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Onset of canopy closure for black pine, Turkish red pine and Scots pine forests

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Abstract

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Canopy closure plays an important role in regeneration and management activities in forestry. Thus, determining the density at which canopy closure occurs is important for the success of silvicultural treatments. Turkish red pine (*Pinus brutia* Tenore), black pine (*Pinus nigra* J.F. Arnold) and Scots pine (*Pinus sylvestris* Linnaeus) forests are usually managed at a density that is near or below the canopy closure. Residual stand density during the management of these species is commonly described by stand basal area – BA ($m^2 \cdot ha^{-1}$), however, the BA levels for the canopy closure have not been clearly indicated for these species. The minimum density for the onset of canopy closure (D_{OCC}) was determined for Turkish red pine, black pine and Scots pine forests in this study. D_{OCC} values were compared across the species. For the D_{OCC}, the maximum tree area that a tree can occupy under open-grown conditions was used. The D_{OCC} curves of black pine and Scots pine seem to be similar, but the canopy closure in Turkish red pine forests occurs with fewer trees per hectare for a given mean tree diameter. According to the D_{OCC} curves, regeneration and tending activities will be more practical and effective in these forests.

Keywords: *Pinus brutia*; *Pinus nigra*; *Pinus sylvestris*; silviculture; stand density

Turkish red pine (*Pinus brutia* Tenore), black pine (*Pinus nigra* J.F. Arnold) and Scots pine (*Pinus sylvestris* Linnaeus) are three main native tree species in Turkey, and they are economically and ecologically important in Turkish forestry (Boydak et al. 2006; Ertekin, Özel 2010). These species have large distribution areas in Turkey (Gülcü, Çelik 2009). The species can be found as pure stands, as well as mixed with each other and with other tree species in Turkey (General Directorate of Forestry 2014). They cover approximately a 12,030.000-ha area which is 55% of the total forested land in the country (General Directorate of Forestry 2014). In addition, Turkish red pine, black pine and Scots pine are among the most commonly used tree species in large plantations throughout Turkey (Öner 2003; Avsar 2004; Ertekin, Özel 2010).

Turkish red pine, black pine and Scots pine are considered as shade-intolerant species, thus, they are commonly managed by silvicultural methods such as clearcutting and shelterwood methods that require relatively low densities. Under these methods, absolute measures of stand density such as basal area – BA ($m^2 \cdot ha^{-1}$) or number of trees per hectare (TPH) are usually employed to describe the target stand densities (Odabaşi et al. 2004). However, available growing space at a given BA or TPH may vary with mean DBH of the stand (Gingrich 1967). For example, a stand with larger DBH represents lower stocking than a stand with smaller DBH

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at a given BA (Goelz 1995; Martin 1996). Therefore, it is likely that canopy closure may play a more important role during regeneration and management activities, and BA and TPH alone may not be a good indicator of canopy closure. For the regeneration and management of shade-intolerant species such as Turkish red pine, black pine and Scots pine, it is essential to know the density for the onset of canopy closure (D_{OCC}).

TPH and individual tree size are strongly related; the smaller the tree size, the higher the number of trees that can potentially occupy a site (Zeide 1995). As open-grown trees develop the largest crown possible relative to their DBH (Krajicek et al. 1961), they can be used to determine the maximum area that a tree can occupy. In other words, relationships which are very strong between crown width (CW) and DBH of open-grown trees are used to determine the D_{OCC}. Age and site quality are not recorded (Smith et al. 1992) since these variables have no influence on tree area (Chisman, Schumacher 1940; Gingrich 1967).

Given the importance of canopy closure on the successful regeneration and management of Turkish red pine, black pine and Scots pine, the determination of the D_{OCC} for these species seems to be highly required. Thus, our research aimed to define and compare the D_{OCC} for Turkish red pine, black pine and Scots pine forests. The relationships between CW and DBH for these tree species were quantified and compared. Using the D_{OCC}, the amount of available light for the new regeneration and residual stand may be anticipated. The D_{OCC} will help forest managers to regenerate and manage their forests successfully and effectively.

MATERIAL AND METHODS

Tree selection. Turkish red pine, black pine and Scots pine were chosen for their commercial importance in Turkey (Gezer 1986). In order to determine the D_{OCC} for these three pine species, open-grown trees that were free of competition were found for each species. All open-grown trees were measured within the city of Kastamonu in Turkey. It should be noted that age and site quality have no influence on the relationship between DBH and CW of open-grown trees (Chisman, Schumacher 1940). Trees with straight trunk and uniform crown were selected as suggested by Smith et al. (1992). When a sign of inter-tree competition was suspected (for example, if there was an old stump near the measured tree), the open-grown tree was cored to see if any growth suppression occurred during the lifespan of the tree. When a previous crown competition of a tree was detected, the tree was excluded from the analysis.

Data collection and model selection. The maximum crown width (CW_{max}) and DBH of open-grown Turkish red pine, black pine and Scots pine trees were recorded as suggested by Smith et al. (1992). First, the widest part of the crown (i.e. CW_{max}) was measured. Then, the second crown measurement was taken perpendicular to the first one. Averages of these two crown measurements were used to determine the crown area of the tree. In addition, DBH of each open-grown tree was recorded to the nearest 0.25 mm (Table 1).

Four different equations for each species were used to fit CW_{max} to DBH (Table 2). Linear relationship, curvilinear relationship, power relationship and logarithmic relationship have been applied to determine the relationships between CW and DBH for several tree species (Harry et al. 1964; Ek 1974; Paine, Hann 1982; Hasenauer 1997). In this study, we compared the four common equations (Table 2) for each species based on their coefficient of determination (R^2), and selected the one with the highest R^2.

Minimum density for onset of canopy closure. For the D_{OCC} of each species, the maximum tree area that a tree can occupy under open-grown conditions is used because the vertical projection of an open-grown tree is considered to be circular (Krajicek et al. 1961). Using the best equation

Table 1. Basic variables of open-grown trees by species

Species	Number	Variable	Maximum	Minimum	Mean	SD
Black pine	68	CW (m)	11.5	1.5	5.6	2.9
		DBH (cm)	56.7	3.3	24.7	15.4
Turkish red pine	68	CW (m)	12.6	1.6	6.2	2.5
		DBH (cm)	62.6	2.5	24.3	14.7
Scots pine	45	CW (m)	10.7	1.6	5.4	2.5
		DBH (cm)	58.6	3.2	23.7	13.7

CW – crown width, SD – standard deviation

Table 2. Equations used in the analysis of open-grown trees

Model	Equation
1 (linear)	$CW = b_0 + b_1(DBH)$
2 (curvilinear)	$CW = b_0 + b_1(DBH) + b_2(DBH^2)$
3 (power)	$CW = b_0 + b_1(DBH^{b_2})$
4 (logarithmic)	$\log(CW) = b_0 + b_1 \log(DBH)$

CW – crown width, b_0, b_1, b_2 – model coefficients

among the models developed, for each 5 cm DBH class, a CW_{max} was calculated in meters for each species. Next, using Eq. 1, the D_{OCC} was determined for each CW_{max} for each species. Finally, BA for each D_{OCC} was calculated using Eq. 2 for each species. A reference curve for the D_{OCC} of each species was developed:

$$D_{OCC} = \frac{10,000}{CW_{max} 2(\Pi/4)} \quad (1)$$

$$BA = QMD^2(0.00007854)D_{OCC} \quad (2)$$

where:

QMD – quadratic mean diameter.

RESULTS

The coefficients of determination suggested that there was a curvilinear relationship between CW and DBH of black pine and Scots pine (Table 3, Fig. 1) while the plot of CW against DBH suggested a power relationship for Turkish red pine (Table 3, Fig. 1). The selected equations had R^2 higher than 0.93 (Table 3). The logarithmic models had the smallest R^2 for all three species. In addition, apart from the other models, only the logarithmic models gave negative intercepts.

The D_{OCC} curves are presented for black pine, Turkish red pine and Scots pine in Figs 2a–c, re-

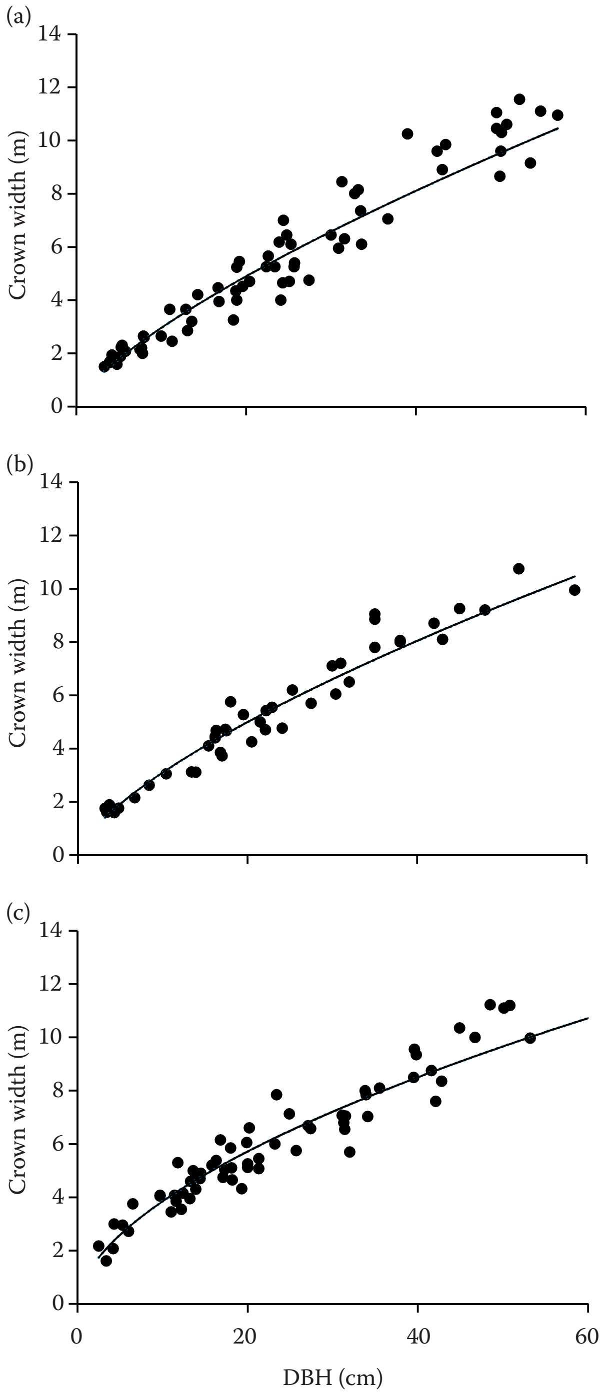

Fig. 1. The relationship between mean crown width and DBH for *Pinus nigra* J.F. Arnold (a), *Pinus sylvestris* Linnaeus (b), *Pinus brutia* Tenore (c)

Table 3. The equations selected for the relationships between CW and DBH for each species

Species	Equation	R^2
Black pine	$CW = 0.8168 + 0.2028(DBH) - 0.0003(DBH^2)$	0.94
Turkish red pine	$CW = 1.6289 + 0.298(DBH^{0.8594})$	0.93
Scots pine	$CW = 0.6874 + 0.2358(DBH) - 0.0011(DBH^2)$	0.95

CW – crown width, R^2 – coefficient of determination spectively. The figures can be used to determine the density (i.e. BA) at which canopy closure occurs for a given TPH. The numbers along the curves indicate the average tree diameter of a stand. For example, in a black pine stand with TPH of 600, canopy closure occurs at approximately 17.0 $m^2 \cdot ha^{-1}$ of BA (Fig. 2a), and average tree diameter of the stand becomes around 19 cm (Fig. 2a). The D_{OCC} line for black pine ranges from 12 to 24 $m^2 \cdot ha^{-1}$ of BA (Fig. 2a) while it ranged from 7 to 24 $m^2 \cdot ha^{-1}$ and from 11 to 26 $m^2 \cdot ha^{-1}$ of BA for Turkish red pine (Fig. 2b) and Scots pine (Fig. 2c), respectively.

The D_{OCC} curves of black pine and Scots pine seem to be similar (Fig. 3). However, the curve of Scots pine is becoming steeper with the increasing tree diameter (Fig. 3). This suggests that the relationship between DBH and CW of open-grown Scots pine trees is not linear. In our study, we selected a curvilinear equation for fitting, as can be seen in Fig. 1. The growth rate of CW of open-grown Scots pines is reduced with increasing DBH, and consequently it makes the D_{OCC} curve steeper for Scots pine. In other words, in comparison with Scots pine, the growth rate in the CW of large diameter open-grown black pine trees is higher (Fig. 1).

Compared to black pine and Scots pine, canopy closure in Turkish red pine forests occurs with fewer trees per hectare for a given average tree diameter (Fig. 3). For example, there should be around 900 trees per hectare with an average tree diameter of 10 cm for canopy closure to occur in Turkish red pine stands, while black pine and Scots pine require at least 1,500 TPH with the same average tree diameter (i.e. 10 cm) for full canopy closure (Fig. 3). This comparison suggests that open-grown Turkish red pine trees develop the larger crown area than black pine and Scots pine, and provide full canopy closure with fewer trees.

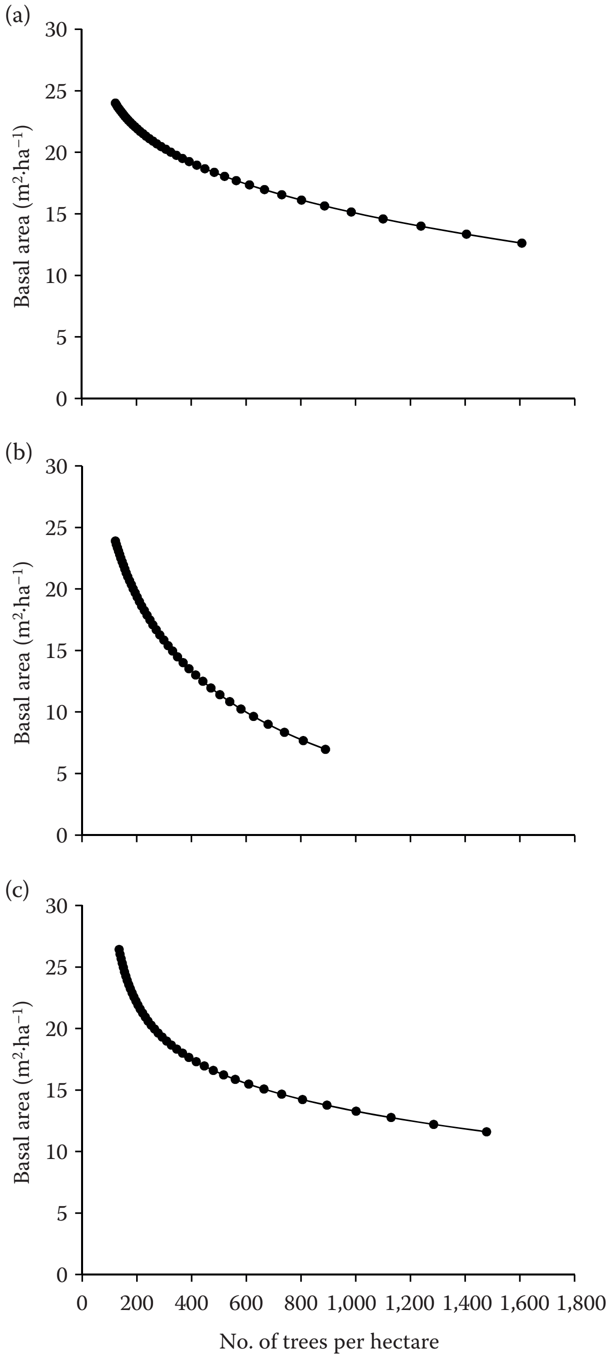

Fig. 2. Minimum density for the onset of canopy closure for *Pinus nigra* J.F. Arnold (a), *Pinus brutia* Tenore (b), *Pinus sylvestris* Linnaeus (c)

DISCUSSION

As stated above, there was a curvilinear relationship between CW and DBH of black pine and Scots pine, and a power relationship for Turkish red pine. The curvilinear and power models have been commonly used for other pine species when fit-

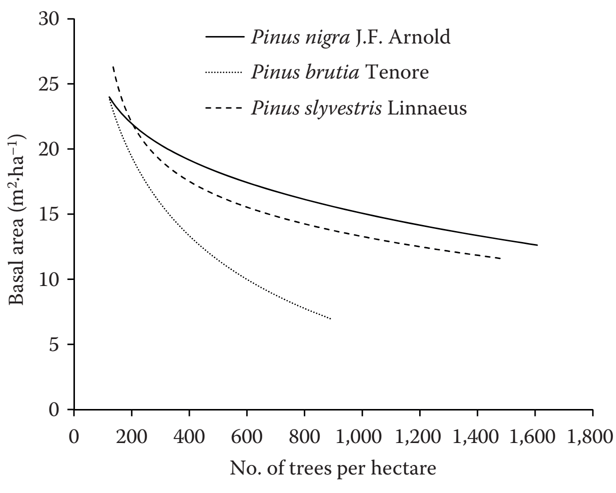

Fig. 3. Comparison of density for the onset of canopy closure among species

ting CW-DBH data. Ek (1974) used a power model for the CW-DBH relationships for Eastern white pine (*Pinus strobus* Linnaeus). In a similar study, Smith et al. (1992) found out a curvilinear relationship between CW and DBH for loblolly pine (*Pinus taeda* Linnaeus) in the USA. Hasenauer (1997) observed relationships between CW and DBH of open-grown Scots pine and black pine in Austria, however, their intercepts for both species were negative. Smith et al. (1992) stated that the relationship between CW and DBH should have a positive intercept, as it was obtained when curvilinear and power models were used in this study (Table 3). On the other hand, Hasenauer (1997) stated that a logarithmic model improved the error structure significantly. Although both linear and nonlinear regressions have been used for predicting CW-DBH relationships (Harry et al. 1964; Ek 1974; Paine, Hann 1982; Hasenauer 1997), Leech (1984) found out that the differences between linear and non-linear CW-DBH relationships were not statistically significant. Therefore, the equations selected for black pine, Turkish red pine and Scots pine seem to correspond to real relationships between variables.

The CW of open-grown trees is used to determine the maximum tree area that a tree can occupy under open-grown conditions (Krajicek et al. 1961). The number of trees per unit area is best predicted by the measurement of the CW of open-grown trees (Yang, Titus 2002). The CW and diameter of open-grown trees are strongly correlated, and their measurement error is usually small (Zeide 1987; Yang, Titus 2002). Sixty-eight open-grown trees were measured for black pine and Turkish red pine while the number of open-grown trees for Scots pine was 45. Given the number of open-grown trees used to determine the relationship between CW and DBH for different tree species (Harry et al. 1964; Ek 1974; Paine, Hann 1982; Hasenauer 1997), 68 and 45 open-grown trees measured in this study seem to be acceptable.

As it has been observed for other species (Gingrich 1967; Hasenauer 1997; Larsen et al. 2010), D_{OCC} curves for black pine, Turkish red pine and Scots pine presented an exponential pattern (Fig. 2a–c). The D_{OCC} curves of black pine and Scots pine seemed to be similar (Fig. 3). In a similar study conducted in Austria, Hasenauer (1997) revealed that these two species represented a similar pattern in terms of CW-DBH relationships.

The comparison of the three pine species suggested that open-grown Turkish red pine trees develop a larger crown area than black pine and Scots pine. This can be associated with the faster growth rate of Turkish red pine (Gezer 1986). In addition, the D_{OCC} curve of Turkish red pine is much steeper than the curves of the other two pine species suggesting that an expansion of the crown area of open-grown Turkish red pine is much slower for the larger tree diameters. Light demand of Turkish red pine is higher than that of black pine and Scots pine (Gezer 1986). Richardson (1998) stated that the tree density of light-demanding trees such as Turkish red pine sharply decreased with increasing average tree diameter suggesting that a tree area is getting smaller with increasing average tree diameter. This statement substantiates our finding that the D_{OCC} curve of Turkish red pine is much steeper than in the other two pine species.

In practice, BA and TPH are commonly used when prescribing the residual stand density. However, D_{OCC} seems to be essential when regenerating and managing shade-intolerant tree species. The D_{OCC} curves will be a handy tool for the management of black pine, Turkish red pine and Scots pine forests within their natural range. As a result, growing space could be more effectively allocated to achieve specific objectives including regeneration, timber production, thinning and wildlife purposes.

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