


Influence of stand density and canopy structure on the germination and growth of Scots pine (*Pinus sylvestris* L.) seedlings

Ferhat Kara  · Osman Topaçoğlu

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Abstract Since the natural regeneration of Scots pine forests is known to be difficult, the effects of canopy structure and environmental variables such as light on germination, seedling growth, and mortality need to be well understood. The knowledge on the relationships between canopy structure, environmental variables, and seedling growth have been helpful for forest managers to formulate silvicultural prescriptions that enhance seedling recruitment. In this study, the influences of stand basal area (BA) ($\text{m}^2 \text{ha}^{-1}$), leaf area index (LAI), light transmittance (LT), and height-to-crown base (HCB) on germination and seedling growth were explored in a naturally regenerated Scots pine forest in Kastamonu, Turkey. The number of germinants was observed following germination, and total root-collar diameter (RCD) and height of seedlings were monitored after five growing seasons following germination. BA, LAI, LT, and HCB were also examined to determine which variable has more influence on Scots pine seedlings. All variables (i.e., BA, LAI, LT, and HCB) had significant influence on the total seedling growth over a 5-year period. LT was the most significant predictor for total RCD growth and height growth of Scots pine seedlings. The data support the importance of light transmittance through the canopy, along with vertical

canopy structure (i.e., HCB) when considering seedling development under a stand canopy.

Keywords Forest structure · Natural regeneration · *Pinus sylvestris* L. · Shelterwood · Silviculture

Introduction

Scots pine (*Pinus sylvestris* L.) has been one of the most economically important tree species in Turkish forestry due to its high-quality timber as well as its wide distribution in the country (Boydak et al. 2011). The species cover about 1.5-million-ha area, which is equivalent to 7% of the total forested land in Turkey (Anonymous 2014). Due to the difficulties with natural regeneration of Scots pine forests (Nilsson and Zackrisson 1992; Hille and Den Ouden 2004), understanding the factors that affect the success of natural regeneration of the current Scots pine forests is essential. In addition, since Scots pine is one of the most planted tree species throughout Turkey (Öner 2003), its early growth and survival are also vital for successful artificial regeneration activities.

For a successful recruitment and establishment of Scots pine, the factors that influence germination, seedling growth, and mortality must be well understood (Hille and Den Ouden 2004). The interactions among the environmental variables influence growth and mortality of forest reproduction (Mason et al. 2004). These environmental factors are affected by stand density such as basal area (BA) ($\text{m}^2 \text{ha}^{-1}$) and forest canopy

F. Kara (✉) · O. Topaçoğlu
Faculty of Forestry, Kastamonu University, 37100 Kastamonu,
Turkey
e-mail: fkara@kastamonu.edu.tr

structures (Assenac 2000; Lhotka and Loewenstein 2008). Thus, the knowledge on the mutual relationships among stand density (i.e., BA), canopy structure, environment, and seedlings help to describe the response of seedlings to a given silvicultural treatment, and as a result, forest managers can modify seedling response through structural manipulations (Lhotka and Loewenstein 2008). Research on the response of Scots pine seedlings in understory to stand BA and canopy structure has been limited (Gaudio et al. 2011).

The complex interactions between the environment and trees can be better explained via quantitative terms (Fang and Bailey 2001; Timilsina and Staudhammer 2012). It has been stated that quantitative relationships between stand structure and seedling growth are especially important for species that are maintained through partial canopies (Brandeis et al. 2001; Pardos et al. 2007). Scots pine is a shade-intolerant tree species (Richardson 1998); thus, the regeneration success and growth of the species are usually associated with partial canopy structures that are commonly created when using the shelterwood method (Odabaşı et al. 2004). Forest managers can formulate silvicultural prescriptions that enhance seedling recruitment under forest canopies using quantitative models that address the relationship between stand structure and seedling growth (Hsu et al. 1984). In addition, understanding the relationship between stand BA, canopy structure, and seedling growth will also promote the establishment of seedlings planted under the forest canopy through artificial regeneration (Lhotka and Loewenstein 2008). Therefore, quantitative relationships that relate stand structure to seedling growth are needed in order to define appropriate residual stand densities for Scots pine forests.

Stand BA is commonly used as a measure of stand density, and it may hinder the germination and growth of seedlings (Kara et al. 2017). In addition, Lhotka and Loewenstein (2008) stated that vertical metrics such as height-to-crown base (HCB) could also affect seedling growth and establishment under the canopy. Light transmittance (LT) under forest canopy is another factor that influences germination and seedling growth, and it is usually associated with leaf area index (LAI) (Bréda and Granier 1996). LAI is known to be a strong parameter used for the analysis of stand structure (Bréda and Granier 1996). Thus, this study incorporates a stand density measure (i.e., BA) and three canopy structural variables, i.e., LAI, LT, and HCB. The natural

regeneration of Scots pine has been widely studied (Castro et al. 2004; Pardos et al. 2007; Barbeito et al. 2009; Gerelbaatar et al. 2015); however, BA, LAI, LT, and HCB explained via quantitative terms have rarely been taken into consideration. Therefore, the main objectives of this study are to determine (i) the relationships between the number of Scots pine germinants and stand BA and canopy structure variables (i.e., BA, LAI, LT, and HCB), and (ii) the relationships between seedling growth and the same variables in Scots pine forests following natural regeneration. This study also aimed to examine BA, LAI, LT, and HCB to determine which variable has more influence on Scots pine seedlings.

Material and methods

Study site

This study was conducted within the Kastamonu Regional Forest Directorate (KRFD) located in Kastamonu City, northern Turkey (Fig. 1). The study area is located within the Euro-Siberian bio-geographic region (Çolak et al. 2009) and within the natural range of Scots pine. A temperate Black Sea climate with cold/wet winters and rainy/wet summers is typical within the region. The average annual precipitation is approximately 580 mm, while the average temperature of the study area is 9.7 °C. The dominant soil type is loamy clay in the study area. The slopes range from 0 to 20% across the study site. Elevation ranges from about 700 to 800 m above sea level. The understory is mainly composed of oak (*Quercus robur* L.), blackberry (*Rubus* spp.), and ferns (*Pteridium aquilinum*).

The study was conducted in a 27-ha, pure, and even-aged Scots pine forest which is managed by Karadere Forest Planning Unit in KRFD. Scots pine BA was 90% or more of total BA in the study forest. The initial average stand BA was approximately 32.3 m² ha⁻¹ within the study forest, and the forest was composed mostly of trees larger than 36 cm in diameter at breast height (DBH). Prior to harvesting, advance Scots pine reproduction was virtually absent or very low across the area. Since it has been suggested that the shelterwood is successful for the regeneration of Scots pine forests (Pardos et al. 2007), the study area was regenerated utilizing this method. Average stand BA was reduced to about 17.2 m² ha⁻¹ (equivalent to 47%) in 2011, which was a good seed crop year in the region. To

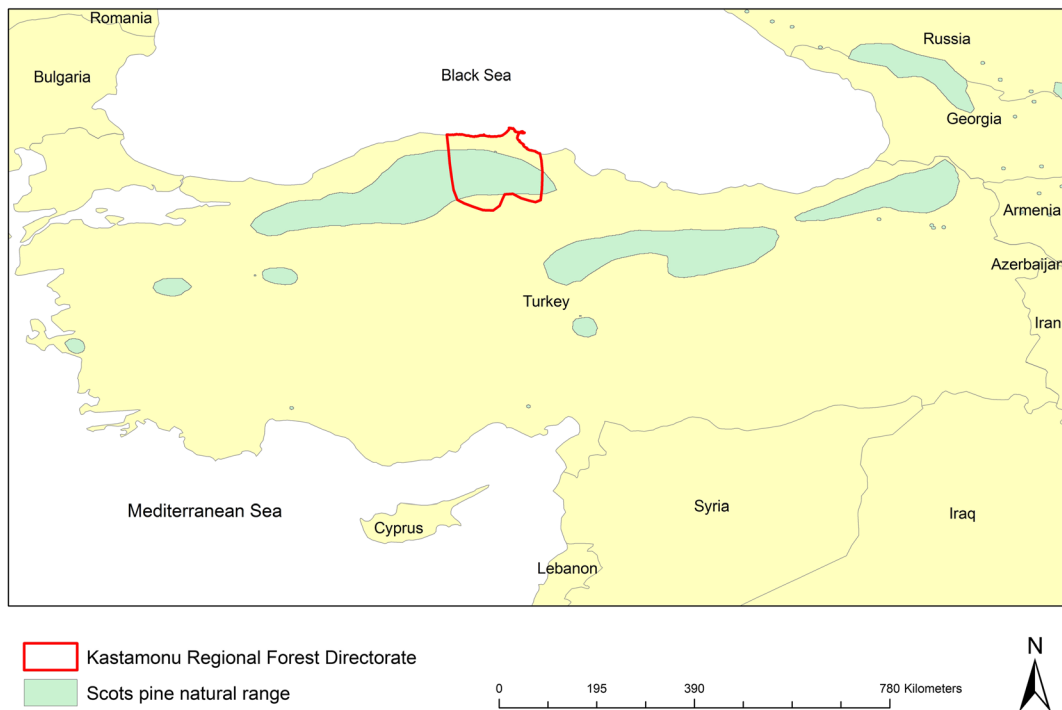


Fig. 1 Natural disturbance range of Scots pine within Turkey and boundary of Kastamonu Regional Forest Directorate

control the competitive vegetation in the regeneration area, understory vegetation cover was removed by mechanical methods using mini-excavators after the harvesting operations and before the seed fall. While removing the understory vegetation, it was also aimed to expose mineral soil and facilitate germination. Special care was given to mitigate soil disturbance during the operation of the mini-excavators.

Study design and measurements

Following the harvesting operations and understory vegetation removal, 30 100-m² (10 × 10 m) square study plots were randomly established within the natural regeneration area in 2011. All trees larger than 5 cm in DBH were measured within each plot, and stand BA was calculated for each plot using the DBH measurements. Each study plot also contained three 1-m² circular quadrats that were randomly placed within the plots. It should be noted that LAI, LT, and HCB measurements were taken within the 1-m² quadrats, and they were averaged to determine the LAI, LT, and HCB of each plot. In addition, the number of germinants and RCD and height growth of seedlings for each study plot were also estimated by the averages of the measurements

conducted in three 1-m² quadrats. It means that there were 30 replications for each variable.

HCB measurements were taken using a TruPulse Laser Rangefinder (Laser Tech Inc.) within the three 1-m² quadrats and averaged. HCB refers to the vertical distance (m) from the ground to the first living green branch of tree crown (Lhotka and Loewenstein 2008). LAI and photosynthetically active radiation (PAR) were measured using a CI-110 Plant Canopy Imager (CID Bio-Science Inc., WA, USA) within the three 1-m² quadrats and averaged. The CI-110 takes an image of overhead cover within a 150° fish-eye view from which LAI is calculated (Geiger et al. 2011). Within each quadrat, an image was taken above the seedlings under the canopy, on nearly cloudless days between 11:00 am and 2:00 pm. The sensors on the CI-110 also measured the PAR in each quadrat, and they were averaged to determine average PAR for each plot. LT (%) through canopy was calculated using the following equation after the PAR measurements taken under the canopy and in an open area (Kara et al. 2017):

$$LT (\%) = \frac{\text{Average PAR under canopy}}{\text{PAR in open area}} \times 100$$

The number of new germinants was counted within each quadrat following the germination period in 2012, and they were individually marked. Additional germinations after 2012 were few or none, and they were not included in the analysis. At the end of the fifth growing season (August 2017), the number of seedlings were re-counted to determine the reduction of seedling densities over 5 years. In addition, the root-collar diameter (RCD) (mm) of seedlings from 2012 was measured in 2017 in order to record their total RCD growth over 5 years. Moreover, at the end of the fifth growing season (August 2017), the height of each seedling from 2012 was also measured in order to determine the total height growth of seedlings over 5 years. Within each quadrat, the understory vegetation cover was visually estimated as a percentage. The aspect of each plot was also determined using a hand compass.

Analysis

Total RCD growth and height growth data were log-transformed to improve residual homogeneity and normality (McDonald 2014). The influences of BA, LAI, LT, and HCB on the number of germinants for the first growing season was found using Poisson regression, while their influences on the total RCD growth and total height growth over five growing seasons were determined using random-effect model which incorporated plots as random effect. Normality and homogeneity of variance were checked using residual analysis. R-Statistical software (R Development Core Team 2010) was used for the analyses.

In order to determine which variable has more influence on Scots pine seedlings, the effect of each independent variable on the dependent variable were compared based on their standardized regression coefficient estimates (β s). It has been stated that the larger absolute value of β refers to a larger effect, and a higher contribution of the independent variable to the prediction of the dependent variable (Bring 1994). If a comparison of the effects of different independent variables with different units within one sample is intended, standardization is recommended in order to facilitate the interpretation (Hox 2002). In addition to magnitude of the relationship between the dependent and independent variables determined using β s, Akaike information criteria (AIC), which aims to compare different models on a given outcome based on an AIC score (AICs) (Snipes and Taylor 2014), was also utilized to evaluate

model fits. The best models are defined with the lowest AICs as suggested (Arnold 2010). Moreover, Akaike weight, which refers to the relative likelihood of a model, was calculated for each model (Snipes and Taylor 2014). The “standardize” and “AIC” functions in the R-Statistical software (R Development Core Team 2010) were utilized for the standardization of the model coefficients and AICs of models, respectively.

Results

BA, LAI, LT, and HCB ranged from 6.3 to 24.6 m² ha⁻¹, from 0.24 to 1.7, from 5.2 to 61.2, and from 4.1 to 16 m, respectively, across all study plots. The amount of light reaching the forest floor ranged from 100 to 1350 $\mu\text{mol m}^{-2} \text{s}^{-1}$ across all study plots. A summary of the canopy structure variables is presented in Table 1. There was a statistically significant relationship between BA and LAI ($p < 0.0001$, $R^2 = 0.56$); LAI increased with increasing BA suggesting that trees develop larger crowns when their DBH increases and, consequently, have a greater LAI (Fig. 2). In addition, a significant inverse relationship was observed between BA and LT ($p < 0.0001$, $R^2 = 0.54$) and between LAI and LT ($p < 0.0001$, $R^2 = 0.68$) (Fig. 2). LT increased with decreasing BA and LAI across all the study plots (Fig. 2). There was no statistically significant relationship between HCB and other variables (i.e., BA, LAI, and LT) ($p > 0.05$). The average understory vegetation cover ranged from 20 to 95% across all the study plots.

Density of germinants

The number of germinants per hectare ranged from 3000 to 33,000 following the germination period (2012) across all the study plots. The average number

Table 1 Descriptive statistics for basal area (BA) (m² ha⁻¹), leaf area index (LAI), height-to-crown base (HCB) (m), and light transmittance (LT) of the study plots. SD refers to the standard deviation of the variables

Variables	Min.	Max.	Mean	SD
BA	6.3	24.6	17.2	4.9
LAI	0.24	1.7	0.8	0.3
LT	5.2	61.2	32	20.4
HCB	3.3	16	8.9	3.3

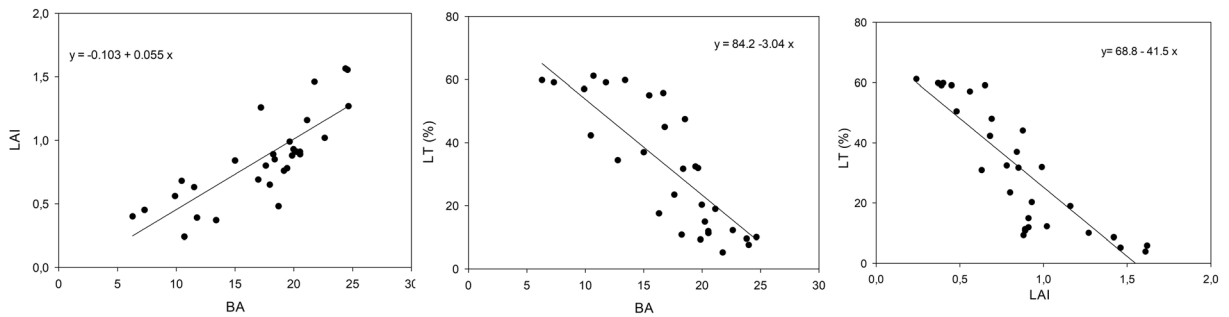


Fig. 2 Relationship between basal area (BA) ($\text{m}^2 \text{ha}^{-1}$), leaf area index (LAI), and light transmittance (LT) (%)

of germinants per hectare was 15,800 within the study area. At the end of the fifth growing season, the average number of seedlings per hectare was approximately 7000 showing that about 44% of the germinants survived five growing seasons. Influences of BA ($p < 0.0001$), LAI ($p < 0.0001$), and LT ($p < 0.0001$) on the number of Scots pine germinants were statistically significant (Table 2). The number of germinants was inversely related to BA and LAI; it increased with decreasing BA and LAI (i.e., with increasing LT) across the study plots, suggesting that light plays an important role on Scots pine seed germination. HCB had no significant influence on the number of germinants across all the study plots ($p = 0.60$). There was no statistical relationship between vegetation cover and the number of germinants across the study plots ($p > 0.05$). Aspect had no significant influence on the number of germinants across all the study plots either ($p > 0.05$). Based on the standardized regression coefficient estimates of BA, LAI, and LT, it was found that the influence of LT ($\beta = 0.86$) on the number of germinants was relatively higher than the influence of BA ($\beta = 0.72$) and LAI ($\beta = 0.79$) after five growing seasons. Moreover, the model with LT seemed to be the best model given its AICs (AICs = 599.68), and it received 57% of the total weight (Table 2).

Seedling growth

The average RCD during five growing seasons was 9.94 mm across all study plots and ranged from 4.1 to 16.85 mm. There were statistically significant relationships between total RCD of Scots pine seedlings and (1) BA ($p < 0.0001$), (2) LAI ($p < 0.0001$), and LT ($p < 0.0001$) (Table 2). Total RCD growth over 5 years increased with decreasing LAI and BA, while it increased with increasing LT and HCB across the study plots (Table 3). These findings suggest that light plays an important role on the RCD growth of natural Scots pine seedlings. Based on the standardized regression coefficient estimates of BA, LAI, LT, and HCB, it was found that the influence of LT ($\beta = 0.78$), HCB ($\beta = 0.78$) and LAI ($\beta = 0.76$) on the total RCD growth of Scots pine seedlings was similar and was higher than the influence of BA ($\beta = 0.45$) after five growing seasons (Table 3). In addition, the model that included LT was the best model given its AICs (AICs = 131.81), and it represented 64% of the total weight (Table 3).

Total height of seedlings following five growing seasons ranged from 22 to 57 cm, while the average height growth was 37.5 cm. Total height growth of natural Scots pine seedlings over 5 years increased with decreasing LAI and BA. The total height increased with increasing LT and HCB across the study plots,

Table 2 Relationships between the number of Scots pine germinants (N_G) and (1) BA, (2) LAI, and (3) LT (%). b_0 and b_1 are coefficients. SE is standard error. β is standardized regression coefficient estimates. AICs is Akaike information criteria score

Regression models	b_0	b_1	SE	R^2	β	p value	AICs	Akaike weight
$N_G = b_0 - b_1 \cdot \text{BA}$	50,391	-1722	5641	0.52	0.72	< 0.0001	605.98	0.0244
$N_G = b_0 - b_1 \cdot \text{LAI}$	29,501	-15,934	5060	0.62	0.79	< 0.0001	600.80	0.4056
$N_G = b_0 - b_1 \cdot \text{LT}$	4621.8	341.1	4854	0.65	0.86	< 0.0001	599.68	0.5699
$N_G = b_0 - b_1 \cdot \text{HCB}$	18,399.7	-237.7	8251	0.01	0.13	0.60	630.59	0.0001

Table 3 Relationships between the total RCD growth of Scots pine seedlings and (1) BA, (2) LAI, (3) LT (%), and (4) HCB. b_0 and b_1 are coefficients. SE is standard error. β is standardized regression coefficient estimates. AICs is Akaike information criteria score

Regression models	b_0	b_1	SE	R^2	β	p value	AICs	Akaike weight
RCD = $b_0 - b_1$.BA	17.3	-0.42	2.40	0.45	0.45	<0.0001	141.72	0.0036
RCD = $b_0 - b_1$.LAI	15.5	-6.54	2.07	0.59	0.76	<0.0001	133.30	0.3054
RCD = $b_0 - b_1$.LT	6.13	0.12	2.02	0.61	0.78	<0.0001	131.81	0.6432
RCD = $b_0 - b_1$.HCB	3.02	0.75	1.86	0.66	0.78	<0.0001	137.01	0.0478

suggesting that light plays a crucial role on height growth. Based on the standardized regression coefficient estimates of BA, LAI, LT, and HCB, it was found that the influence of LT on the total height of seedlings after five growing seasons was the highest ($\beta=0.78$) and followed by LAI ($\beta=0.76$) and HCB ($\beta=0.78$). The influence of BA on the total height of seedlings was the lowest ($\beta=0.47$). Neither understory vegetation cover nor aspect had a significant influence on the total RCD growth and height growth of Scots pine seedlings over the 5-year period across all the study plots ($p>0.05$) (Table 4). Among the models examined, the model with LT was defined as the best model given its AICs (AICs = 183.63), and it received 93% of the total weight (Table 2).

Discussion

Density of germinants

LT was the most significant predictor on number of Scots pine germinants (Table 2). Pardos et al. (2007) found that light transmittance ranged from 50 to 1800 $\mu\text{mol m}^{-2} \text{s}^{-1}$ in a Scots pine stand regenerated using the shelterwood method. Similarly, in this study, the amount of light reaching the forest floor ranged from 100 to 1350 $\mu\text{mol m}^{-2} \text{s}^{-1}$. In this study, it was found that the germination of Scots pine was mostly stimulated

by light transmittance, as observed in other studies in the literature (Haack 1912; Pardos et al. 2007; Barbeito et al. 2009). Several studies have monitored the influence of light on germination of Scots pine seedlings and found that light irradiation favors seedling emergence in Scots pine forests (Haack 1912; Pardos et al. 2007; Barbeito et al. 2009). Noémie et al. (2011) stated that germination density is dependent on the light transmittance through the canopy. However, for Scots pine germination, it has been stated that the duration of light irradiation during day is more crucial than the amount of light measured at a certain time understory (Nyman 1963). Haack (1912) determined that an 8-h irradiation in a day stimulated the same amount of germination as the continuous light, but a 4-h irradiation was not sufficient for germination. This also substantiates our findings; it is likely that plots with lower BA and lower LAI were exposed to longer periods of light irradiation and provided more suitable conditions for germination.

An average of 50,000 seedlings/ha following germination has been recommended under the shelterwood method, while approximately 10,000 seedlings/ha need to be recruited for a successful regeneration of Scots pine using this method (Odabaşı et al. 2004). In a similar study, Calama et al. (2015) observed the number of seedlings at year 5 using the shelterwood method in Central Range, Spain. They obtained more than 50,000 germinants per hectare in the first year and 6300 seedlings/ha in the fifth year (Calama et al. 2015).

Table 4 Relationships between the total height growth of Scots pine seedlings and (1) BA, (2) LAI, (3) LT (%), and (4) HCB. b_0 and b_1 are coefficients. SE is standard error. β is standardized regression coefficient estimates. AICs is Akaike information criteria score

Regression models	b_0	b_1	SE	R^2	β	p value	AICs	Akaike weight
Height = $b_0 - b_1$.BA	56.89	-1.13	6.25	0.45	0.47	<0.0001	199.48	0.0003
Height = $b_0 - b_1$.LAI	52.06	-17.0	5.48	0.58	0.76	<0.0001	191.65	0.0169
Height = $b_0 - b_1$.LT	26.94	0.33	4.80	0.68	0.82	<0.0001	183.63	0.9345
Height = $b_0 - b_1$.HCB	20.14	1.90	5.3	0.61	0.78	<0.0001	189.56	0.0481

Although the average number of germinants (i.e., 33,000 germinants/ha) observed in this study was less than the recommended number, the average number of seedlings obtained at age 5 (i.e., 7000 seedlings/ha) was close to that presented previously in the literature. This suggests that germination is not a major hindrance to the regeneration of Scots pine forests in the region. One reason for the relatively lower number of germinants may be the amount of precipitation between Kastamonu and Central Range, which is 580 mm versus 1000 mm, respectively.

It has been suggested that the higher mortality of Scots pine seedlings is commonly observed in the first year following germination (Pardos et al. 2007), and this may be associated with drought, frost, disease, and grazing (Castro et al. 2004). In this study, the average mortality across the study plots was 55% after five growing seasons. In previous studies, higher mortality rates of Scots pine seedlings have been observed (Castro et al. 2004; Calama et al. 2015; Gerelbaatar et al. 2015). Castro et al. (2004) stated that seedling mortality could reach 50–75% in the first growing season following germination and continue to rise up to 90–100% by year 4, depending on the microhabitats in the stand. Summer drought is considered as the major obstacle that hinders seedling growth and survival in Scots pine forests (Rojo and Montero 1996). Climate is known to be very humid in Kastamonu region where the study plots were located (Akkemik et al. 2008), and there has not been a decrease in the average precipitation in the last 40 years in Kastamonu (Ertugrul et al. 2014). Therefore, drought is not considered a major hindrance for survival of Scots pine seedlings within the study area. Browsing is known to be another agent that influences the survival of Scots pine seedlings (Pardos et al. 2007); thus, the other reason for the high survival rate within the study area might be that the regeneration area was fenced in order to protect seedlings from browsing. Given the suggested numbers of seedling in the literature, current stands seem to have an adequate number of seedlings to be recruited at the end of the five growing seasons, and the mortality rate after 5 years is acceptable. The average mortality rate after the five growing seasons suggests that the study site provided suitable conditions for the survival of germinants.

Seedling growth

The relationship between canopy structure and seedling growth is crucial for the development and recruitment of understory seedlings when natural regeneration is

sought. Canopy structure contributes to the understory light environment (Kara et al. 2017). The results in this study suggest that LT was the most significant predictor of total RCD growth and total height growth of Scots pine seedlings over 5 years. As explored by previous studies (Assenac 2000; Collet et al. 2001; Lhotka and Loewenstein 2008), this study substantiated the notion that light transmittance through the canopy and the vertical canopy heights influence diameter growth and height growth of seedlings. The insignificant relationships between understory vegetation cover and growth of Scots pine seedlings has been supported by the previous studies. Pardos et al. (2007) monitored the effects of environmental conditions on germination, survival, and growth of Scots pine seedlings and found that the presence of understory vegetation had no significant influence.

Although Scots pine is known to be a shade-intolerant species, Scots pine seedlings can survive under the shade of parent trees for a prolonged time (Odabaşı et al. 2004). However, their growth is usually associated with moderate light environments (Castro et al. 2004; Pardos et al. 2007). Several studies have noted that light is considered as the most limiting factor that affects Scots pine seedling growth (Carus 2004; Pardos et al. 2007). Gaudio et al. (2011) monitored growth of understory Scots pine saplings in response to light and found that Scots pine can survive in shaded conditions, but its height growth is affected by light. Our findings also show that light reaching the forest floor, which is negatively correlated with BA and LAI, influences the total RCD and height growth of Scots pine seedlings when a shelterwood method is used. Even though it is suggested that a partial canopy cover may be maintained following germination in Scots pine forests (Pardos et al. 2007), for recruitment into the forest canopy, seedlings require lower canopy cover for higher amounts of light reaching the forest floor (Gaudio et al. 2011). Therefore, following the germination and before the final removal of the overstory trees in shelterwood method, canopy cover may be reduced once or twice to promote seedling establishment in Scots pine stands (Gerelbaatar et al. 2015).

The influence of stand BA on regeneration have been commonly observed (Lundqvist and Fridman 1996; Brockway and Lewis 1997; Gaudio et al. 2011; Kara et al. 2017), but the knowledge on the effects of vertical canopy structure such as HCB is limited. Few studies have revealed that vertical canopy height may affect

understory microclimatic conditions and, consequently, influence seedling growth and survival (Vales and Bunnell 1988; Assenac 2000; Lhotka and Loewenstein 2008). The significant relationships between vertical canopy height and seedling growth observed in this study points out that vertical canopy structural measures such as HCB should be also taken into account when prescribing a silvicultural treatment in Scots pine stands.

The average RCD growth and height growth of Scots pine seedlings after the five growing seasons were approximately 10 mm and 38 cm, respectively. In a similar study, Gerelbaatar et al. (2015) observed the growth of Scots pine seedlings following varying intensities of logging and found that the average RCD growth and height growth of seedlings at year 5 were 13 mm and 33 cm, respectively. Egnell and Leijon (1999) monitored growth of Scots pine seedlings planted under a canopy in Sweden and found that the average height of the seedlings was about 40 cm at the end of the fifth growing season. Compared to the studies in the literature, current data suggest that the study site provided favorable conditions for the growth of Scots pine seedlings.

Our findings suggest that stand density (i.e., BA per hectare) had relatively less significant influence on the total RCD and height growth of Scots pine seedlings across the study plots. This is supported with the fact that BA may not be a better indicator of stand density (Gingrich 1967), because stands with larger trees in DBH have more growing space compared to stands with smaller trees in DBH at a given BA. Ricard et al. (2003) monitored the relationships between overstory tree density and seedling growth and stated that below-ground competition with overstory trees does not influence the growth of Scots pine seedlings. Similarly, Pardos et al. (2007) stated that understory competition does not significantly affect seedling growth in Scots pine stands as long as precipitation and light are at acceptable levels. This is likely because seedling growth is more influenced by understory microclimatic parameters, including light and soil moisture (Castro et al. 2004).

Conclusion

In this study, the relationships between stand BA, canopy structural variables, and germination and seedling growth were explored in a naturally regenerated Scots

pine forest using the shelterwood method. The initial data suggest that Scots pine seedlings can survive and grow under the shade of parent trees when the shelterwood method is utilized to regenerate this forest type, but their establishment is associated with reduced canopy cover following germination. Findings in this study also recommended that germination and seedling growth of Scots pines are associated with the canopy structural variables quantified (i.e., BA, LT, LAI, and HCB). To our knowledge, previous research have presented limited information on the influences of these variables for establishment and growth of Scots pine seedlings under shelterwood method. The relationships developed in this study may be helpful for forest managers and landowners to formulate silvicultural prescriptions that are aimed at enhancing seedling recruitment in Scots pine forests. Current data support the importance of light transmittance through the canopy. Given the previous studies and the equations developed in this study, LT of higher than 50% may be recommended to obtain adequate number of germinants when implementing shelterwood method in Scots pine forests. Moreover, the models also indicate that LT below 60% may hinder seedling growth following germination. Stand BA on regeneration is commonly a utilized measure of stand density in forestry. Stand BA of less than $15 \text{ m}^2 \text{ ha}^{-1}$ to obtain adequate number of germinants and stand BA of less than $12 \text{ m}^2 \text{ ha}^{-1}$ for seedling growth may be recommended when implementing shelterwood method in these forests. The knowledge on the effects of vertical canopy structure is limited in Scots pine forests, and the findings showed the importance of vertical canopy structure (i.e., HCB) when evaluating seedling development under a stand canopy in these forests. Therefore, this study pointed out that vertical canopy structural measure such as HCB should also be taken into account when prescribing a silvicultural treatment. The equations presented in this study may be integrated into seedling growth models based on canopy variables. The models developed in this study can also complement the measures that are commonly taken by foresters and do not need inputs collected by featured devices such as Plant Canopy Imager that result in higher cost and more time of sampling.

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