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RESEARCH ARTICLE

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Effects of spacing on early growth rate and carbon sequestration in *Pinus brutia* Ten. plantations

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Abstract

Aim of study: The aim of this study was to analyze the effects of initial spacing on early growth and carbon sequestration rates in Turkish red pine plantations up to 12 years old, established with improved seeds and deep soil cultivation.

Area of study: The study was conducted on experimental sites established in two locations within the Turkish red pine natural distribution areas, namely Duacı and Nebiler close to Antalya city.

Material and methods: Data were collected from the experimental sites established as a Nelder design (fan-shaped), with 72 rays and 18 arcs (circles), and trees were planted (almost square) at distances ranging from 1.15 to 4.77 m. Soil type of both sites is loamy, with soil clay content varying between 70-87% in Duacı and 51-70% in Nebiler. Soils are deep being more than one m in both sites, but rockier in Nebiler, providing better soil drainage in this site.

Main results: The results showed that mean total height was greater at closer spacing than those of wider spacing until age eight. Growth retardation at wider spacing in early years may be related to water loss due to evaporation in hot summer days and weed suppression. Following the age eight, competition among trees appears to be the major factor reducing the growth and carbon fixation. Diameter at breast height and individual tree volume increased, while stand volume, mean annual volume increment and annual carbon storage per hectare considerably decreased for wider spacing. Our results suggest that in order to obtain higher yield and more carbon fixation, short rotation plantations should initially be established in closer spacing, followed by thinning in subsequent years as required by silvicultural concerns. In this context, spacing 3.0 × 1.0 m or 3.0 × 1.5 m (3.0 and 4.5 m^2 growing area per tree, respectively) seems to be more plausible, providing farm machinery for maintenance and harvesting. We also found that mean annual volume increment per unit area can be considerably increased by using improved seed and deep soil cultivation in plantations.

Research highlights: Results encourage managers for short rotation management in industrial plantations using closer spacing in terms of carbon sequestration as well as wood production.

Keywords: *Pinus brutia* Ten.; spacing; forest growth and yield; carbon sequestration; Nelder experimental design.

Abbreviations: TFS: Turkish Forest Service; **OGM:** General Directorate of Forestry; **Dbh:** Diameter at breast height.

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Introduction

Initial spacing affects the stand growth rate and mean tree size (Zhang *et al.*, 1996; Harms *et al.*, 2000; Sharma *et al.*, 2002; Harrington *et al.,* 2009; Amateis & Burkhart, 2012) and determines the timing and intensity of competition among trees for resources (Harrington *et al.*, 2009). Therefore, quantitative evaluations of effects of initial spacing on stand growth rates are needed for a better understanding of the effects of spacing in achieving specific management objectives. Additionally, determination of proper spacing is important for producing not only more wood, but also to increase its quality. A closer spacing induces branch mortality, which consequently leads to production of higher quality stem volume (Kerr, 2003; Rais *et al.*, 2014).

There have been rather limited studies on the effects of spacing on various stand parameters on Turkish red pine (*P. brutia* Ten.) native to Turkey. For example, Boydak (1982) investigated the effects of spacing on growth of *P. brutia* in Northwestern part of Turkey on different soil types and ecological conditions using seedlings from different provenances. He found that growth of plantations on different soil types was also different, and that depending on the soil types optimal spacing ranged from 1.00 × 2.25 m to 2.25 × 2.25 m. He suggested that further studies are needed on spacing using the most adapted seed sources in a given locality. A study by Usta (1991) focused on typical growth and yield performances of Turkish red pine plantations established in conventional ways. However, evaluations of the effects of spacing in tree plantations established with genetically improved seeds and with the aid of deep soil cultivation are scarce in Turkey. Westfall *et al.* (2004) found that predicted mean volume growth of loblolly pine per unit area for various site preparations (including bedding, disking, herbaceous weed control and fertilization practices) applied prior to start of inter-tree competition was considerably higher than control at age 30.

Although most of the forests in Turkey have been naturally regenerated, reinforced by establishing plantations on limited areas, there has been a considerable change in Turkish forestry about wood production policy. In recent decades, the Turkish Forest Service (TFS) has started a strong plantation program to provide an ever increasing industrial wood demand (*i.e.* industrial plantations) and increase carbon sequestration. The TFS adapted an action plan to establish short rotation (in average 25 years, depending on targeted wood production) plantations in relatively good sites (I. and II. site classes, considering the five class classification), both inside and outside forested areas with suitable spacing and deep (more than 60 cm) soil cultivation using fast growing species. While there is a number of natural and introduced tree species suitable for these plantations, Turkish red pine appears to be the best option for this purpose, especially for southern and western parts of the country. Turkish red pine is a fast growing (Eraslan, 1983; Usta, 1991; Koski & Antola, 1993; Erkan, 1996; Isik & Kara, 1997) and the most important tree species in Turkish forestry with its approximately 5.8 million ha of natural and planted forest areas (OGM, 2012) and 4.3 million m^3/year of wood production (OGM, 2013) that represents about 31% of total wood production of the country. In 2000, the Turkish red pine plantations accounted for approximately 707,000 ha which represented almost 40% of the total plantation areas (1.8 million ha) (Konukçu, 2001).

Forestry is also a major issue for climate change. Plantation forests have been identified as one of the most cost-effective ways to mitigate high atmospheric carbon dioxide (CO_2) concentrations and thus prevention of global warming. In this context, fast growing tree plantations are considered highly efficient carbon sinks (IPCC, 2001; Laclau, 2003; Malmsheimer *et al.*, 2011). It is clear that higher carbon sequestration rate is directly related to more wood production, which can be manipulated by initial spacing in plantations. To assess the carbon sequestration, potential contribution of Turkish red pine plantations to the above- and below-ground biomass at stand level needs to be studied.

The main objective of this study is to investigate the effects of planting spacing on individual tree growth (diameter, height, and wood volume) of Turkish red pine stands in young ages (4 to 12 years-old). We expect that the most appropriate initial spacing will be determined for future short rotation plantation areas in order to get more wood production. In addition, we aimed at assessing carbon sequestration based on above- and below-ground biomass calculations of the species, depending on initial spacing at stand level.

Material and methods

The experimental sites were established in two locations within the Turkish red pine natural distribution areas, namely Duacı and Nebiler (Duacı: 36º57'52.96" N, 30º39'19.60" E, elevation: 290 m, Nebiler: 36º57'40.03"N, 30º36'59.09"E, elevation: 294 m) close to Antalya city (Figure 1). Based on site index values presented by Usta (1991) on *P. brutia,* both sites are productive for conifers and site indexes are very high, both being site class I (i.e., 23 m at index age of 30 years). Duacı was used for agriculture purposes before plantation while Nebiler was previously occupied by a 70 year-old *P.brutia* stand. Top soil contained 1.8% and 3.3% organic matter with soil pH of 6.6 and 7.8 for the sites, respectively. Long term (for the period of 1950-2014) annual average temperature is 18.6ºC and total precipitation 1,075.4 mm per year for both sites (TSMS, 2015). Soil type of both sites is loamy, with soil clay content varying between 70-87% in Duacı and 51-70% in Nebiler. Soils are deep being more than one m in both sites, but rockier in Nebiler, providing better soil drainage in this site.

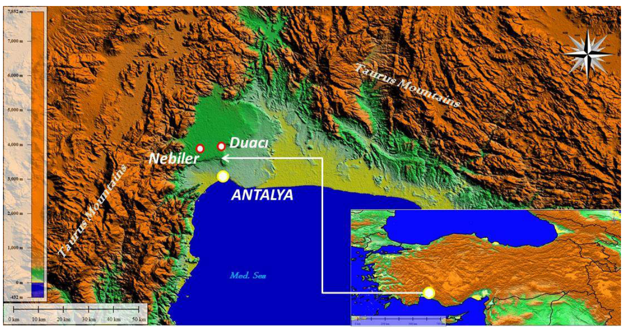

Figure 1. Locations of the experimental sites near Antalya city, Turkey.

The experiments in both study sites were established as a Nelder design (fan-shaped) (Nelder, 1962), with 72 rays and 18 arcs (circles) in total, and trees were planted (almost square) at distances ranging from 1.15 to 4.77 m (Figure 2). Trees on the first two arcs near the center of the plot and trees on the most outside arc were used as buffers, providing a range of growing areas from 1.78 to 18.54 m^2 per tree (5,618- 539 trees per ha, respectively). The Nelder experimental design has been described as a good approach to evaluate the effects of spacing on a relatively small area with relatively uniform sites (Stape & Binkley, 2010). Both sites selected for the experiment were uniform, flat and without any notable within-site variation in soil properties. The sites were deeply (60 cm) tilled and cultivated before planting. Seeds were obtained from a first generation seed orchard originated from Alanya-Kargı and Çameli-Göldağ provenances, which are the recommended origins for plantation sites in the region (Öztürk *et al.*, 2004). Seedlings were grown in 2004 in plastic pot trays with 9 × 5 = 45 cells, each cell 4 × 5 × 10 cm in size, and then planted when they were 1+0 years old in February 2005 in both test sites.

Data in this study are based on measurement of trees at different ages (from 4th to 12th years) and 15 different spacings. There were about 72 trees measured by age eight, after which about 36 trees were measured on each test sites for each treatment (spacing). The reduction in the number of measured trees was due to removal of certain trees under a thinning trial linked with this experiment. Data on dead (or missing) trees were excluded from evaluation. Furthermore, data on neighboring trees surrounding the dead trees were also excluded so that neighborhood effects due to opened spaces by dead trees are minimized or eliminated.

Each tree was annually measured starting at age 4th years for total height (cm). We started measuring dbh following age 5 years when all the trees reached at breast height (1.30 m). A CRAIN® telescopic device was used for height measurements.

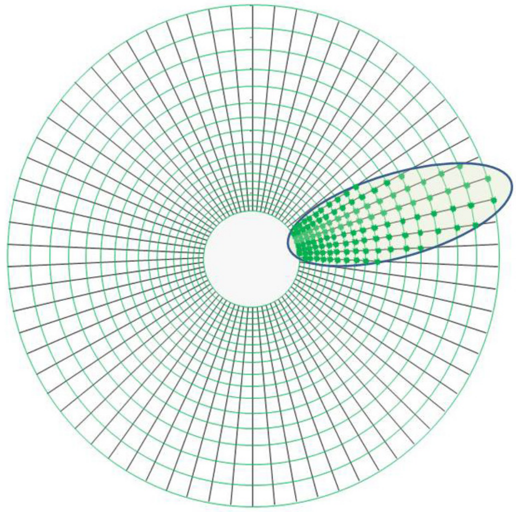

Figure 2. Diagrammatic representation of the Nelder design as applied in this study, with 72 rays and 18 arcs. The diameter of the outmost circle is 109.4 m, with an area of 0.94 ha [each dot at intersections of rays and arcs (as shown in detail within an ellipse) represents a tree].

Stand density, which is one of the important factor affecting the growth of even-aged stands, can be expressed as crown cover, basal area and number of trees per ha (Husch *et al.*, 1982; Kalıpsız, 1984). Basal area is the most appropriate measure commonly used for natural stand growth and yield modeling when stand history is considered, while the number of trees (spacing) is used for planted stand modeling (Avery & Burkhart, 1994; Laar & Akça, 1997). Therefore, growing area is an important criterion for each tree in a plantation. In Nelder experimental design, the distances between trees are not in square shape, but close to square shape (Figure 2). We calculated individual tree growing area by considering the distances to all four closest neighboring trees. Equation 1 was used to calculate the growing area of the i^{th} tree. We used growing area as a base for individual tree- and stand level calculations. Table 1 shows the growing areas that correspond to a given spacing as calculated with Equation 1.

Table 1. Size of individual tree growing area as related to distances between neighboring trees planted in a Nelder design.

No. of arcs from center	Distance (m) between two trees on the same arc	Growing area per tree (m^2)	No. of arcs from center	Distance (m) between two trees on the same arc	Growing area per tree (m^2)	No. of arcs from center	Distance (m) between two trees on the same arc	Growing area per tree (m^2)
1	1.15	1.32	7	1.90	3.48	13	3.14	9.49
2	1.25	1.51	8	2.07	4.11	14	3.42	11.22
3	1.36	1.78	9	2.25	4.86	15	3.71	13.27
4	1.48	2.11	10	2.44	5.75	16	4.04	15.68
5	1.61	2.49	11	2.66	6.79	17	4.39	18.54
6	1.75	2.94	12	2.89	8.03	18	4.77	21.91

Individual tree growing area on a specific ray and arc was calculated as followings:

$$A_i = \pi \left[\left(\frac{r_{i+1} + r_i}{2} \right)^2 - \left(\frac{r_i + r_{i-1}}{2} \right)^2 \right] / n \qquad [1]$$

where: A_i is growing area of i^{th} tree (m^2), r_i is the radius of i^{th} arc (m), is the number of rays (n = 72).

Height / maximum-height ratio was calculated for each spacing (growing area) within each age, where **height** being the mean height for a given spacing, and **maximum height** being the maximum height value among spacing values within a given age. Values from these ratios were used to observe relative change of growth over time depending on growing area.

Usta (1991), by taking 45 sample plots in areas covering all over the distribution range of *P. brutia* in Turkey, prepared an empirical yield table based on site index, age and spacing for *P. brutia* plantations. This yield table has been used as a standard reference point for comparing growth of various *P. brutia* stands. Stem volume of individual trees was estimated by equation 2 (Usta, 1991), using dbh and height measurements that were taken at both sites:

$$ln\ V = \ln\left(-2{,}0775\right) + 1{,}6768\ \ln\ dbh + 0{,}8451 \ln h \qquad [2]$$

where: V is volume of individual tree (dm^3); *ln* is natural logarithm; *dbh* is diameter at breast height (cm); and h is tree height (m) (Correction factor was 1.007987).

In order to compare growth parameters in our study, we also calculated MAI per unit area, which is the most important parameter for spacing evaluation. We calculated MAI by dividing total stem volume to age, and analyzed it and compared with the yield table values presented by Usta (1991).

Annual carbon stock changes for the AFOLU (Agriculture, Forestry and Other Land Use) sector are estimated as the sum of changes in all land-use categories. For land use “forest land remaining forest land”, changes in ecosystem carbon stocks consist of: 1) above-ground and below-ground biomass, 2) dead organic matter (*i.e.*, dead wood and litter), and 3) soil organic matter. Annual carbon stock changes in any pool can be estimated using the Gain-Loss Method (IPCC, 2006). We calculated total annual Carbon storage (in above-ground + below-ground biomass) at the stand level by spacing using the Equations 3 and 4 (IPCC, 2003; IPCC, 2006):

$$\Delta C_G = \left[\left(Iv * BCEF_1\right) * \left(1 + R\right)\right] * CF \qquad [3]$$

$$BCEF_1 = BEF_1 * D \qquad [4]$$

where: ΔC_G is annual increase in biomass carbon stocks due to biomass growth, tons C yr^{-1} ha^{-1}; Iv is average net annual increment, m^3 ha^{-1} yr^{-1}; $BCEF_I$ is biomass conversion and expansion factor for conversion of net annual increment in volume (including bark) to above-ground biomass growth, dimensionless; R is root-to-shoot ratio appropriate to increments, dimensionless; and CF is carbon fraction of dry matter (default = 0.5), tons C (tons dry matter)$^{-1}$; BEF_I is biomass expansion factor for conversion of annual net increment (including bark) to above-ground tree biomass increment, dimensionless; D is basic wood density, tons dry matter m^{-3}

In Equation 4, for BEF_I factor we used 1.2209 as calculated by Sun *et al.* (1980) for *P. brutia*, R ratio = 0.32 as suggested by IPCC (2003) guidance for conifers in temperate zones covering Turkey, and D = 0.53 as calculated by As *et al.* (2001) for *P.brutia*.

Statistical analysis, mostly based on ANOVA tests and correlation analyses, were performed with SPSS statistical software v. 22.0®, and the following ANOVA model was used to test for the effect of spacing on tree growth:

$$y_{ik} = \mu + \alpha_i + \varepsilon_{ik} \qquad [5]$$

where y_{ik} is growth trait (dbh, height, volume) of k^{th} tree within i^{th} spacing intensity; is overall mean; is the effect of spacing intensity; and ε_{ik} is the error term.

Results and Discussion

Height Growth

Correlation (Spearman’s) analyses showed a significant negative relationship (α=0.01) between spacing and total height until age eight. Height was considerably greater at closer spacing than those of wider spacing (Figure 3), and ANOVA results indicated significant differences (α=0.05) in total height due to spacing until age eight.

Spacing-height growth relationships for ages four to twelve are shown as the ratio of height to maximum height (% of maximum height) to observe relative progressive change of height growth in time (Figure 4). This height/maximum height ratio reached the peaks at younger ages in closer than in wider spacing. For example, at age four the ratio was 99.99 for closer spacing [1.78 m^2 (1.36 × 1.36 m)], and it was 91.32 for wider spacing [4.86 m^2 (2.25 × 2.25m)]. However, the highest value of this ratio shifts from closer to wider spacings starting at age eight (Figure 4), so that at age nine the ratio was 99.99 for wider spacing [4.86 m2

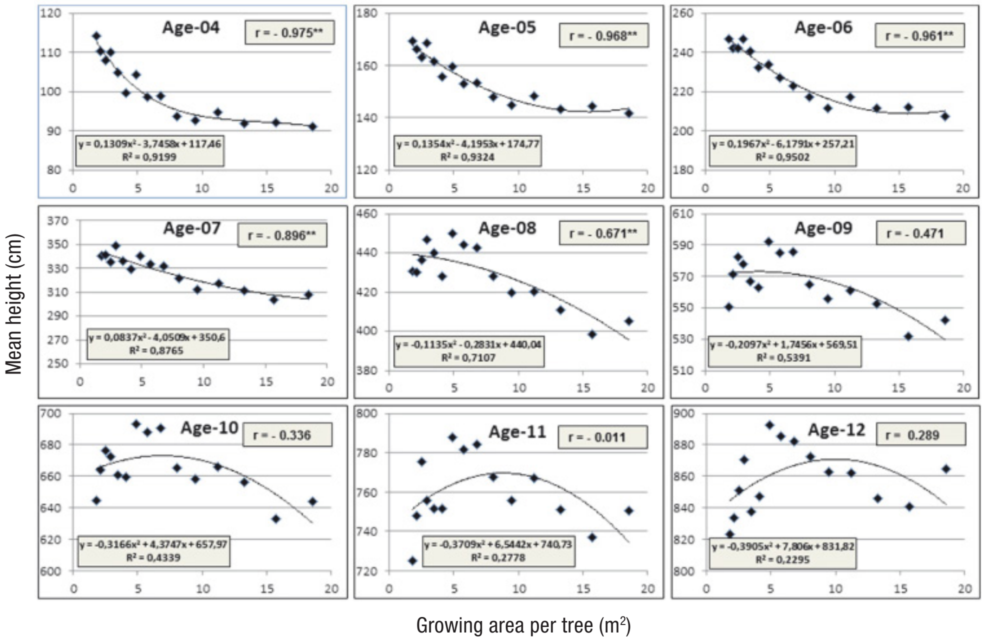

Figure 3. Relationships between mean height and growing area (spacing) per tree at different ages at Duacı test site (N=15, **: significant at the 0.01 level) (Regression equations and R^2 values are shown for each age in the figures).

(2.25 × 2.25 m)] and 93.00 for closer [1.78 m² (1.36 × 1.36 m)] spacing. This result was consistent with that of found by Scott *et al.* (1998) for coast Douglas-fir (*Pseudotsuga menziesii*(Mirb.) Franco var *menziesii*), by Knowe & Hibbs (1996) for young red alder (*Alnus rubra* Bong) and by Kerr (2003) for ash (*Fraxinus excelsior* L.), and with other similar researches.

Larger height values at early ages in closer spacing compared to wider spacing may be due to better micro ecological conditions in closer spacing. It is because wider spacing at early ages appears to increase water loss due to evaporation caused by wind, resulting in less water content of the soil, which leads to growth retardation in trees especially in hot summer days (Kerr, 2003; Harrington *et al.*, 2009). In fact, the experimental sites have typical Mediterranean climate, which already has water deficiency in June-September period. Indeed, long term meteorological data for the period of 1950-2014 for June, July, August and September for the sites show that total monthly precipitation are 7.7, 2.8, 3.1, 13.5 mm, respectively. Monthly mean temperature for the same months are 25.4, 28.4,

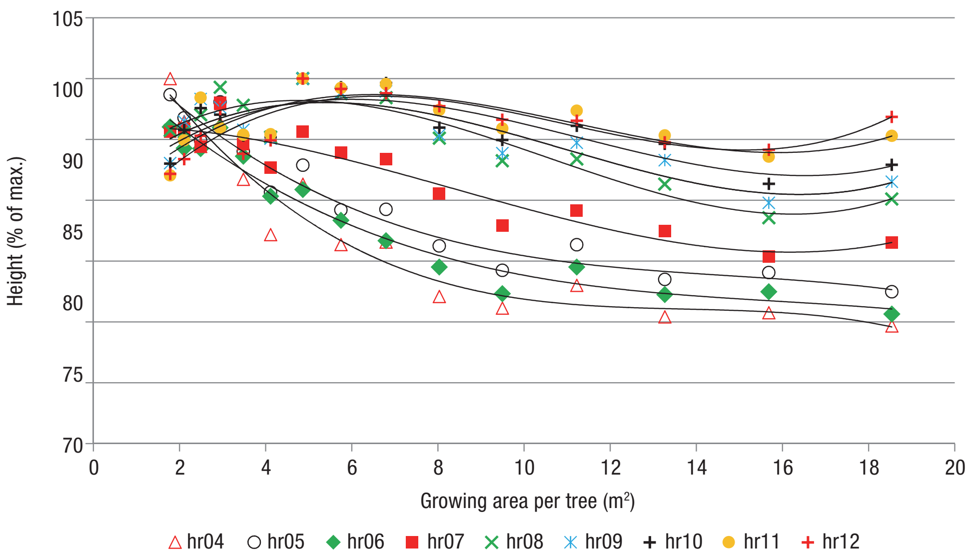

Figure 4. Change of height/maximum height ratio over time depending on growing area per tree (hr04, hr05, …= height/maximum height ratio at age 4, age 5, etc.).

28.2, 24.8 ºC respectively (TSMS, 2015), which leads to serious water deficiency in the region. Another effect may be due to more weed suppression on trees at wider spacing, which, in addition to competition for nutrient elements, also affects water budget negatively in early ages (Westfall *et al.*, 2004).

Diameter at breast height (dbh) growth

Diameter growth is the most sensitive tree characteristic affected by stand density, such that number of trees and spacing are effective predictors of individual tree diameter growth in even aged stands (Kalıpsız, 1982). ANOVA results showed that mean diameter was significantly (α=0.05) affected by initial spacing following crown closure and thereby the initiation of intertree competition about at age eight. This effect was clearer in the years following age eight, depending on severity of competition (Figure 5). These trends showed consistency with previous studies performed on several conifer species (Usta, 1991; Sharma *et al.*, 2002; Hummel, 2000; Harms *et al.*, 2000; Timothy *et al.*, 2009). However, there was a significant positive effect of closer spacing to induce dbh growth before age eight, which was also the case for height growth. Several studies also indicated that there is a strong positive correlation between height and diameter for a given spacing and growing area on forest trees (Kalıpsız, 1984; Husch *et al.*, 1982; Erkan, 1996). Following the beginning of competition at about age eight, wider spacing provides higher dbh growth rate (Figure 5). For instance, at Duacı site at age 12, average dbh is only 77.5 mm for 1.78 m^2 growing area per tree, while at the same age average dbh is 154.8 mm for 18.54 m^2 growing area. A similar trend is also observed in the Nebiler site where average dbh for the corresponding spacings are 70.0 mm and 139.0 mm, respectively (Figure 5).

Volume Growth

Individual tree stem volume showed similar growth pattern as diameter growth due to the fact that tree volume is strongly correlated with tree diameter. Thus tree volume increases with wider spacing mainly due to decreasing competition (Figure 6).

ANOVA results indicated significant differences (α=0.05) in total individual stem volume, stand volume per hectare and mean annual volume increment following age eight.

Our results showed that individual tree volume increased (Figure 6) while stand volume per hectare decreased as spacing becomes wider (Figure 7). Therefore, before any decision on spacing in plantations, it is necessary to consider not only the volume growth of individual trees, but also production of higher volume (and volume growth) per unit area. Volume growth behavior of individual trees as compared with volume growth of a stand for a given spacing is directly related to area use efficiency and number of trees per unit area (Zhang *et al.*, 1996; Sharma *et al.*, 2002; Harrington *et al.*, 2009; Amateis & Burkhart, 2012). By age twelve, even if the competition has already started at closer spacing, area use by trees was still effective. By age 12th years, we observed no dead trees due to negative effects of closer spacing. However, in the absence of thinning, the shape of the curve would change due to increasing number of dead trees in advanced ages and for longer rotations. In such cases stem volume per unit area will decrease, being more heavily so, as the spacing becomes closer (Amateis & Burkhart, 2012).

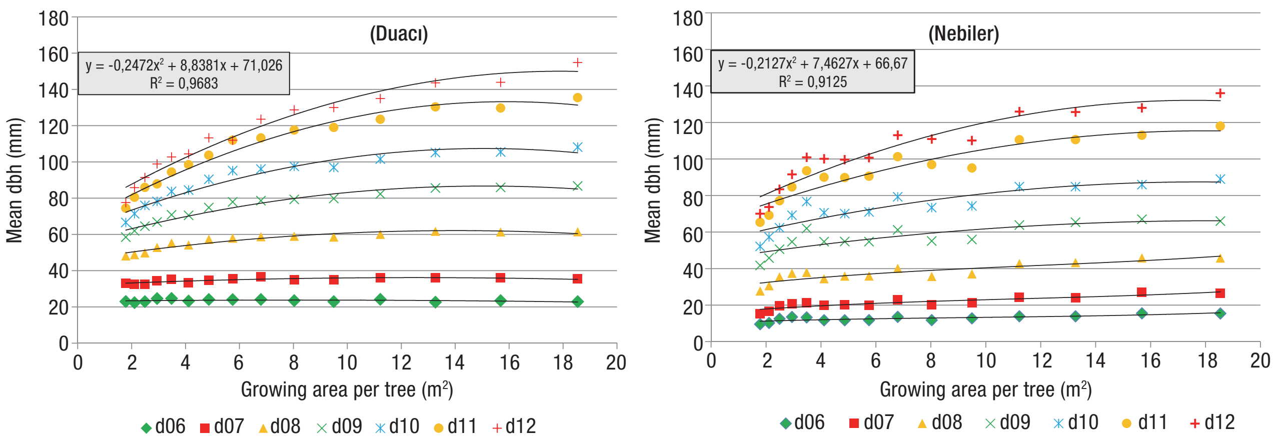

Figure 5. Development of the mean dbh over time depending on growing area per tree (d06, d07, … = mean diameter at age 6, age 7, etc) (Regression equations and R^2 values are shown only for age 12 in the figures).

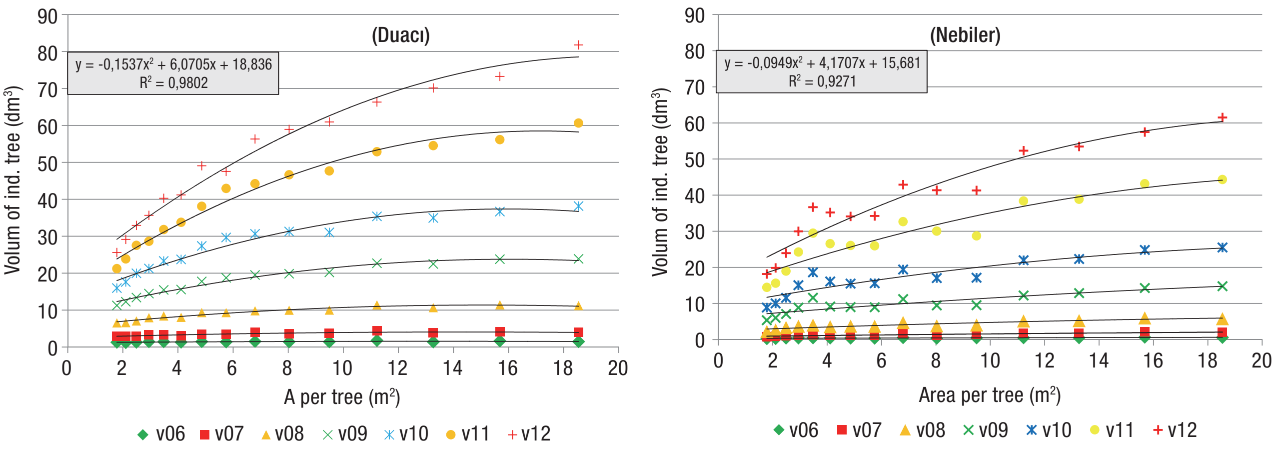

Figure 6. Development of mean individual tree volume over time depending on individual tree growing area (v06, v07, … = mean volume per tree at age 6, age 7, etc.) (Regression equations and R^2 values are shown only for age 12 in the figures).

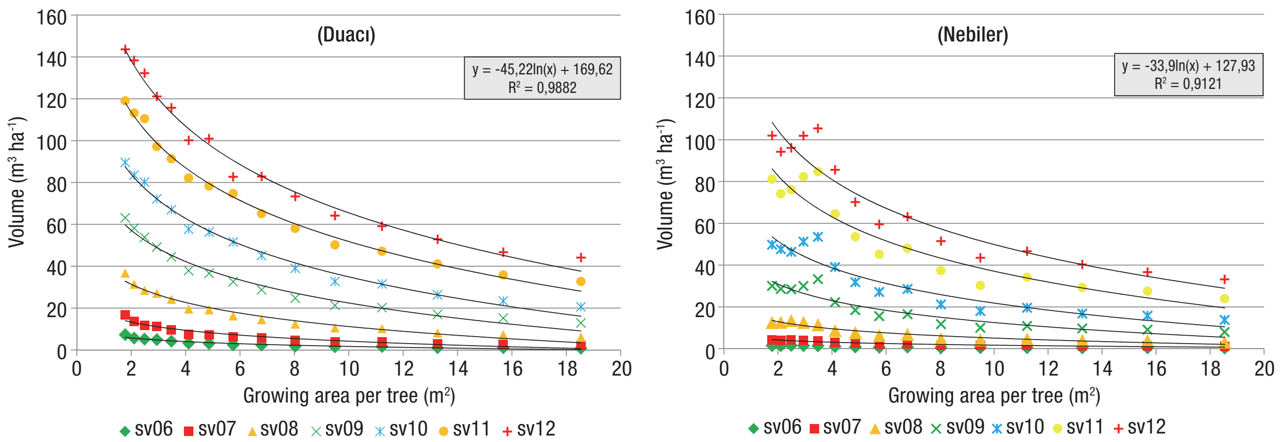

Figure 7. Development of the mean stand volume in hectare over time by growing area per tree (sv06, sv07, … = mean stem volume per hectare at age 6, age 7, etc.) (Regression equations and R^2 values are shown only for age 12 in the figures).

Mean annual volume increment (MAI) per unit area is the most important criterion in terms of forest management when wood production is prioritized. Therefore, MAI has been used to set an optimal rotation age to maximize total wood production in even aged stands (Kalıpsız, 1982; Avery & Burkhart, 1994). Our results showed that MAI decreased with increasing spacing in both test sites by age 12 (Figure 8). A closer spacing provides much more wood production and seems to be advantageous for short rotation forestry. Our overall results are consistent with those of various reports (Harms *et al.*, 2000; Timothy *et al.*, 2009; Amateis & Burkhart, 2012). For instance, Amateis & Burkhart (2012) found that closer spacing (1.22 × 1.22 m), in a loblolly pine plantation, produced more total volume yield through age 13 than the other spacing treatments. However, at age 15 of the same species, volume yield was reduced in closer spacings compared to wider spacings, mostly due to increased mortality.

Comparison to yield table

Empirical yield table prepared by Usta (1991) are based on data obtained from plantations which were established by conventional methods; i.e., without deep soil cultivation and using ordinary seeds collected from natural forests. However, our test sites (Duacı and Nebiler), which were chosen from among good sites (I. class), were established using improved seeds from first generation seed orchards, and the soil was cultivated deeply, which are accepted as essential activities in commercial tree plantations. We compared our volume growth results with Usta's (1991) yield table presented for good sites (Figure 9).

As illustrated in Figure 9, there were statistically significant (α=0.05) differences in growth performances (MAI) between Usta's Yield table values and those of the experimental sites. Main differences between the test sites and Usta's Yield table values

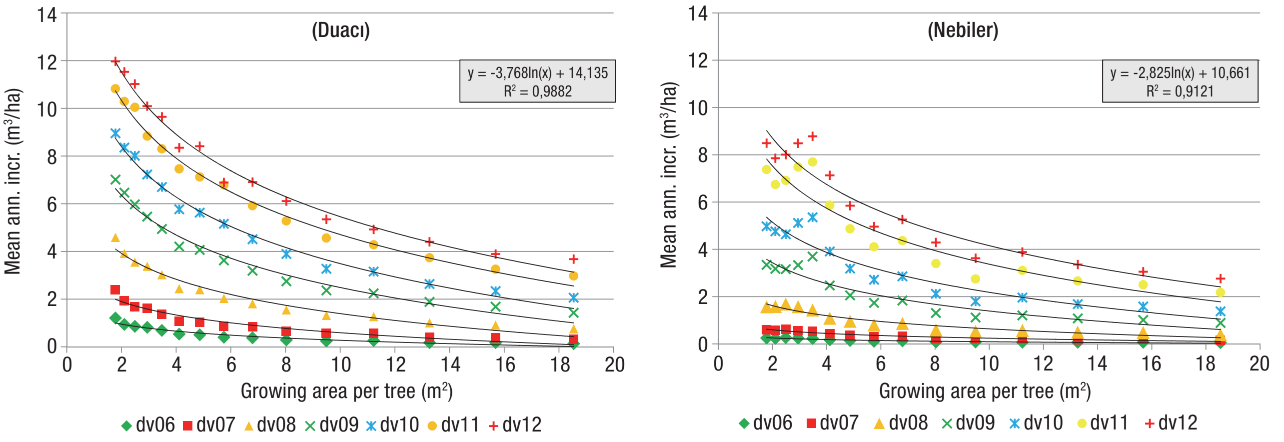

Figure 8. Mean annual volume increment (MAI) per hectare for different growing areas per tree at different ages (dv06, dv07, … = MAI per hectare at age 6, age 7, etc.) (Regression equations and R^2 values are shown only for age 12 in the figures).

may be originated by two reasons: The main reason may arise from the use of improved seeds in the test sites, along with site preparation implemented with deep soil cultivation (Boydak, 1982; Ürgenç, 1986; Westfall *et al.*, 2004). It appears that additional site treatments (such as site preparation, weed control and fertilization practices) prior to plantation establishment would have long term positive effects on growth and increase of final crop (Westfall *et al.*, 2004). The second reason might be that, Usta's table values are the averages of measurements of 45 good sites, having a range of values around the averages as reflected in Figure 9. As to growth difference between Duacı and Nebiler test sites, which were again significant (α=0.05), it might be due to minor site-quality differences among the test sites. Indeed, top height at age 12 was 10.0 m in Duacı, and it was smaller (8.9 m) in Nebiler.

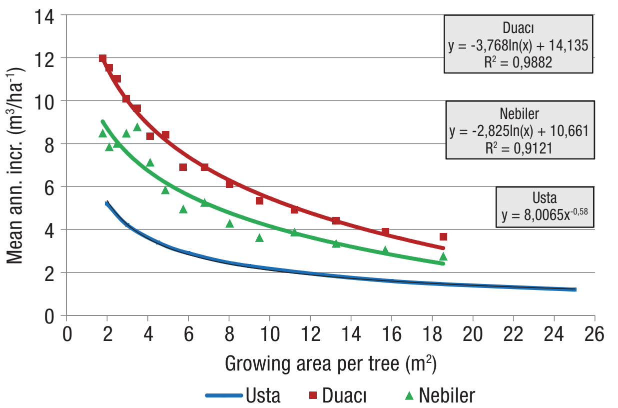

Figure 9. Comparison of mean annual increment (at age 12) of the test sites (Duacı, Nebiler) with Usta's Yield table values (Usta, 1991) (Regression equations and R^2 values are shown only for age 12 in the figures).

Carbon sequestration depending on spacing

Carbon (C) storage per hectare in tree biomass (above-ground + below-ground) in a stand changed with spacing (Figure 10). Total C storage (above-ground + below-ground) in a tree decreased drastically from 5.11 to 1.57 tons year^{-1} ha^{-1} for tree growing areas of 1.78 and 18.54 m^2, respectively in Duacı site. C storages were 3.63 and 1.18 tonsyear^{-1} ha^{-1} for the corresponding growing areas in Nebiler.

Forest management that aims for maximizing wood production looks for maximum MAI to determine optimal rotation ages. Carbon sequestration is closely related to yield and particularly to the volume increment of a stand. Although rotations shorter than maximum MAI lead to reduced C sequestration, it can provide earlier revenue that could be invested to increase growth (consequently, C storage) in other forests. Thus, longer rotation may both reduce the long-term mean annual wood production and increase the risk of carbon losses, such as through wildfires (Malmsheimer *et al*,, 2011).

Conclusion

As a result of this study, we can conclude that;

— Height growth was greater in closer spacing than in wider spacing in early stages of the plantation sites, namely before inter-tree competition starts. Closer spacing could lead to maximize industrial wood production especially for short rotations. In this context, growth stimulating measures at closely spaced plantations in young ages, namely before inter-tree competition starts, should be exploited. Such measures may include implementing site preparations, herbaceous

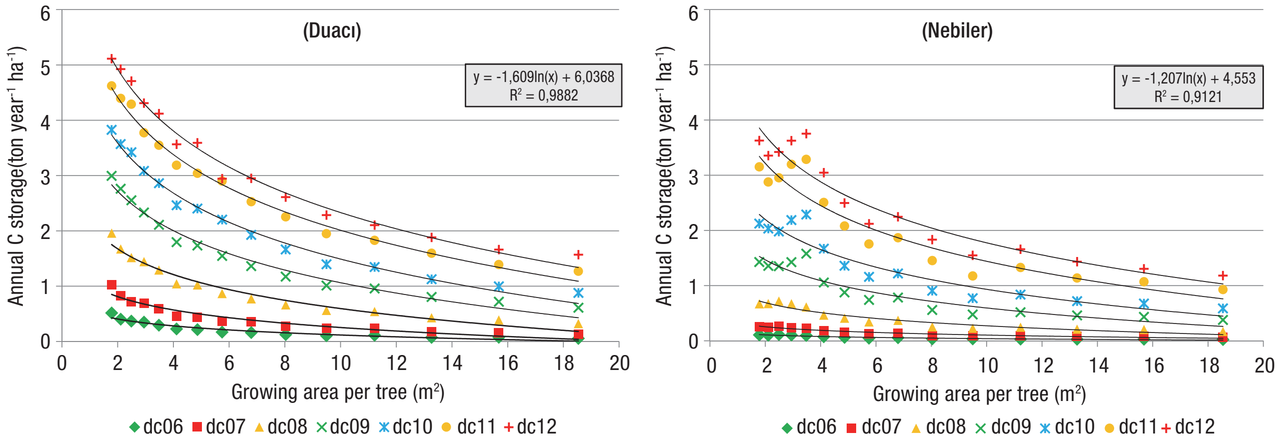

Figure 10. Annual Carbon storage per hectare in tree biomass (above-ground + below-ground) over time from 6th to 12thages, depending on spacing (dc06, dc07, … = annual C storage at age 6, age 7, etc.) (Regression equations and R^2 values are shown only for age 12 in the figures).

weed control and fertilization before the onset of inter-tree competition, each of which alone or in combination would induce considerable increase in mean volume per unit area at final crop.

— Spacing directly affects mean annual increment which is an important criterion to maximize total wood production in even aged stands. Based on the results of this study, quantity of end-product could be increased in short rotation management by controlling initial spacing. If short rotation management objective focuses on realizing industrial wood (i.e. pulpwood or chip wood), more wood could be produced from industrial plantations established with closer spacing. In this context, assuming no thinning, spacings 3.0 × 1.0 m and 3.0 × 1.5 m (3.0 and 4.5 m^2 growing area per tree, respectively), which allow farm machinery use for maintenance and harvesting, would provide more wood production per unit area. We expect that the results of this study would encourage managers for short rotation management in industrial plantations using closer spacing. Even if our results based on nearly square spacing as dictated by Nelder design, for operational reasons such as machinery application in industrial forestry, we would recommend rectangular spacing. Results of several studies evaluating square and rectangular spacings indicate that, as long as individual trees has more or less equal growing area, a ratio of between-row to within-row planting spacing of less than 3:1 does not affect significantly average tree size and yield production (Sharma *et al.*, 2002; DeBell & Harrington, 2002; Amateis *et al.*, 2004; Amateis & Burkhart, 2012).

— Mean annual increment (MAI) can considerably be increased by using improved seed and deep soil cultivation, even without any other silvicultural implementations.

— Carbon sequestration potential, highly related to wood production, explicitly varied depending on spacing. Closer spacings are more effective than that of wider to maximize carbon sequestration along with wood production for short rotation in Turkish red pine plantations.

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References

Amateis RL, Radtke PJ, Hansen GD, 2004. The effect of spacing rectangularity on stem quality in loblolly pine plantations. Can J Forest Res, 34: 498-501. http://dx.doi.org/10.1139/x03-210

Amateis RL, Burkhart HE, 2012. Rotation-age results from a Loblolly Pine spacing trial. Southern J App Forestry, 36: 11-18. http://dx.doi.org/10.5849/sjaf.10-038

As N, Koç H, Doğu, D, Atik C, Aksu B, Erdinler S, 2001. Turkiye'de yetişen endüstriyel öneme sahip agaçların anatomik, fiziksel, mekanik ve kimyasal özellikleri. Istanbul Universitesi, Orman Fakültesi Dergisi, Seri B, 1: 71-88.

Avery TE, Burkhart HE, 1994. Forest Measurement. Fourth edition, McGraw Hill, New York. 408 pp.

Boydak M, 1982. Effects of cultural methods and physiographic factors on growth of pure *Pinus brutia* Ten. plantations at Keşan Region and determination of spacing. Publication of Istanbul University, Forestry Faculty, Turkey. No: 325, 158 pp.

DeBell DS, Harrington CA, 2002. Density and rectangularity of planting influence 20-year growth and development of red alder. Can J Forest Res, 32(7): 1244-1253. http://dx.doi.org/10.1139/x02-040

Eraslan İ, 1983. Hızlı büyüyen agaç türlerinin önemi, tanımı ve Türkiye'de bu türlerle kurulacak plantasyonların potansiyel üretim kapasitesi. Istanbul Universitesi, Orman Fakültesi Dergisi, Turkey. Seri B, 2: 1-27.

Erkan N, 1996. Stand simulation for *Pinus brutia* Ten. (Published in Turkish, summary in English), Souteastern Anatolian Forest Research Institute, Technical Bulletin No: 1, 148 pp.

Harms WR, Whitesell CD, DeBell DS, 2000. Growth and development of loblolly pine in a spacing trial planted in Hawai. Forest Ecol Manag, 126: 13-24. http://dx.doi.org/10.1016/S0378-1127(99)00079-1

Harrington TB, Harrington CA, DeBell DS, 2009. Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). Forest Ecology and Management, 258: 12-25. http://dx.doi.org/10.1016/j.foreco.2009.03.039

Hummel S, 2000. Height, diameter and crown dimensions of *Cordia alliodora* associated with tree density. Forest Ecology and Management, 127: 31-40. http://dx.doi.org/10.1016/S0378-1127(99)00120-6

Husch B, Miller CI, Beers TW, 1982. Forest Mensuration. Third edition, Krieger Pub. Company, Florida. 402 pp.

IPCC, 2001. Climate change 2001: Mitigation. http://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/.

IPCC, 2003. Good practice guidance for land use, land-use change and forestry. In: IGES, Eds. Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, Pipatti R, Buendia L, Miwa K, Ngara T, Tanabe K, Wagner F, IPCC/OECD/IEA/IGES, Hayama, Japan. http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_contents.html.

IPCC, 2006. IPCC Guidelines for national greenhouse gas inventories guidelines for national greenhouse gas inventories. Prepared by the National Greenhouse Gas Inventories Programme, In: IGES, Japan (Eds.: Eggleston HS, Buendia L, Miwa K, Ngara T and Tanabe K). http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.

Işık K, Kara N, 1997. Altitudinal variation in *Pinus brutia* Ten. and its implication in genetic conservation and seed transfers in southern Turkey. *Silvae Genetica* 46 (2-3): 113-120.

Kalıpsız A, 1982. Orman hasılat bilgisi. Ders kitabı, İstanbul Üniversitesi, Orman Fakültesi yayın No:388, Istanbul, Turkey. 349 pp.

Kalıpsız A, 1984. Dendrometri. Ders kitabı. Istanbul Üniversitesi, Orman Fakültesi Yayın No:354, Istanbul, Turkey. 407 pp.

Kerr G, 2003. Effects of spacing on the early growth of planted *Fraxinus excelcior* L. Can J Forest Res, 33: 1196-1207. http://dx.doi.org/10.1139/x03-041.

Knowe SA, Hibbs DE, 1996. Stand structure and dynamics of young red alder as affected by planting density. Forest Ecol Manag, 82: 69-85. http://dx.doi.org/10.1016/0378-1127(95)03690-3.

Konukçu M, 2001. Ormanlar ve ormancılıgımız. DPT Yayın No: 2630, Ankara, Turkey. 238 pp.

Koski V, Antola J, 1993. Turkish national tree breeding and seed production program for Turkey (1994-2003). Prepared with Cooperation ENSO Forest Development Inc. and Research Directorate Forest Tree Seeds and Tree Breeding, Ankara, Turkey. 49 pp.

Laar AV, Akça A, 1997. Forest mensuration. First edition. Cuvillier Verlag, Göttingen, Germany. 418 pp.

Laclau P, 2003, Biomass and carbon sequestration of ponderosa pine plantations and native cypress forests in northwest Patagonia. Forest Ecol Manag, 180: 317-333. http://dx.doi.org/10.1016/S0378-1127(02)00580-7.

Malmsheimer RW, Bowyer JL, Fried JS, Gee E, Izlar RL, Miner RA, Munn IA, Oneil E, Stewart WC, 2011. Managing Forests because Carbon Matters: Integrating Energy, Products, and Land Management Policy, J Forestry 109: Supplement 1, 51 pp.

Nelder JA. 1962. New kinds of systematic designs for spacing experiments. Biometrics, 18: 283-309. http://dx.doi.org/10.2307/2527473.

OGM, 2012. Forest areas in Turkey. General Directorate of Forestry, Forest Management and Planning Department, Publication No: 85, Ankara, Turkey. 28 pp. http://www.ogm.gov.tr/ekutuphane/Yayinlar/T%C3%BCrkiye%20Orman%20Varl%C4%B1%C4%9F%C4%B1.pdf.

OGM, 2013. Report for forestry statistics in Turkey. Unpublished documents, General Directorate of Forestry, Exploitation and Marketing Department, Ankara, Turkey.

Öztürk H, Şıklar S, Alan M, Ezen T, Korkmaz B, Gulbaba AG, Sabuncu R, Tulukcu M, Derilgen SI, 2004. Akdeniz Bölgesi alcak islah zonunda (0-400m) Kizilcam (*Pinus brutia* Ten.) döl denemeleri (4. yas sonuclari). Orman Agaclari ve Tohumlari Islah Arastirma Müdürlügü, Teknik Bülten No: 12, Ankara. 147 pp.

Rais A, Poschenrieder W, Pretzsch H, Kuilen J-WG, 2014. Influence of initial plant density on sawn timber properties for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Ann Forest Sci, 71: 617-626. http://dx.doi.org/10.1007/s13595-014-0362-8.

Scott W, Meade R, Leon R, Hyink D, Miller R, 1998. Planting density and tree-size relations in coast Douglas-fir. Can J Forest Res, 28(1): 74-78. http://dx.doi.org/10.1139/x97-190.

Sharma M, Burkhart HE, Amateis RL, 2002. Modeling the effect of density on the growth of loblolly pine trees. Southern J Appl Forestry, 26: 124-133.

SPSS Inc. (2015) SPSS 22.0 Guide to Data Analysis, Published by Prentice Hall, Upper Saddle River, New Jersey, USA. 637 pp.

Stape JL, Binkley D, 2010. Insights from full-rotation Nelder spacing trials with *Eucalyptus* in Sao Paulo, Brasil. Southern Forests, 72(2): 91-98. http://dx.doi.org/10.2989/20702620.2010.507031.

Sun O, Uğurlu S, Özer E, 1980. Kızılçam (*P. brutia* Ten.) Türüne ait biyolojik kütlenin saptanması. Ormancılık Araştırma Enstitüsü Yayınlari, Teknik Bulten Serisi No: 104, 32 pp.

Timothy BH, Harrington CA, DeBell DS, 2009. Effects of planting spacing and site quality on 25-year growth and mortality relationships of Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*). Forest Ecol Manag, 258(1): 18-25. http://dx.doi.org/10.1016/j.foreco.2009.03.039.

TSMS, 2015. Meteorological data from Turkish State Meteorological Service. http://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m=ANTALYA.

Usta HZ, 1991. A study on the yield of *Pinus brutia* Ten. Plantations, (Published in Turkish, summary in English), Turkish Forest Research Institute, Technical Bulletin No: 219, 138 pp.

Ürgenç S, 1986. Ağaçlandırma tekniği. Istanbul Universitesi, Orman Fakültesi, Yayın No: 375, Istanbul. 507 pp.

Westfall JA, Burkhart HE, Allen L, 2004. Young stand growth modeling for intensively-managed Loblolly Pine plantations in Southeastern U.S. Forest Science, 50(6): 823-835.

Zhang S, Burkhart HE, Amateis RL, 1996. Modeling individual tree growth for juvenile loblolly pine plantations. Forest Ecol Manag, 89: 157-172. http://dx.doi.org/10.1016/S0378-1127(96)03851-0.