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Effects of canopy gap size on the regeneration of Scots pine (*Pinus sylvestris* L.) in Eskişehir-Çatacık region of Turkey

Auswirkungen der Lückengröße auf die Regeneration der Weißkiefer (*Pinus sylvestris* L.) in der Eskişehir-Çatacık Region, Türkei

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Keywords: *Canopy gaps size, gap-based silviculture, gap regeneration, sapling growth*

Schlüsselbegriffe: *Lückengröße, naturnaher Waldbau, Verjüngung, Pflanzenwachstum*

Abstract

The study was undertaken in Scots pine shelterwood forests in central Anatolia at the edge of the Eurasian distribution of Scots pine and thus adding significance in terms of understanding the ecology of this important species. Canopy gap size and the position of the sapling within the regeneration cores were chosen within nine different strip-sample plots comprising 20 sapling regeneration cores. Those sapling regeneration cores under the gaps were divided into two portions (individuals at the edge and middle of the regeneration cores) and from each portion three individuals were selected. The growth relationships of individual saplings within the regenera-

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tion cores were determined from the age-height graph of 95 sapling-stem analyses. Gap-size classes that compromise a gap size gradient were chosen: small gaps (< 20 m²); intermediate gaps (20 - 177 m²); large gaps (178 - 707 m²). Spatial structure of mature trees were determined using the Clark-Evans index. In addition, differentiation index (diameter, height, crown lenght, and crown radius) were calculated for each stand projections.

Gaps with sapling regeneration cores ranged from 15 to 240 m², with a mean of 91.55 ± 23.69 m² by Student's t-test ($p = 0.05$). The maximal gap-size classes were found in the intermediate (90%), followed by large (5%) and small (5%). Compared with saplings in the middle of regeneration cores, those at the edge were always reduced in terms of mean height. Significant difference was found between the 'Main crop' and the 'Edges 1-2' of the regeneration cores. There was no significant difference for sapling age in regeneration cores. Fraction of land area in gap regeneration cores was found between 20 and 66% of total stand area. The age-height graph of 95 sapling-stems derived from stem analyses showed that the saplings grow very well without any obvious deceleration in the gaps.

These findings can further inform forest managers about how to optimize growth of sapling by means of canopy gap regulation. The results are discussed in the context of future silvicultural modelling and new ways of assessing forest regeneration dynamics when gap-regeneration is important.

Zusammenfassung

Die Studie wurde in Weißkiefernwäldern in Zentralanatolien am Rande des eurasischen Verbreitungsgebietes der Weißkiefer durchgeführt und trägt damit zum Verständnis der Ökologie dieser in ganz Eurasien sehr wichtigen Baumart bei. Die Größe von Bestandeslücken und die Position der Pflanzen innerhalb der Lücken wurden mit Hilfe von neun streifenförmigen Probeflächen mit insgesamt 20 Verjüngungs-Kernbereiche untersucht. Die Verjüngungs-Kernbereiche in den Lücken wurden in zwei Teile geteilt (Individuen am Rand und Individuen in der Mitte der Verjüngungs -Kernbereiche) und aus jedem Teil wurden drei Individuen ausgewählt und näher untersucht. Die Wachstumsbeziehungen der einzelnen Pflanzen innerhalb der Verjüngungs-Kernbereiche wurden mittels Alters-Höhen-Diagramm von 95 Pflanzenstammanalysen ermittelt. Es wurden drei Größenklassen gewählt um unterschiedliche Lückengrößen zu berücksichtigen: kleine Lücken (<20 m^2); mittlere Lücken (20-177 m^2) und große Lücken (178-707 m^2). Die räumliche Struktur der Oberschicht wurde mit dem Clark-Evans Index beschrieben. Zusätzlich wurde für jeden Bestand vier Differenzierungsindeces berechnet (Durchmesser, Höhe, Kronenlänge und Kronenradius). Die Lückengröße der Verjüngungs-Kernbereiche lagen zwischen 15 und 240 m^2, mit einem Mittelwert von 91.55 ± 23.69 m^2 im Student's t-Test ($p=0.05$). Der

Großteil der untersuchten Lücken befand sich in der mittleren Größenklasse (90%), gefolgt von der großen (5%) und kleinen (5%) Klasse. Die mittlere Höhe der Pflanzen in der Mitte der Verjüngungs-Kernbereiche ist signifikant geringer als die Höhe der Bäume am Rand der Lücke. Es wurden allerdings keine signifikanten Unterschiede im Pflanzenalter zwischen Lückenrand und Lückenmitte gefunden. In den untersuchten Beständen betrug der Anteil der Verjüngungs-Kernbereichen zwischen 20 und 66% der gesamten Bestandesfläche. Die Stammanalyse und das Alters-Höhen-Diagramm der 95 untersuchten Pflanzen belegt, dass es zu keinem Verzögerung des Höhenwachstums innerhalb der Lücken kommt. Diese Erkenntnisse sich wichtig für die Forstwirtschaft um das Wachstum von Pflanzen in Bestandeslücken besser zu verstehen und durch die Regulierung der Lückengröße zu optimieren. Dies kann unter anderem für die zukünftige waldbauliche Modellierung und Entwicklung neuer Methoden zur Bewertung der Waldverjüngungsdynamik angewandt werden.

1. Introduction

When one or a few canopy trees die (or are injured) in a forest mainly because of natural disturbance, small openings, which are called 'gaps' are formed in the forest canopy and are then filled by other trees. This phenomenon is defined as 'gap dynamics'. Many forest scientists and ecologists have been attracted to gap dynamics, because gap dynamics is closely related with practical forest applications (e.g., forest conservation practice, natural regeneration method) as well as basic ecological theories (e.g., niche partitioning, species adaptation, latitudinal gradient of species diversity) (Yamamoto 2000). Holeksa & Cybulski (2001) stated that gaps smaller than 100m² are typical structural elements of forests in the western Carpathian Mountains and they comprise 34% of the forest area. For this reason, in studies on forest disturbance regimes, measuring gap size is an important issue (Runkle 1982; de Lima 2005), and gap area is a good index with which to characterize light entrance and resource availability (de Lima 2005).

Understanding the interrelations between gap size and environmental change, and their effects on regeneration processes is a prerequisite for developing techniques of nature-based forestry (Gálhidy et al. 2006). When gaps are formed in a forest canopy, growth of advance regeneration (regenerated in gaps from seedlings or saplings recruited before gap formation) within gaps is promoted and/or new seedlings colonize into gaps. Seedlings of shade-intolerant species can establish in larger gaps, frequently with exposed mineral soils, while in smaller gaps advance regeneration of shade-tolerant species is dominant. Like these, the pattern of tree regeneration in gaps varies among constituent species in the gap-regenerating forests (Yamamoto 2000). The basal area of the different species in the canopy is an indirect measure of the understory micro-environment that affects seedbed conditions, light, understory composition, and other biotic and abiotic factors that directly determine the potential for the establishment of advance regeneration (Çoban et al. 2016). A local measure of basal area may therefore give an estimate of canopy cover (Jennings et al. 1999). In addition, position of the seedling beneath the canopy gap (i.e., in the centre of the gap or close to mature trees) also influence seedling survival (Çoban et al. 2016).

Although forest ecologists and silviculturalists have emphasized the importance of creating gaps to generate spatial variation in order to promote tree regeneration, the effects of gap on seedling recruitment may be offset by the development of dense forest understoreys. This limits regeneration even in gap conditions, and reduces the effectiveness of gaps (Beckage et al. 2005; Ruuska et al. 2008). Understanding the behaviour of the seedlings of different tree species in relation to canopy shade is therefore important (Çoban et al. 2016).

There is an abundant literature on the factors affecting natural regeneration in Scots pine forests. Scots pine seed trees have an effect on the structure of pine seedlings (i.e. morphological characteristics), their spatial pattern, and their size distribution (Kuuluvainen 1994; Valkonen et al. 2002; Castro et al. 2004; Zagidullina & Tikhodeyeva 2006). Both height and seedling density decrease close to the parent trees (Siipilehto 2006). Competition from the mother trees inhibits development of saplings in close proximity (Montes and Canellas, 2007). However, the growth of naturally occurring saplings in response to variations in canopy cover density of Scots pine stands are poorly studied in the southern zone of its distribution area (Kuuluvainen et al. 1993; Cameron & Ives 1997; Beckage et al. 2005; Andrzejczyk 2007; Löf et al. 2007). Studies on regeneration and advance growth have shown that the effects of the long-term retention of seed trees has a strong negative impact on the development of young Scots pine stands, especially on relatively infertile sites in the northern areas of its natural distribution (Ruuska et al. 2008). However, the relationship beween sapling height development and the position within gap regeneration cores is not known for semi-arid site conditions.

The aims of this study were 1) to determine the growth characteristics of the sapling affected by the position within the regeneration cores, 2) to predict the most appropriate gap-size classes for the development of regeneration cores of shade-intolerant Scots pine saplings, 3) to consider whether responses vary with the shade-tolerance variation of Scots pine saplings.

2. Materials and Methods

2.1 Site description

Much of current knowledge of tree-canopy development is based on studies of trees occurring in naturally-regenerated forest communities (Ellenberg 1996). This research was therefore undertaken in a naturally-regenerated Scots pine forest in Çatacık (Eskişehir) in the northwest of Turkey (Figure 1: latitude between 39°57' and 39°58' N, longitude between 31°06' and 31°08' E) which is characterised by a high degree of naturalness (Çolak et al. 2003). The research area is typically covered by Scots pine stands of between 110 years and 140 years in age, located between 1,517 and 1,607 m altitude on the northern slopes (inclination 5° to 19°) of the Sündiken Mountains. Stands have densities of between 118 and 360 trees ha^{-1} and basal areas between 18.1 and 40.3 m² (see Table 5 for the detailed stand structural characteristics). Silviculture in the area is based on natural regeneration following a shelterwood system and silvicultural interventions are infrequent during the early stages of development.

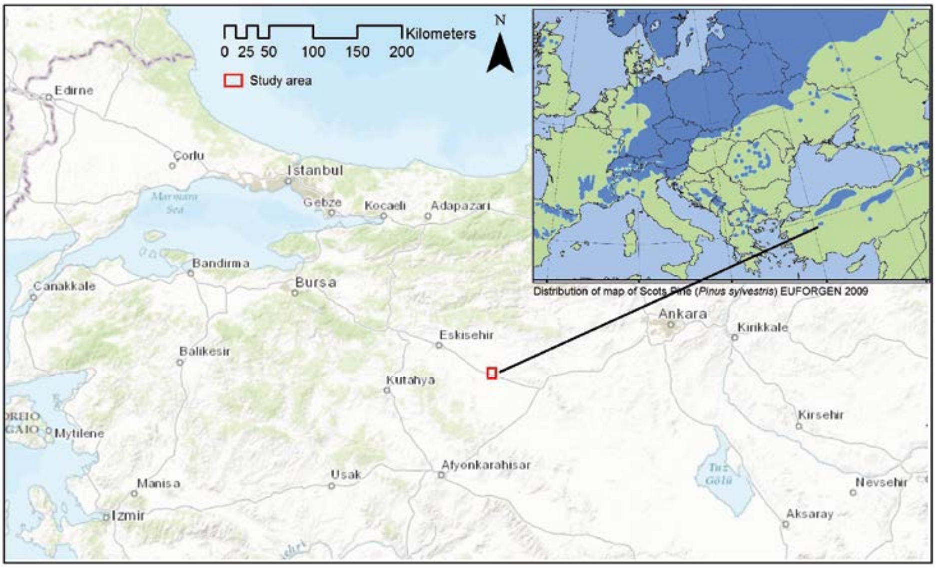


Figure 1: Natural distribution range of Pinus sylvestris L. (EUFORGEN, 2009) and location of sample plots.

Abbildung 1: Natürliches Verbreitungsgebiet von *Pinus sylvestris* L. (EUFORGEN, 2009) und Lage der Probeflächen.

The climate of the Çatacık region (1,550 m) is classified as B3C'2 sb'2 by the Thornthwaite climate classification system which translates as characterised by humid, micro-thermal (cold climate types), moderate summer water deficiency, and close to oceanic climate types. Summer water deficiency occurs from August to October (Boydak 1977), and the Çatacık subalpine Scots pine forest develops in harsh mountain environments with low temperatures, strong winds, and abundant snowfall. Furthermore, the study area is situated in Scots pine (*Pinus sylvestris* L.) shelterwood forests in a pine site typical of the area, and at the border between Mediterranean evergreen forests, temperate deciduous broadleaf forests, and steppe/grasslands (according to Whittaker's biome classification) (Figure 1).

2.2 Gradients and measurements of Gap Size

Runkle (1982) defined gaps as the land surface directly under the canopy opening containing young trees up to 10 m high. The 10-m cut-off is slightly less than half the average height of canopy trees (Holeksa and Cybulski, 2001). In this study, a canopy gap was defined as the ground area under a canopy-opening with sapling regeneration cores which extend to the bases of canopy trees surrounding the canopy-opening (modified from Runkle (1982)).

Gap classes were measured and presented in square metres (m²) since gap shape varies greatly and the gap size classes of Çoban et al. (2016) presenting a gap-size gradient were chosen. The Scots pine stands were allocated into 1 of 3 different gap sizes (Small, intermediate and large gaps) distinguished by gap size gradients in the shelterwood. These three gap size gradients are as follows (Çoban et al. 2016):

1) Small gaps with a diameter of < 5 m (<20 m²);

2) Intermediate gaps with a diameter of 5 to15 m (20 to177 m²);

3) Large gaps with a diameter of 15 to 30 (178 to 707 m²).

Measures of gaps with sapling regeneration cores assess the presence or absence of canopy vertically above a sample of points across an area of forest by the vertical projection of the tree crowns. Gaps under a canopy opening with sapling regeneration cores were calculated from horizontal projection in the stand projection (10 x 50 m) on the millimetric graph paper in square metres. As it was also found by Çoban et al. (2016), average diameter of regeneration cores did not exceed 8-10 m. In order to determine the relation between stand structure and regeneration cores, horizontal stand projections were laid to cover regeneration cores. In addition, gap sizes were also measured out from stand projection when it exceeded horizontal projection. Since all of the regeneration cores except those under large gaps were included in the stand projection, the width of the stand projection was not increased.

Gaps were taken to become indistinguishable from the background overstory when regeneration within the gap has young trees of 10 m or more in height. All individuals taller than 1 m within gaps are referred to as saplings (Runkle 1981).

2.3 Selection of sample plots and field procedures

Shelterwood cutting areas in the Scots pine stands of 110 to 140 years-old had uniform levels of shade resulting from regular thinning and felling. Gaps in these stands were assessed and placed into different gap size gradients. Samples were separated depending on typical sapling regeneration cores under different gap sizes within these stands. Sampling in the stands was conducted with a simple random sampling method. Measurements were taken for 9 rectangular (10 x 50 m) sample plots with different gap size gradients and chosen from natural regeneration cores of Scots pine saplings. The standard alternative to gap sizes for the regeneration cores is by means of ‘rectangular sample plots’ (10 x 50 m; Aksoy (1978)) and shows longitudinal (profile) and vertical projection of the stand.

In each sample plot, diameter at breast height (DBH), height, living branch height, vertical projection of crowns and position of trees were recorded (Figure 2). Longitudinal (profile) and vertical projection of the stands were drawn using these data. Areas of regeneration cores were also drawn for sample plots (Figure 3).

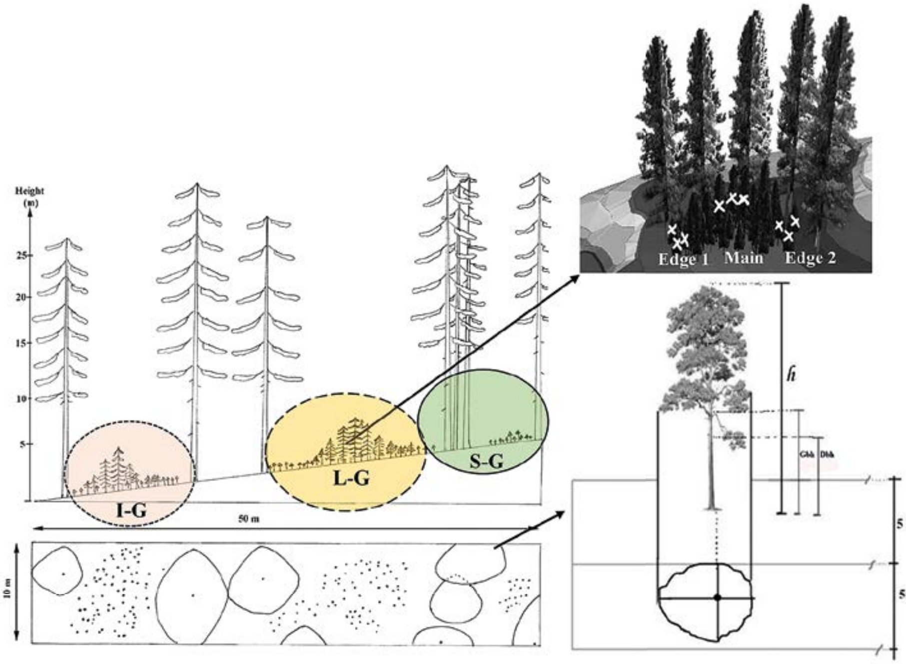


Figure 2: The gap size gradient models of Scots pine stands with three gap gradients (Zhang & Zak 1995): Small gaps (S) with a diameter of < 5 m (< 20 m²); Intermediate gaps (I) with a diameter of 5 - 15 m (20 - 177 m²); Large gaps (L) with a diameter of 15 - 30 m (178 - 707 m²) (longitudinal and vertical projection of stands from (Coban 2007, Coban et al. 2016).

Abbildung 2: Die Modelle der Waldlückengradienten der Weißkiefer mit drei Lückengradienten (Zhang & Zak 1995): Kleine Lücken (S) mit einem Durchmesser von <5 m (<20 m²); Mittlere Lücken (I) mit einem Durchmesser von 5-15 m (20-177 m²); Große Lücken (L) mit einem Durchmesser von 15-30 m (178-707 m²) (Längs- und Vertikalprojektion von Beständen aus Çoban 2007, Çoban et al. 2016).

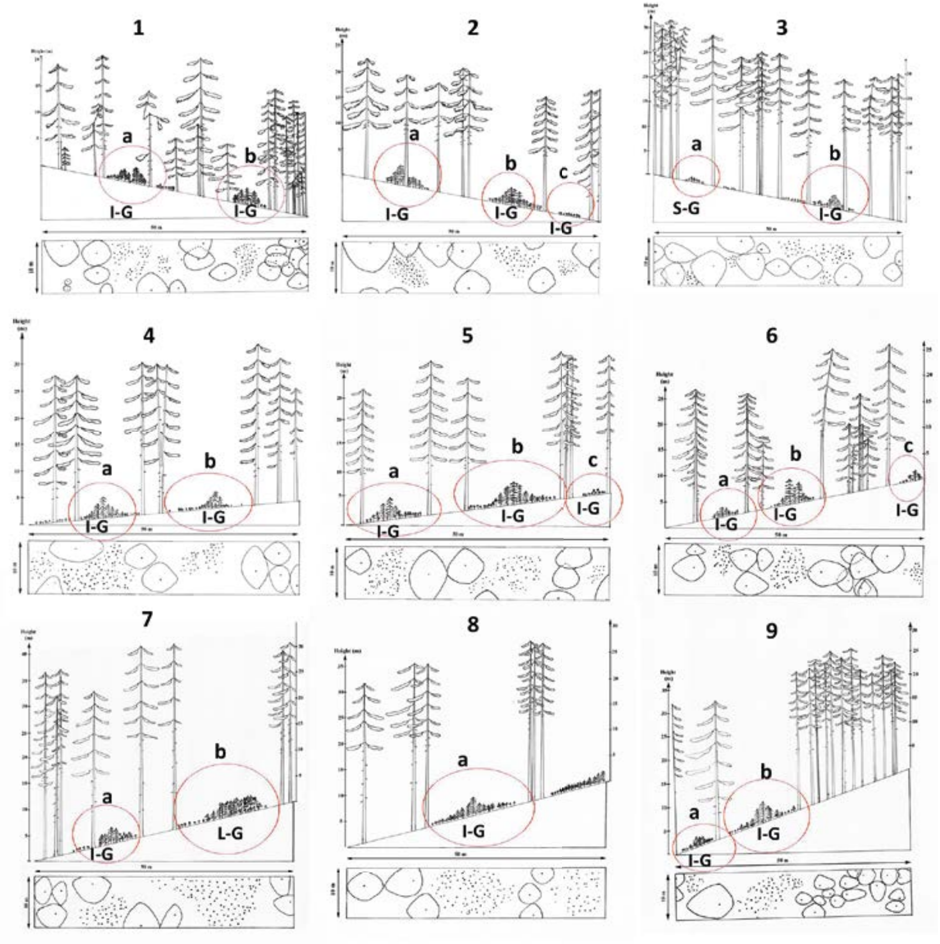


Figure 3: Longitudinal (profile) and vertical stand projection of 20 sample plots with different gap size gradients within the regeneration cores (S-G: Small gaps; I-G: Intermediate gaps; L-G: Large gaps) in pure Scots pine stands.

Abbildung 3: Längs- (Profil) und Vertikalprojektion von 20 Probeplots mit unterschiedlichen Waldlücken-Gradienten innerhalb der Verjüngungs-Kernbereiche (S-G: Kleine Lücken; I-G: Mittlere Lücken; L-G: Große Lücken) in reinen Weißkiefernbeständen.

2.4 Analysis of regeneration cores in the gaps

For the growth analysis, 11 most typical regeneration cores were randomly selected from sample plots. Typical regeneration cores were those which had a distinct height difference between edge and middle saplings and most were above 1.5 m. According to this criterion, only regeneration cores under intermediate gaps were chosen for further analysis.

From each of the edges three individuals were taken (six individuals in total from edges) and three individuals were taken from the middle (Figure 2). A total of 99 saplings were cut at ground level and their ages were estimated by ring counting. Among these saplings which are higher than 1.5 m were used in sapling-stem analysis (64 Edge saplings and 31 Main crop saplings). Those individuals at the edge of the natural sapling regeneration cores were selected as “Edge saplings” (Figure 2) of which at the lower side of the core was named as Edge 1 and upper side as Edge 2. The saplings were scored considering the height position (dominant/codominant/intermediate/suppressed) and damage (healthy/low damage/moderate damage/highly damaged) of individuals in regeneration cores: 1) "Main crop sapling" the highest score in both variables and 2) "Edge sapling" with the lowest score in both variables. The Main crop saplings were located in the middle of the typical natural sapling regeneration cores (Figure 2). The term "Main crop sapling", that is the trees selected to become a component of a future commercial harvest, refers to those saplings with the highest score in both variables (dominant and healthy) (González-Martínez & Bravo 2001).

2.5 Sapling-stem analysis

Sample saplings were cut down to ground level and stem cuts were taken at 1 m intervals for stem analysis (Atıcı 1998; Kalıpsız 1998; Atıcı 2003). In the stem analysis, ages at each cross-section were calculated from the differences in annual rings for the cross-sections to give sapling age. Then, the height-growth model which was firstly proposed by Prodan (1961) and used many authors (Akalp 1976; Asan 1984; Usta 1990; Erkan 1996; Özcan 2003; Özdemir 2005; Şenyurt 2005; Çatal 2009; Özdemir & Özdemir 2016; Özdemir & Saraçoğlu 2016) was calculated (Eq. 1).

$$H = \frac{t^2}{a_0 + a_1 \times t + a_2 \times t^2} \qquad \text{(Eq. 1)}$$

(*t*: years to reach cross-section height; *H*: Cross-section height (m); a_0, a_1, a_2: equation coefficients).

2.6 Analysis of stand structure of sample plots

The spatial distribution of mature trees was determined using the nearest-neighbour method in order to show its effect on regeneration cores. For this reason, the Clark-Evans index of clumping (CE) which is based on distances between individuals was used. This index is a measure of the extent to which the observed population differs from the randomly distributed one. A population distributed randomly shows CE = 1.0, while regularity can be assumed if CE > 1.0 and index CE < 1.0 indicates the clumped distribution of individuals (Clark & Evans 1954; Kint 2004; Szmyt 2014). In addition, the differentiation index which describes the degree of dissimilarity of sizes between neighbouring trees (i.e., diameter (TD), height (Th), crown length (TCL) and crown radius (TCr)) was calculated for all stand projections. This index has values varying between 0 (no differentiation) and 1 (complete differentiation) (Pommerening 2002). For 4 nearest neighbours the 5 differentiation classes can be applied (Aguirre et al. 2003; Kint 2004; Szmyt 2014)(Aguirre et al. 2003; Kint 2004; and Vorčak at al. 2008):

1) 0.0 - 0.20 (very small differentiation),

2) 0.20 - 0.40 (small differentiation),

3) 0.40 - 0.60 (clear differentiation),

4) 0.60 - 0.8 (large differentiation)

5) 0.80 - 1.00 (very large differentiation).

All of the parameters noted above were calculated using the SIAFOR program (Kint 2004).

2.7 Data analysis

The following equation (Eq. 2) was used to calculate 95% confidence intervals of populations of all measured data (Sachs 1970; Kalıpsız 1981; Atıcı et al. 2008):

$$\mu = \bar{x} \pm tSE_{\bar{x}} \quad \text{(Eq. 2)}$$

Where $\bar{x}$ is arithmetic mean; SE_x is std. error; t is Student's t coefficient ($t_{1-\alpha/2;\, n-1}$); for 8 degrees of freedom = 2.306, n is 9 number of samples.

Statistical evaluation including nonparametric test (Kruskal-Wallis H-Test), One-way Variance Analyses (ANOVA) and t-tests were applied to the data using SPSS 21 software for Windows.

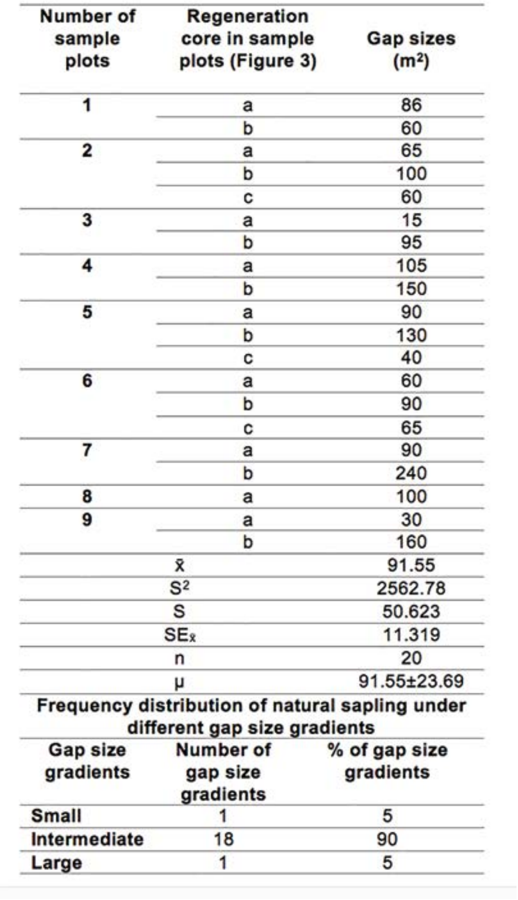
3. Results

3.1 The frequency distribution of natural sapling under different gap size gradients

Gaps with sapling regeneration cores ranged from 15 to 240 m². Arithmetic mean of 95% confidence interval of total population (μ value) by Student's t-test ($p = 0.05$) is 91.55 ± 23.69 m² (Table 1). The maximal gap size classes were found in the intermediate (90%), followed by large (5%) and small (5%) (Table 1 and 2). These differences were shown to be statistically significant ($p < 0.001$, Table 2) by the Kruskal-Wallis H test (Table 1). The results suggest that large (5%) and small (5%) were rare within gap size classes (Figure 3; Tables 1 and 2) and this was significant. This test was applied to the difference in the gap size gradients of regeneration cores. The situation was consistent in all sample plots with longitudinal (profile) and vertical projection of stands (Figure 3). The shapes of gap areas vary from elliptic to circular within Scots pine stands, which affects the micro-environment within a gap (Figure 3).

Table 1: Descriptive analysis of the 20 canopy gap areas with sapling regeneration cores obtained using 9 stand projection method of measurement in Scots pine stands. Data and statistical analysis from 20 regeneration cores ($n = 20$, $v = 19$, $t = 2.093$), μ (Eq.2). This was confirmed by Student's t-test ($p = 0.05$): Arithmetic mean of 95% confidence interval of total population.

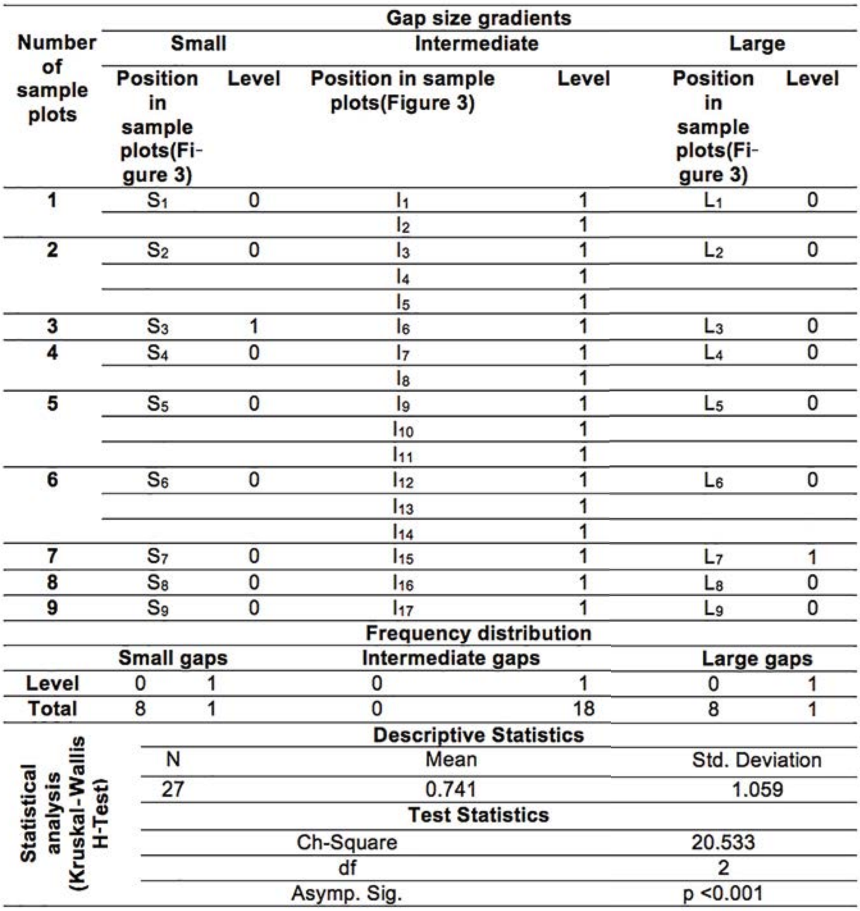
Tabelle 1: Beschreibende Analyse der 20 Flächen mit Waldlücken und mit Verjüngungs-Kernbereichen, die mit Hilfe der 9 Bestandesprofile in Weißkiefernbeständen gewonnen wurden. Daten und statistische Auswertung von 20 Regenerations-Kernbereichen ($n=20$, $v=19$, $t=2.093$), μ (Gl.2). Dies wurde durch den Student's t-Test ($p=0.05$) bestätigt: Arithmetisches Mittel von 95% Konfidenzintervall der Gesamtpopulation.



Number of sample plots	Regeneration core in sample plots (Figure 3)	Gap sizes (m²)
1	a	86
	b	60
2	a	65
	b	100
	c	60
3	a	15
	b	95
4	a	105
	b	150
5	a	90
	b	130
	c	40
6	a	60
	b	90
	c	65
7	a	90
	b	240
8	a	100
9	a	30
	b	160
	$\bar{x}$	91.55
	S^2	2562.78
	S	50.623
	$SE_{\bar{x}}$	11.319
	n	20
	μ	91.55±23.69
Frequency distribution of natural sapling under different gap size gradients		
Gap size gradients	**Number of gap size gradients**	**% of gap size gradients**
Small	1	5
Intermediate	18	90
Large	1	5

Table 2: Frequency distribution of natural sapling under different gap size gradients. The data and statistical analysis from 20 sapling regeneration cores with different gap size gradients. This was confirmed by Kruskal-Wallis H-test (Level; 0: Absence of gap size classes within sample plots; 1: Presence of gap size classes within sample plots).

Tabelle 2: Häufigkeitsverteilung des natürlichen Pflanzen unter verschiedenen Gradienten von Waldlücken. Die Daten und statistische Auswertungen von 20 Verjüngungs-Kernbereichen mit unterschiedlichen Gradienten von Waldlücken. Dies wurde durch den Kruskal-Wallis H-Test bestätigt (Level; 0: Fehlen von Lückengrößenklassen innerhalb von Stichprobenplots; 1: Vorhandensein von Lückengrößenklassen innerhalb von Stichprobenplots).



Number of sample plots	**Gap size gradients**					
	Small		**Intermediate**		**Large**	
	Position in sample plots(Figure 3)	**Level**	**Position in sample plots(Figure 3)**	**Level**	**Position in sample plots(Figure 3)**	**Level**
1	S_1	0	I_1	1	L_1	0
			I_2	1		
2	S_2	0	I_3	1	L_2	0
			I_4	1		
			I_5	1		
3	S_3	1	I_6	1	L_3	0
4	S_4	0	I_7	1	L_4	0
			I_8	1		
5	S_5	0	I_9	1	L_5	0
			I_{10}	1		
			I_{11}	1		
6	S_6	0	I_{12}	1	L_6	0
			I_{13}	1		
			I_{14}	1		
7	S_7	0	I_{15}	1	L_7	1
8	S_8	0	I_{16}	1	L_8	0
9	S_9	0	I_{17}	1	L_9	0
	Frequency distribution					
	Small gaps		**Intermediate gaps**		**Large gaps**	
Level	0	1	0	1	0	1
Total	8	1	0	18	8	1

Statistical analysis (Kruskal-Wallis H-Test)			
	Descriptive Statistics		
	N	Mean	Std. Deviation
	27	0.741	1.059
	Test Statistics		
		Ch-Square	20.533
		df	2
		Asymp. Sig.	p <0.001

3.2 The height growth of older sapling in regeneration cores

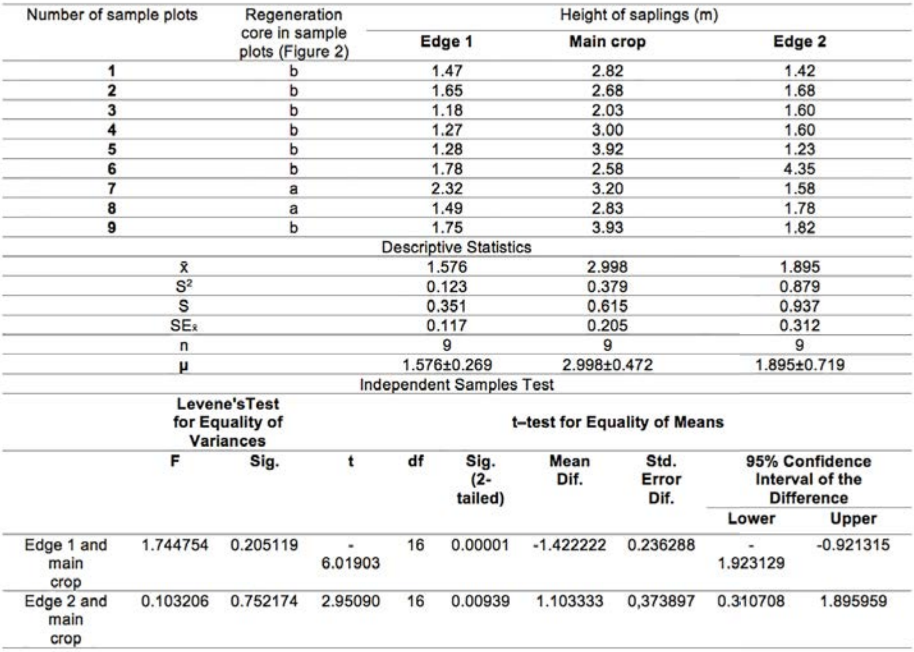
Compared with saplings in the middle of a regeneration core or cluster, those on the edge were always shorter with µ value (Table 3). The differences in µ value were found for Edge 1: 1.576 ± 0.269 m; Main crop: 2.998 ± 0.472 m; Edge 2: 1.895 ± 0.719 m. Due to height differentiation between edges and Main crop, a regeneration core form develops (Table 3; Figure 3).

The distribution of saplings in different height classes in the sapling regeneration cores revealed that they were shorter beneath the canopy than beyond the canopy (Figure 3). These were statistically significant between the Main crop and Edge 1 ($t = 6.019$; $p = 0.000$) and between the Main crop and Edge 2 ($t = 0.752$; $p = 0.009$) (Table 3). One-way Variance Analysis (ANOVA) was carried out to test the differences in sapling age between Main crop saplings and both Edge saplings in the regeneration cores.

There was no significant difference (between the Main crop and Edge 1: $F = 0.412$; $p = 0.149$; between the Main crop and Edge 2: $F = 0.005$; $p = 0.440$) for sapling age in regeneration cores. These µ values were found for Edge 1: 12.48 ± 3.59 year; Main crop: 16.29 ± 4.54 years; Edge 2: 13.79 ± 5.69 years (Table 4; Figure 4).

Table 3: The effect of the position of the sapling within the regeneration core on height of saplings in the regeneration core. Data and statistical analysis from nine regeneration cores (n = 9, v = 8, t = 2.306), μ (Eq. 2). This was confirmed by Student's t–test (p = 0.05): Arithmetic mean of 95% confidence interval of total population.

Tabelle 3: Der Einfluss der Position von Pflanzen innerhalb des Verjüngungs-Kernbereiches auf die Höhe der Pflanzen im Regenerations-Kernbereich. Daten und statistische Auswertung von neun Verjüngungs-Kernbereichen (n=9, v=8, t=2.306), μ (Gl. 2). Dies wurde durch den Student's t-Test (p = 0,05) bestätigt: Arithmetisches Mittel von 95% Konfidenzintervall der Gesamtpopulation.



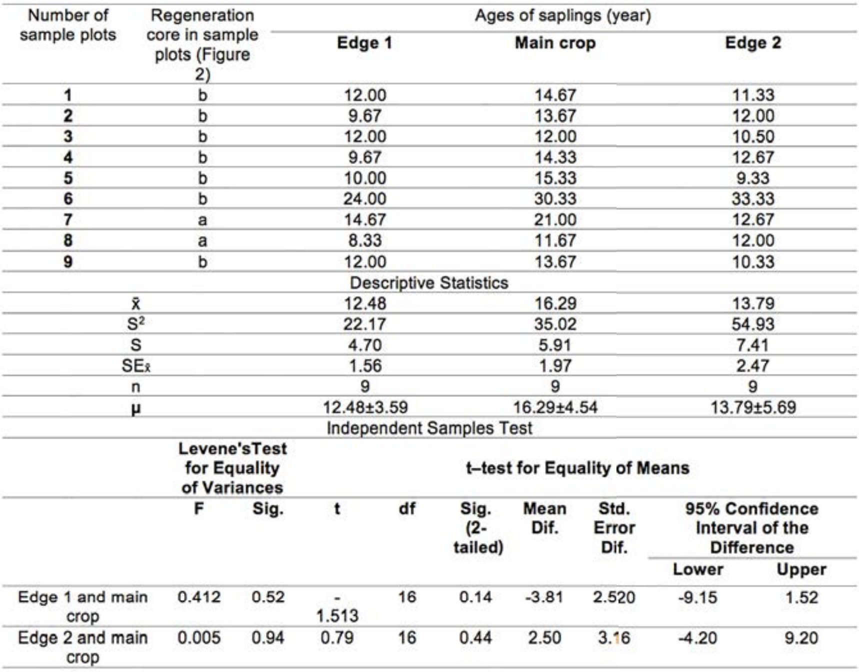
Number of sample plots	Regeneration core in sample plots (Figure 2)	Height of saplings (m)		
		Edge 1	**Main crop**	**Edge 2**
1	b	1.47	2.82	1.42
2	b	1.65	2.68	1.68
3	b	1.18	2.03	1.60
4	b	1.27	3.00	1.60
5	b	1.28	3.92	1.23
6	b	1.78	2.58	4.35
7	a	2.32	3.20	1.58
8	a	1.49	2.83	1.78
9	b	1.75	3.93	1.82
Descriptive Statistics				
$\bar{x}$		1.576	2.998	1.895
S^2		0.123	0.379	0.879
S		0.351	0.615	0.937
$SE_{\bar{x}}$		0.117	0.205	0.312
n		9	9	9
μ		1.576±0.269	2.998±0.472	1.895±0.719

Independent Samples Test

	Levene'sTest for Equality of Variances		**t–test for Equality of Means**						
	F	**Sig.**	**t**	**df**	**Sig. (2-tailed)**	**Mean Dif.**	**Std. Error Dif.**	**95% Confidence Interval of the Difference**	
								Lower	**Upper**
Edge 1 and main crop	1.744754	0.205119	-6.01903	16	0.00001	-1.422222	0.236288	-1.923129	-0.921315
Edge 2 and main crop	0.103206	0.752174	2.95090	16	0.00939	1.103333	0,373897	0.310708	1.895959

Table 4: The effect of the position of the sapling within the regeneration core on age of saplings in the regeneration core. Data and statistical analysis from nine regeneration cores (n = 9, v = 8, t = 2.306), μ (Eq. 2). This was confirmed by Student's t–test (α = 0.05): Arithmetic mean of 95% confidence interval of total population.

Tabelle 4: Der Einfluss der Position von Pflanzen im Regenerations-Kernbereich auf das Alter der Pflanzen im Verjüngungs-Kernbereich. Daten und statistische Auswertung von neun Verjüngungs-Kernbereichen (n=9, v=8, t=2.306), μ (Gl. 2). Dies wurde durch den Student's t-Test bestätigt (α=0,05): Arithmetisches Mittel von 95% Konfidenzintervall der Gesamtpopulation.



Number of sample plots	Regeneration core in sample plots (Figure 2)	Ages of saplings (year)		
		Edge 1	**Main crop**	**Edge 2**
1	b	12.00	14.67	11.33
2	b	9.67	13.67	12.00
3	b	12.00	12.00	10.50
4	b	9.67	14.33	12.67
5	b	10.00	15.33	9.33
6	b	24.00	30.33	33.33
7	a	14.67	21.00	12.67
8	a	8.33	11.67	12.00
9	b	12.00	13.67	10.33
		Descriptive Statistics		
$\bar{x}$		12.48	16.29	13.79
S^2		22.17	35.02	54.93
S		4.70	5.91	7.41
$SE_{\bar{x}}$		1.56	1.97	2.47
n		9	9	9
μ		12.48±3.59	16.29±4.54	13.79±5.69

Independent Samples Test

	Levene'sTest for Equality of Variances		**t–test for Equality of Means**						
	F	**Sig.**	**t**	**df**	**Sig. (2-tailed)**	**Mean Dif.**	**Std. Error Dif.**	**95% Confidence Interval of the Difference**	
								Lower	**Upper**
Edge 1 and main crop	0.412	0.52	-1.513	16	0.14	-3.81	2.520	-9.15	1.52
Edge 2 and main crop	0.005	0.94	0.79	16	0.44	2.50	3.16	-4.20	9.20

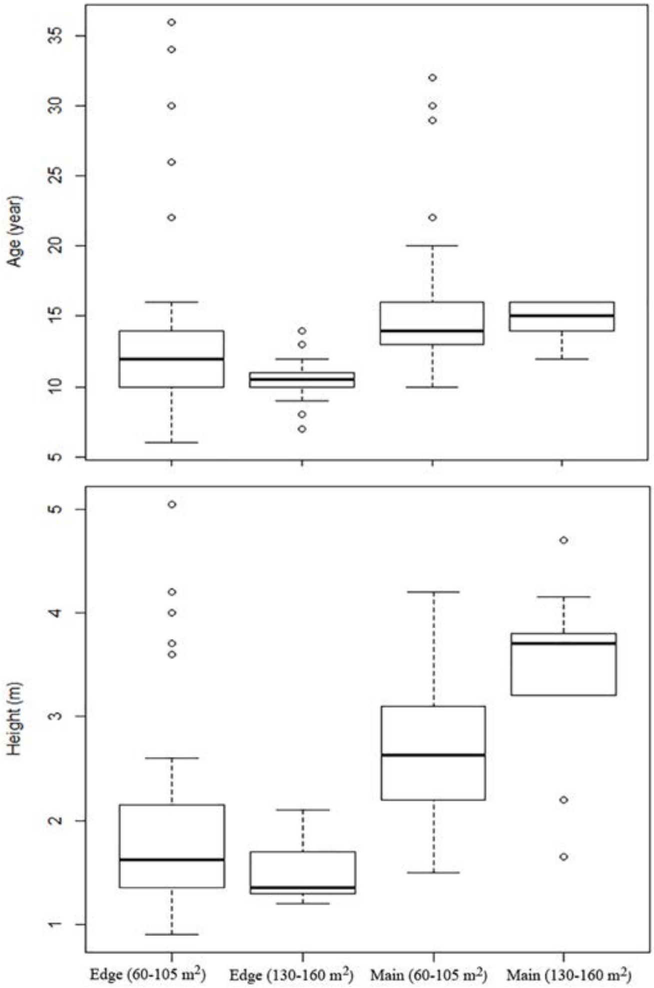


Figure 4: Boxplots of sapling age (above) and height (below) in relation to their position in the regeneration core and sizes of intermediate gaps.

Abbildung 4: Boxplots des Pflanzenalters (oben) und der Höhe (unten) in Abhängigkeit von ihrer Position im Verjüngungs-Kernbereich und der Größe der Waldlücken.

3.3 The growth of individual saplings in the regeneration cores

Regeneration cores under small gaps do not show good development since most saplings are below 1.5 m height and unhealthy. On the other hand, there is not a distinct growth difference among saplings of large gaps.

The age-height graph of 95 sapling-stems derived from stems analyses showed that the saplings grow very well without any obvious deceleration in the intermediate gaps (Figure 5ab). According to the stem analysis of the saplings, there was a slow height growth increment at the early stages which increased after 10 years. For the 25 to 30-year-old saplings, an increment occurred even after 15 years. In addition, the height-growth rate of Edge saplings was lower than those of Main crop saplings. On the other hand, Main crop saplings had a higher height-growth performance under wide intermediate gaps (between 130 and 160 m^2) compared to saplings under small intermediate gaps (60 and 105 m^2) but Edge saplings did not show a clear difference between these gap sizes (Figure 4).

3.4 Stand structure characteristics of Scots pine stands with gap regeneration cores

Canopy cover rates in the sampling plots ranged from 24% to 43%. The arithmetic mean of canopy cover rates in the sampling plots 95% confidence intervals of total population (μ value) by Student's t-test ($p = 0.05$) was 33.09 ± 4.29% (Table 5). This indicates that Scots pine gap regeneration cores can develop under these conditions with a good growth performance and vitality in Scots pine stands of 110 to 140 years in age. On the other hand, regeneration cores may also occur in the stands with clumped or regular spatial distribution of trees. Indeed, values of CE indicate that spatial distribution of trees within the sample plots are mostly clumped (CE < 1.0) for most of the sample plots with the exception of the plot 1, 2, 3 and 5 which showed regular distributions (CE > 1.0) (Table 5). Both horizontal and vertical differentiation for stand dimensions (Index TD, TH, TCl, and TCr) was found to be low or moderate. Only sample plot 1 showed clear differentiation for diameter (Table 5). The proportion of land area in gap regeneration cores was between 20% and 66% of total stand area according to the evaluation of Scots pine stands in excess of 110 years in age. The arithmetic mean of gap regeneration area of 95% confidence interval of total population (μ value) using Student's t-test ($p = 0.05$) was 40.68 ± 11.57% (Table 5).

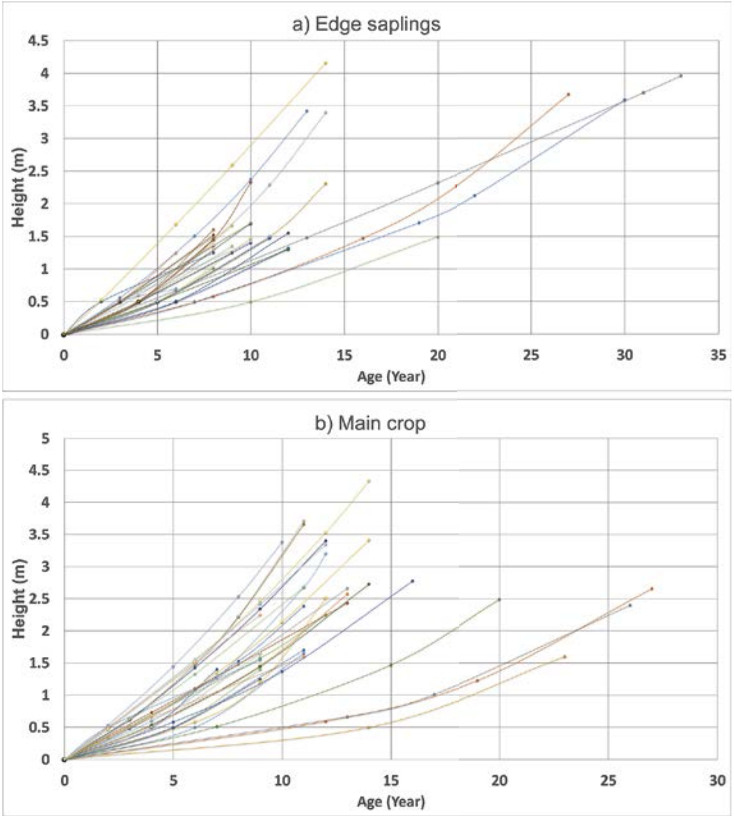
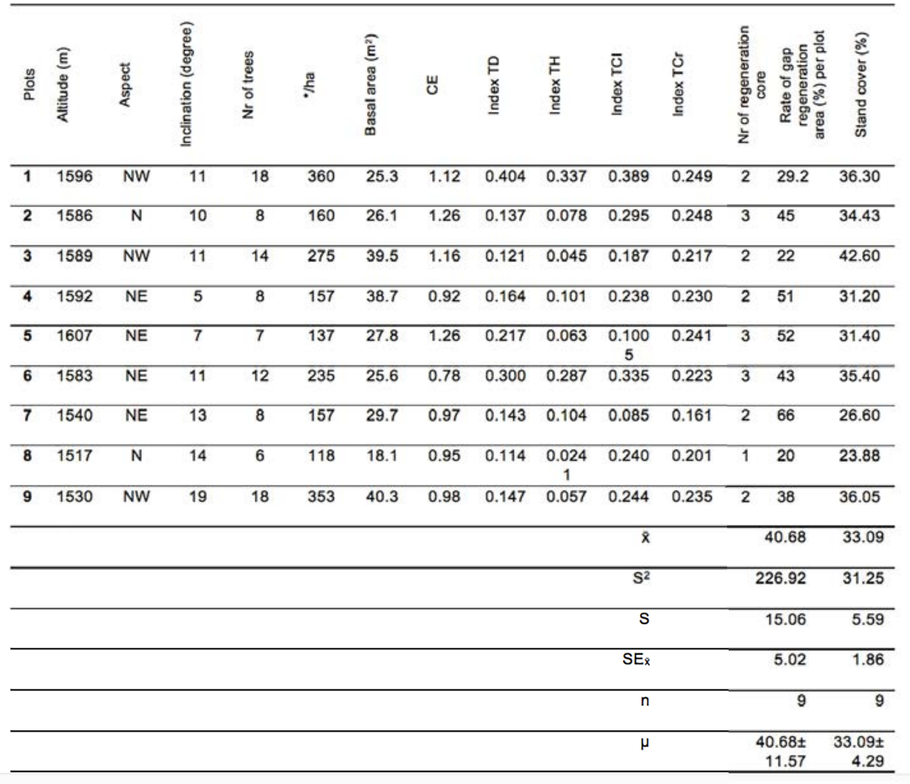


Figure 5 ab: Height of saplings within regeneration cores under Intermediate gap size gradient (Stem analyses from 64 Edge saplings and 31 Main crop saplings are shown in the graph).

Abbildung 5ab: Höhe der Pflanzen innerhalb der Verjüngungs-Kernbereiche entlang des Gradienten der Waldlücken (Stammanalysen von 64 Pflanzen von Randbereichen der Verjüngungs-Kernbereiche und 31 Pflanzen von Mitte der Verjüngungs-Kernbereiche sind in der Grafik dargestellt).

Table 5: Description of sample plots with spatial indices. Data and statistical analysis from nine regeneration cores (n = 9, v = 8, t = 2.306), μ (Eq. 2). This was confirmed by Student's t–test (p = 0.05): Arithmetic mean of 95% confidence interval of total population.

Tabelle 5: Beschreibung von Musterplots mit räumlichen Indizes. Daten und statistische Auswertung von neun Verjüngungs-Kernbereichen (n=9, v=8, t=2.306), μ (Gl. 2). Dies wurde durch den Student's t-Test (p = 0,05) bestätigt: Arithmetisches Mittel von 95% Konfidenzintervall der Gesamtpopulation.



Plots	Altitude (m)	Aspect	Inclination (degree)	Nr of trees	*/ha	Basal area (m²)	CE	Index TD	Index TH	Index TCI	Index TCr	Nr of regeneration core	Rate of gap regeneration area (%) per plot	Stand cover (%)
1	1596	NW	11	18	360	25.3	1.12	0.404	0.337	0.389	0.249	2	29.2	36.30
2	1586	N	10	8	160	26.1	1.26	0.137	0.078	0.295	0.248	3	45	34.43
3	1589	NW	11	14	275	39.5	1.16	0.121	0.045	0.187	0.217	2	22	42.60
4	1592	NE	5	8	157	38.7	0.92	0.164	0.101	0.238	0.230	2	51	31.20
5	1607	NE	7	7	137	27.8	1.26	0.217	0.063	0.1005	0.241	3	52	31.40
6	1583	NE	11	12	235	25.6	0.78	0.300	0.287	0.335	0.223	3	43	35.40
7	1540	NE	13	8	157	29.7	0.97	0.143	0.104	0.085	0.161	2	66	26.60
8	1517	N	14	6	118	18.1	0.95	0.114	0.0241	0.240	0.201	1	20	23.88
9	1530	NW	19	18	353	40.3	0.98	0.147	0.057	0.244	0.235	2	38	36.05
										$\bar{x}$			40.68	33.09
										S^2			226.92	31.25
										S			15.06	5.59
										SE_x			5.02	1.86
										n			9	9
										μ			40.68± 11.57	33.09± 4.29

4. Discussion and Conclusions

Research on forest dynamics commonly requires measurement of gap sizes (Whitmore et al. 1993), and measurements may be compared across gap size-classes and with closed canopy portions of these systems (Bolton & D'Amato 2011). There have been many definitions and measurement methods for gaps, so this is noted in the review of the literature (Yamamoto 2000). Runkle (1982) was one of the first who summarized the gap terminology and methodical aspects in the context of field measurements. He introduced two different patterns: 'canopy gap' and 'expanded gap', which differ in edge definition of gap area (Huth & Wagner 2006). Currently, several methods are available to define and estimate gap size and no single method seems to have been universally adopted. This is a critical issue because the use of different methods can generate different values while measuring the same phenomenon. For example, gap sizes can vary by up to eight times depending on the definition used (de Lima 2005). In this context, a definition of gaps containing trees up to 10 m is considered appropriate for the evaluation of natural regeneration in old-growth forests with irregular stand structure.

In the last two decades, many ecologists working on forest dynamics have focused their attention on gaps or openings created in the forest canopy (Kuuluvainen 1994; Kubo et al. 1996; Holeksa & Cybulski 2001; Schlicht & Iwasa 2004; de Lima 2005; Gálhidy et al. 2006; Huth & Wagner 2006; Kathke & Bruelheide 2010; Bolton & D'Amato 2011). Although numerous studies on gap dynamics of natural forests have been conducted, applications of gap dynamics to forest practice are limited. However, accumulated knowledge on gap dynamics is useful for sustainable forest ecosystem management (Yamamoto 2000). Neverthless, little attention has been paid to gaps as an important element of forest structure (Holeksa & Cybulski 2001). Breaks in the canopy have an important influence on the regeneration of different species of trees. The variation may be responsible for initiating and sustaining diversity within the ecosystem by providing a variety of different local micro-environments for regeneration of trees (Schlicht & Iwasa 2004). There is an abundant literature on population structure and factors affecting natural regeneration in Scots pine in Europe (González-Martínez & Bravo 2001; Valkonen et al. 2002; Montes et al. 2007) and in Turkey (Pamay 1962). However, the characteristics of naturally-occurring Scots pine saplings under the different gap sizes are only poorly studied. Yet estimates of gap sizes are becoming increasingly important in forest management. The demand for natural landscapes, the multi-resource use of forests, and the high cost of plantations all help to focus European foresters' attention on natural regeneration (González-Martínez & Bravo 2001). In this context, the determination of gap size classes in Scots pine stands within the regeneration core (Small, intermediate and large), the regeneration cores of natural Scots pine saplings (Figure 3), and sapling growth-rates in the gaps (Table 2), have been reported by Çoban et al. (2016), Pamay (1962), Genç (2004) and Odabaşı et al. (2004).

The size of gaps and the processes of gap formation and canopy recovery have been studied intensively, and extensive data are now available from different field sites (Schlicht & Iwasa 2004). Mean gap size (extending to the bases of trees surrounding the gap) was found to be about 200 m² in some old-growth forests of the Eastern United States (Runkle 1982). Huth & Wagner (2006) reported that most of the gaps were between 50 and 100 m², although study areas and environmental factors differ greatly. It has been reported that the mean gap size is 30 to 140 m² for temperate forests (Yamamoto 2000). In Japan, Yamamoto (1996) indicated that mean gap size was 77.1 m² in warm-temperate forests, 92.0 m² in cool-temperate forests, and 43.3 m² in subalpine forests. In this study, gaps with sapling regeneration cores had a mean size of 91.55 ± 23.69 m² (Table 1). Therefore, the results of this research, with the study area at the edge of the Eurasian distribution of Scots pine, were found to be consistent with previous research findings.

Gálhidy et al. (2006), indicated that gap size had a profound effect on the environmental variables measured. While relative light intensity values in small gaps did not reach those in large gaps, soil moisture levels did reach similar maximum values in gap centres regardless of gap size (Gálhidy et al. 2006). In addition, Yu et al. (2014), found no significant difference between the diameters of middle gap and large gap seedlings, but the diameter of middle gap seedlings was higher than that of large gap, suggesting the middle gap would promote the regeneration and high-quality timber cultivation. The current study also showed that most of the gaps size classes were intermediate gaps (90%) while large (5%) and small gaps (5%) were rare. This indicates that Scots pine takes the advantage of relative light intensity values in the gaps. In addition, typical regeneration cores were not developed under small gaps where saplings are mostly sparsely distributed. Saplings under small gaps were mostly degenerated with a low growth potential. However, sapling regeneration was almost absent under closed stands. Gaps create a range of light conditions within and around the gap opening which depend on the sun angle (aspect and topography), tree height, and sky condition. As the size of an opening increases, the amount of light reaching the centre of the gap also increases as a function of both the diameter of the gap and the height of the surrounding stand, i.e., the sky view factor. At night, the sky view factor is related to radiation loss to the sky and the occurrence of summer frosts (Lieffers et al. 1999).

The practical application of this study requires the determination of sapling growth-rates in Scots pine stands within regeneration cores for the new silvicultural treatments based on gaps. This must then be linked to observations of field light regimes. The studies have revealed a significant relationship between gaps and regeneration core of saplings. Decreased canopy cover had a significant positive effect on sapling growth and this has been found by most studies in the past (Pamay 1962; Valkonen et al. 2002; Genç 2004; Odabaşı et al. 2004; Çoban et al. 2016). In this study, appropriate gap size classes and sapling growth in relation to the position within the regeneration cores were determined (Tables 1 and 2). Similar responses were found by Pukkala et al. (1993) with the correlation between the radiation parameters and Scots pine sapling growth significantly positive. As stated by Tegelmark (1998), regeneration core of naturally-occurring Scots pine saplings is potentially important in future stand development and sapling properties change with the evolving stages of the stand. Like Çoban et al. (2016), this study also found, that compared with saplings in the middle of regeneration cores (crop saplings), those at the edge were always reduced in terms of mean height. In this respect, other key factors except light were intraspecific competition (Kuuluvainen & Juntunen 1998; González-Martínez & Bravo 2001), sapling position in the regeneration cores (Pamay 1962), and root competition with mature trees (Valkonen 2000; Siipilehto 2006; Montes & Cañellas 2007). Examination of the positions of previously removed trees indicated that root system shape and extent resulted from past competition prior to regeneration works (Valkonen 2000).

Research on shade tolerance suggests that there are species-specific physiological and growth adaptations which influence the ability to survive and grow at different levels of light. For example, in low light, shade-tolerant *Abies* species exhibit reduced height and diameter growth without mortality, but this is not true for pine species (Kobe & Coates 1997; Mason et al. 2004). Scots pine is a typical shade-intolerant pioneer (Coates & Burton 1999; de Chantal et al. 2003; Ewald 2007; Kowalska et al. 2016) for which regeneration is practically restricted to open, non-forest vegetation. Its behaviour in native pinewoods in Scotland certainly reflects this (Ewald 2007). While the broad classification of species as 'shade tolerant', 'intermediate', or 'light demanding' appear to be consistent between regions (Mason et al. 2004). However, the behaviour is not totally fixed and shade tolerance within species may be affected by site quality (Carter & Klinka 1992). Consequently, the magnitude of the competition effect may vary between geographical areas along with differences in site productivity. However, there is little published research available to evaluate or quantify this hypothesis (Valkonen 2000). Sapling establishment and development continues out of the dense groups of the younger cohort, under the protection of the low density groups of remaining mother trees. This semi-shade tolerant behaviour found in the southern distribution of Scots pine, i.e. the Sistema Central range, the Iberian Mountain Range, and other enclaves in Spain, is quite different from the poor shade tolerance shown by the species in the rest of its distributional area (Montes & Cañellas 2007). Although Scots pine is generally considered a shade intolerant species (de Chantal et al. 2003), with increasing site quality it can survive for long periods under a dense forest canopy (Odabaşı et al. 2004; Çoban et al. 2016). Species-specific growth responses show little difference under high available light conditions, but performance at low light levels is generally consistent with shade tolerance rankings in the literature. The exception was that Scots pine shade intolerance was higher than expected (Claveau et al. 2002). Some previous studies suggest that Scots pine saplings cannot survive long under a dense forest canopy (Ata 1995; Genç 2004). However, the results of stem sapling analyses and inspection of the age-height graph showed that naturally-occurring saplings of Scots pine in the gaps have intermediate shade-tolerant characteristics (Figure 5; Table 2). Scots pine saplings as a shade-intolerant species act as intermediate shade-tolerant saplings in the gaps, that are able to thrive in the intermediate shade and do not require full sunlight (Figure 3 and 5; Table 2). It seems that for the time-periods considered, naturally-occurring Scots pine saplings in the gaps are intermediate-tolerant even though they are suppressed. Pamay (1962) described this situation as the "semi-shade type" of Scots pine. This is important since a more detailed understanding of species response to different light levels can help the development of appropriate silvicultural prescriptions to promote varied forest structures with improved species diversity. Linked to other decision-making tools this can inform the potential impacts of different stand management regimes (Mason et al. 2004).

Recent studies of shade tolerance have examined the relationships between mortality and growth in varying light conditions (Kobe et al. 1995; Kobe & Coates 1997; Wyckoff & Clark 2002; Kunstler et al. 2005; Löf et al. 2007). Furthermore, Ata (1995), suggested that older suppressed saplings must be accepted as degenerated individuals that are located under a dense forest canopy and lost their vigour. However, Çoban et al. (2016) indicated that these older saplings retain their growth potential during suppression and can recover when the opportunity arises. Vaat & Vildo (2005) concluded that for Scots pine such management intervention with thinning and opening up the canopy needed to be within the first six years and stand densities should be radically reduced (recommended to be to the minimum values allowed by forest legislation or guidance). Additionally, high-density stands will be unsuitable for shelterwood cutting due to shorter crowns and a higher risk of windfall after repeated over-storey removals. This research found a good sapling survival in the gaps under the semi-shade conditions (Figure 5). It is suggested that key elements to the interpretation of this situation are the local differences and distinctiveness of landscapes, together with variations in forest product extraction and management. The application of similar management regimes for all forest zones regardless of stand properties is not sustainable.

As a conclusion, this study supports the point of view that one of the most important rules of close-to-nature silviculture is in the protection and generation of irregular stand structures (multi-layer stand, uneven-aged stands etc.). However, is such a scenario possible? It can be speculated that ageing of the stands and their further thinning will accelerate gap formation. Once old stands start to decrease in density, then more and more trees are likely to be exposed to wind gusts and deposits of snow and rime. At the same time the development of a new generation will probably lag behind enlargement of open areas (Holeksa & Cybulski 2001). According to the findings of this study, the stands of parent Scots pine and older saplings in gap regeneration cores may occur together. In this manner, a model based on gap-regenerating forests can be established as an alternative to a shelterwood system. Although many studies have been conducted on gap dynamics of natural forests, the application of gap dynamics to forest practice is limited (Yamamoto 2000). However, as many studies suggested, accumulated knowledge on gap dynamics should be useful for sustainable forest ecosystem management.

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