in the initial planting density of 3333 stem ha^{-1} was higher than in the others, but the $q_{5.50}$ and the $d_{5.5}/d_{3.30}$ ratios of the trees did not change according to initial planting density. This might indicate that the commercially important 3.30 m stem parts of the trees in the initial planting density of 3333 were more cylindrical than in the other planting densities. This supports the conclusion that tree growth in dense stands forms a more cylindrical body (Muhairwe 1994). Some studies on conifer trees have suggested that the diameter increases because after thinning or wide spacing treatments, the lower part of the stem grows relatively faster than the upper part (Muhairwe 1994; Peltola et al. 2002; Mäkinen and Isomäki 2004a; Mäkinen and Isomäki 2004b). However, the stem form may change in the following years depending on age and increasing competition.

The branch-stem dry biomass ratio, as one of the indicators of tree form, was not affected by the initial planting density. A similar result was also reported in a five years old common ash planting density experiment (Kerr 2003). This can be explained by the fact that branch mortality did not start more effectively because the closure was not fully formed.

Branch characteristics – *Karakteristike grana*

The natural pruning ability of common ash is very high compared to other broadleaved species such as beech and oak (Hein and Spiecker 2009). This high self-pruning ability is attributed to the high light demand of the ash leaves. Its low resistance to branch rot may also play an important role in natural pruning. As with the common ash (Kerr 1995), at the end of the narrow-leaved ash rotation period, a clear bole diameter of 40–60 cm and a height of at least 6.0 m is desired. Initial spacing can affect the height of the lowest branch (height of clear bole), branch thickness and length. The size of the branches is largely controlled by the space they have in which to develop (Daniel et al. 1979). Live branches in higher initial planting densities are shorter and have small diameters (Smith and Strub 1991; Niemistö 1995; Mäkelä 1997; Mäkinen and Hein 2006; Wang et al. 2015; Hébert et al. 2016; Wang et al. 2018) and the height of the lowest branch is higher (Odabaşı et al. 2004; Kuehne et al. 2013).

Similarly, in a study performed with common ash (Kuehne et al., 2013), the height of the lowest branch also increased with higher initial planting density. At a planting density of 3333 stem ha^{-1}, a 4-m height of the lowest branch can be sufficient for the clear bole (>6 m). Since the average crown base height at the adjacent 32-year-old narrow-leaved ash plantation (3.7 × 3.7 m spacing) can reach up to 15-20 m (Özbayram and Çiçek 2018; Özbayram 2019), the height of the clear bole in this study can be expected to increase further.

It is stated that in some broadleaved species the maximum diameter of live branches increases as the spacing increases (Neilsen and Gerrand 1999; Mehari and Habte 2006). According to the present study, although the maximum diameter of dead branches was similar in all spacing treatments, the maximum diameter of live branches differed. Kuehne et al. (2013) reported that the maximum diameter of live and dead branches showed only a slight increase with increased spacing. In the present study, the difference between the maximum diameter of live branches for the narrowest and the widest spacing was 0.37 cm, while this difference was greater than 3.0 cm in the common ash (Kuehne et al. 2013). It can be said that at the initial planting density of 3333 stem ha^{-1}, the maximum diameter of live branches did not significantly reduce the quality of the trees in the narrow-leaved ash plantation.

CONCLUSIONS
ZAKLJUČCI

Ash is one of the few species of deciduous trees that can be established in lowland stands, and in Turkey they are planted for the production of large-diameter and quality timber. Our results indicate that an initial planting density of 3333 trees per hectare should be applied for narrow-leaved ash plantations in lowland sites with high weed competition. Ash, perhaps as a silvicultural characteristic, can be more negatively affected by interspecific competition than by intraspecific competition. Initial planting densities of 2500 and 3333 stems per hectare are recommended in narrow-leaved ash plantations because the DBH, height, stand volume, height to lowest dead branch, and H/D ratio were similar for the two stockings. However, the cost of a planting density of 3333 trees per hectare (seedlings, planting, post-planting maintenance) will be higher; therefore, forest managers might instead prefer a planting density of 2500 stems per hectare (2.5 × 1.6 m).

Although the trees in the planting densities of 2500 and 3333 stems per hectare had reached the height and stem quality for the first thinning, no stand closure had occurred in the other initial planting densities. Thus, the first thinning at an early age can focus on higher planting densities, as well as the possibility of choosing a sufficient number and quality crop trees in the first thinning (mechanic or selective thinning).

Similar to the findings of planting interval studies on narrow-leaved ash in different growing environments, this study also recommends investigations into whether the growth and quality contributions provided by ecosilvi high planting density continue into an older age in these areas.

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SAŽETAK

Poljski jasen (*Fraxinus angustifolia* Vahl.) je izvor vrijednog drva u Europi, a plantaže poljskog jasena u Turskoj daju visoke prinose. Gotovo sve prirodne nizinske šume u kojima dominira poljski jasen pretvorene su u posljednjih 60 godina u čiste plantaže poljskog jasena u regiji Adaparazi, u kojoj se nalaze najveće šume ove vrste drveća. Potražnja za pilanskim trupcima velikih promjera je u stalnom porastu pa je stoga važno osigurati optimalnu gustoću sadnje. Iz razloga što je početna gustoća sadnje najvažniji čimbenik koji određuje gustoću, rast i kvalitetu stabala, ophodnju i troškove gospodarenja na plantažama. Godine 2004. postavljen je dugotrajni pokus gustoće sadnje s četiri različite početne gustoće sadnje, koja je uključivala 1111, 1667, 2500 i 3333 stabala ha^{-1} u Akyazi-Adapazan, regiji Turske u kojoj su plantaže poljskog jasena česte. Sadnice poljskog jasena s golim korijenom starosti 1+0 (visine od 65 do 75 cm) proizvedene su u rasadniku Hendek i posađene u prosincu 2004. godine. Cilj ovog rada je utvrditi desetogodišnji utjecaj početne gustoće sadnje na rast i kvalitetu stabala (oblik stabla i karakteristike grana) poljskog jasena. Godine 2015., deset godina nakon sadnje, izmjerene su prsne visine, visine stabla, visine do najniže mrtve grane i najniže žive grane te maksimalni promjer živih i mrtvih grana, a nakon toga su izračunati omjer između visine i prsnog promjera, (H/D), omjer živih grana, volumen debla, kvocijenti oblika i nadzemne suhe biomase.

Nakon deset godina rasta, nije primijećen mortalitet ni u jednoj od četiriju početnih gustoća sadnje. Početna gustoća sadnje nije imala nikakav učinak na srednji promjer debla; međutim, s porastom početne gustoće sadnje od 1111 na 3333 debla ha^{-1}, srednji visina stabla je značajno porastao a omjer živih krošnji se smanjio. Omjeri H/D pri početnim gustoćama sadnje od 2500 i 3333 stabala ha^{-1} bili su 21% viši nego oni pri manjim gustoćama sadnje. Na nivou sastojine, nadzemna suha biomasa porasla je s porastom početne gustoće sadnje, premda su veličine pojedinih stabala bile slične. Općenito, oblik stabla i karakteristike grana su se poboljšale s porastom početne gustoće sadnje. Uz to, pošto je sklop krošanja kod početne gustoće sadnje od 2500 i 3333 stabala po hektaru bio potpuno sklopljen, rast korova bio je slab i rijedak. Međutim, gusti rast visokog korova pri početnim gustoćama sadnje od 2500 i 3333 stabala po hektaru mogu izrazito otežati njegu sastojine. Dosadašnji rezultati sugeriraju da početna gustoća sadnje bude od 2500 i 3333 stabala po hektaru na plantažama poljskog jasena, jer su prsni promjer, visina, volumen sastojine, visina do najniže mrtve grane i omjer H/D slični pri ove dvije sadnje. Međutim, troškovi gustoće sadnje od 3333 stabala po hektaru (sadnice, sadnja, njega nakon sadnje) bit će viši; prema tome, uzgajivači bi se umjesto veće početne gustoće sadnje mogli odlučiti za manju s 2500 stabala po hektaru.

KLJUČNE RIJEČI: *Fraxinus angustifolia,* poljski jasen, početni razmak, sadnja, Turska