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

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1 **Effects of canopy gap size on the regeneration of Scots pine (*Pinus sylvestris* L.) in**

2 **Eskişehir-Çatacık region of Turkey**

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9 # Abstract

10 The study was undertaken in Scots pine shelterwood forests in central Anatolia at the edge of the

11 Eurasian distribution of Scots pine and thus adding significance in terms of understanding the

12 ecology of this important species. Canopy gap size and the position of the sapling within the

13 regeneration cores were chosen within 9 different strip-sample plots comprising 20 sapling

14 regeneration cores. Those sapling regeneration cores under the gaps were divided into two portions

15 (individuals at the edge and middle of the regeneration cores) and from each portion three

16 individuals were selected. The growth relationships of individual saplings within the regeneration

17 cores were determined from the age-height graph of 95 sapling-stem analyses. Gap-size classes that

18 compromise a gap size gradient were chosen: small gaps (< 20 m^2); intermediate gaps (20 - 177

19 m^2); large gaps (178 - 707 m^2). Spatial structure of mature trees were determined using the Clark-

20 Evans index. In addition, differentiation index (diameter, height, crown lenght, and crown radius)

21 were calculated for each stand projections.

22 Gaps with sapling regeneration cores ranged from 15 to 240 m^2, with a mean of 91.55 ± 23.69 m^2

23 by Student's t-test (p = 0.05). The maximal gap-size classes were found in the intermediate (90%),

24 followed by large (5%) and small (5%). Compared with saplings in the middle of regeneration

25 cores, those at the edge were always reduced in terms of mean height. Significant difference was

26 found between the 'Main crop' and the 'Edges 1-2' of the regeneration cores. There was no

27 significant difference for sapling age in regeneration cores. Fraction of land area in gap

28 regeneration cores was found between 20 and 66% of total stand area. The age-height graph of 95

1   sapling-stems derived from stem analyses showed that the saplings grow very well without any

2   obvious deceleration in the gaps.

3   These findings can further inform forest managers about how to optimize growth of sapling by

4   means of canopy gap regulation. The results are discussed in the context of future silvicultural

5   modelling and new ways of assessing forest regeneration dynamics when gap-regeneration is

6   important.

7   **Keywords**: Canopy gaps size; gap-based silvicultur; gap regeneration; sapling growth

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 $100m^2$ 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).

1   Although forest ecologists and silviculturalists have emphasized the importance of creating gaps to

2   generate spatial variation in order to promote tree regeneration, the effects of gap on seedling

3   recruitment may be offset by the development of dense forest understoreys. This limits

4   regeneration even in gap conditions, and reduces the effectiveness of gaps (Beckage et al. 2005;

5   Ruuska et al. 2008). Understanding the behaviour of the seedlings of different tree species in

6   relation to canopy shade is therefore important (Çoban et al. 2016).

7   There is an abundant literature on the factors affecting natural regeneration in Scots pine forests.

8   Scots pine seed trees have an effect on the structure of pine seedlings (i.e. morphological

9   characteristics), their spatial pattern, and their size distribution (Kuuluvainen 1994; Valkonen et al.

10   2002; Castro et al. 2004; Zagidullina & Tikhodeyeva 2006). Both height and seedling density

11   decrease close to the parent trees (Siipilehto 2006). Competition from the mother trees inhibits

12   development of saplings in close proximity (Montes and Canellas, 2007). However, the growth of

13   naturally occurring saplings in response to variations in canopy cover density of Scots pine stands

14   are poorly studied in the southern zone of its distribution area (Kuuluvainen et al. 1993; Cameron

15   & Ives 1997; Beckage et al. 2005; Andrzejczyk 2007; Löf et al. 2007). Studies on regeneration and

16   advance growth have shown that the effects of the long-term retention of seed trees has a strong

17   negative impact on the development of young Scots pine stands, especially on relatively infertile

18   sites in the northern areas of its natural distribution (Ruuska et al. 2008). However, the relationship

19   beween sapling height development and the position within gap regeneration cores is not known for

20   semi-arid site conditions.

21   The aims of this study were 1) to determine the growth characteristics of the sapling affected by the

22   position within the regeneration cores, 2) to predict the most appropriate gap-size classes for the

23   development of regeneration cores of shade-intolerant Scots pine saplings, 3) to consider whether

24   responses vary with the shade-tolerance variation of Scots pine saplings.

Materials and Methods

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 $39^{\circ}57'$ and $39^{\circ}58'$ N, longitude between $31^{\circ}06'$ and $31^{\circ}08'$ 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 m 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 m^2 (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.

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).

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

1 (Holeksa and Cybulski, 2001). In this study, a canopy gap was defined as the ground area under a

2 canopy-opening with sapling regeneration cores which extend to the bases of canopy trees

3 surrounding the canopy-opening (modified from Runkle (1982)).

4 Gap classes were measured and presented in square metres (m^2) since gap shape varies greatly and

5 the gap size classes of Çoban et al. (2016) presenting a gap-size gradient were chosen. The Scots

6 pine stands were allocated into 1 of 3 different gap sizes (Small, intermediate and large gaps)

7 distinguished by gap size gradients in the shelterwood. These three gap size gradients are as

8 follows (Çoban et al. 2016):

9   1) Small gaps with a diameter of < 5 m (<20 m^2);

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

11   3) Large gaps with a diameter of 15 to 30 (178 to 707 m^2).

12 Measures of gaps with sapling regeneration cores assess the presence or absence of canopy

13 vertically above a sample of points across an area of forest by the vertical projection of the tree

14 crowns. Gaps under a canopy opening with sapling regeneration cores were calculated from

15 horizontal projection in the stand projection (10 m x 50 m) on the millimetric graph paper in

16 square metres. As it was also found by Çoban et al. (2016), average diameter of regeneration cores

17 did not exceed 8-10 m. In order to determine the relation between stand structure and regeneration

18 cores, horizontal stand projections were laid to cover regeneration cores. In addition, gap sizes

19 were also measured out from stand projection when it exceeded horizontal projection. Since all of

20 the regeneration cores except those under large gaps were included in the stand projection, the

21 width of the stand projection was not increased.

22 Gaps were taken to become indistinguishable from the background overstory when regeneration

23 within the gap has young trees of 10 m or more in height. All individuals taller than 1 m within

24 gaps are referred to as saplings (Runkle 1981).

25 **Selection of sample plots and field procedures**

26 Shelterwood cutting areas in the Scots pine stands of 110 to 140 years-old had uniform levels of

27 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 m 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 m 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).

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

1 commercial harvest, refers to those saplings with the highest score in both variables (dominant and

2 healthy) (González-Martínez & Bravo 2001).

3 **Sapling-stem analysis**

4 Sample saplings were cut down to ground level and stem cuts were taken at 1 m intervals for stem

5 analysis (Atıcı 1998; Kalıpsız 1998; Atıcı 2003). In the stem analysis, ages at each cross-section

6 were calculated from the differences in annual rings for the cross-sections to give sapling age.

7 Then, the height-growth model which was firstly proposed by Prodan (1961) and used many

8 authors (Akalp 1976; Asan 1984; Usta 1990; Erkan 1996; Özcan 2003; Özdemir 2005; Şenyurt

9 2005; Çatal 2009; Özdemir & Özdemir 2016; Özdemir & Saraçoğlu 2016) was calculated (Eq. 1).

10 $H = \frac{t^2}{a_0 + a_1 \times t + a_2 \times t^2}$ (Eq. 1)

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

12

13

14 **Analysis of stand structure of sample plots**

15 The spatial distribution of mature trees was determined using the nearest-neighbour method in

16 order to show its effect on regeneration cores. For this reason, the Clark-Evans index of clumping

17 (CE) which is based on distances between individuals was used. This index is a measure of the

18 extent to which the observed population differs from the randomly distributed one. A population

19 distributed randomly shows CE = 1.0, while regularity can be assumed if CE > 1.0 and index CE <

20 1.0 indicates the clumped distribution of individuals (Clark & Evans 1954; Kint 2004; Szmyt

21 2014). In addition, the differentiation index which describes the degree of dissimilarity of sizes

22 between neighbouring trees (i.e., diameter (TD), height (Th), crown length (TCL) and crown radius

23 (TCr)) was calculated for all stand projections. This index has values varying between 0 (no

24 differentiation) and 1 (complete differentiation) (Pommerening 2002). For 4 nearest neighbours the

25 5 differentiation classes can be applied (Aguirre et al. 2003; Kint 2004; Szmyt 2014)(Aguirre et al.

26 2003; Kint 2004; and Vorčak at al. 2008):

27   1) 0.0 - 0.20 (very small differentiation),

1   2) 0.20 - 0.40 (small differentiation),

2   3) 0.40 - 0.60 (clear differentiation),

3   4) 0.60 - 0.8 (large differentiation)

4   5) 0.80 - 1.00 (very large differentiation).

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

6   **Data analysis**

7   The following equation (Eq. 2) was used to calculate 95% confidence intervals of populations of all

8   measured data (Sachs 1970; Kalıpsız 1981; Atıcı et al. 2008):

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

10 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

11 freedom = 2.306, n is 9 number of samples.

12 Statistical evaluation including nonparametric test (Kruskal-Wallis H Test), One-way Variance

13 Analyses (ANOVA) and t-tests were applied to the data using SPSS 21 software for Windows.

14

15 # Results

16 **The frequency distribution of natural sapling under different gap size gradients**

17 Gaps with sapling regeneration cores ranged from 15 to 240 m^2. Arithmetic mean of 95%

18 confidence interval of total population (μ value) by Student's t-test (p = 0.05) is 91.55 $\pm$ 23.69 m^2

19 (Table 1). The maximal gap size classes were found in the intermediate (90%), followed by large

20 (5%) and small (5%) (Table 1 and 2). These differences were shown to be statistically significant

21 (p < 0.001, Table 2) by the Kruskal-Wallis H test (Table 1). The results suggest that large (5%)

22 and small (5%) were rare within gap size classes (Figure 3; Tables 1 and 2) and this was

23 significant. This test was applied to the difference in the gap size gradients of regeneration cores.

24 The situation was consistent in all sample plots with longitudinal (profile) and vertical projection of

25 stands (Figure 3). The shapes of gap areas vary from elliptic to circular within Scots pine stands,

26 which affects the micro-environment within a gap (Figure 3).

27 **The height growth of older sapling in regeneration cores**

1   Compared with saplings in the middle of a regeneration core or cluster, those on the edge were

2   always shorter with μ value (Table 3). The differences in μ value were found for Edge 1: 1.576 ±

3   0.269 m; Main crop: 2.998 ± 0.472 m; Edge 2: 1.895 ± 0.719 m. Due to height differentiation

4   between edges and Main crop, a regeneration core form develops (Table 3; Figure 3). The

5   distribution of saplings in different height classes in the sapling regeneration cores revealed that

6   they were shorter beneath the canopy than beyond the canopy (Figure 3). These were statistically

7   significant between the Main crop and Edge 1 (t = 6.019; p = 0.000) and between the Main crop

8   and Edge 2 (t = 0.752; p = 0.009) (Table 3). One-way Variance Analysis (ANOVA) was carried

9   out to test the differences in sapling age between Main crop saplings and both Edge saplings in the

10   regeneration cores. There was no significant difference (between the Main crop and Edge 1: F =

11   0.412; p = 0.149; between the Main crop and Edge 2: F = 0.005; p = 0.440) for sapling age in

12   regeneration cores. These μ values were found for Edge 1: 12.48 ± 3.59 year; Main crop: 16.29 ±

13   4.54 years; Edge 2: 13.79 ± 5.69 years (Table 4; Figure 4).

14   **The growth of individual saplings in the regeneration cores**

15   Regeneration cores under small gaps do not show good development since most saplings are below

16   1.5 m height and unhealthy. On the other hand, there is not a distinct growth difference among

17   saplings of large gaps.

18

19   The age-height graph of 95 sapling-stems derived from stems analyses showed that the saplings

20   grow very well without any obvious deceleration in the intermediate gaps (Figure 5ab). According

21   to the stem analysis of the saplings, there was a slow height growth increment at the early stages

22   which increased after 10 years. For the 25 to 30-year-old saplings, an increment occurred even

23   after 15 years. In addition, the height-growth rate of Edge saplings was lower than those of Main

24   crop saplings. On the other hand, Main crop saplings had a higher height-growth performance

25   under wide intermediate gaps (between 130 and 160 m^2) compared to saplings under small

26   intermediate gaps (60 and 105 m^2) but Edge saplings did not show a clear difference between these

27   gap sizes (Figure 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, TCI, 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).

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).

1　The size of gaps and the processes of gap formation and canopy recovery have been studied

2　intensively, and extensive data are now available from different field sites (Schlicht & Iwasa 2004).

3　Mean gap size (extending to the bases of trees surrounding the gap) was found to be about 200 m^2

4　in some old-growth forests of the Eastern United States (Runkle 1982). Huth & Wagner (2006)

5　reported that most of the gaps were between 50 and 100 m^2, although study areas and

6　environmental factors differ greatly. It has been reported that the mean gap size is 30 to 140 m^2 for

7　temperate forests (Yamamoto 2000). In Japan, Yamamoto (1996) indicated that mean gap size was

8　77.1 m^2 in warm-temperate forests, 92.0 m^2 in cool-temperate forests, and 43.3 m^2 in subalpine

9　forests. In this study, gaps with sapling regeneration cores had a mean size of 91.55 ± 23.69 m^2

10　(Table 1). Therefore, the results of this research, with the study area at the edge of the Eurasian

11　distribution of Scots pine, were found to be consistent with previous research findings.

12　Gálhidy et al. (2006), indicated that gap size had a profound effect on the environmental variables

13　measured. While relative light intensity values in small gaps did not reach those in large gaps, soil

14　moisture levels did reach similar maximum values in gap centres regardless of gap size (Gálhidy et

15　al. 2006). In addition, Yu et al. (2014), found no significant difference between the diameters of

16　middle gap and large gap seedlings, but the diameter of middle gap seedlings was higher than that

17　of large gap, suggesting the middle gap would promote the regeneration and high-quality timber

18　cultivation. The current study also showed that most of the gaps size classes were intermediate gaps

19　(90%) while large (5%) and small gaps (5%) were rare. This indicates that Scots pine takes the

20　advantage of relative light intensity values in the gaps. In addition, typical regeneration cores were

21　not developed under small gaps where saplings are mostly sparsely distributed. Saplings under

22　small gaps were mostly degenerated with a low growth potential. However, sapling regeneration

23　was almost absent under closed stands. Gaps create a range of light conditions within and around

24　the gap opening which depend on the sun angle (aspect and topography), tree height, and sky

25　condition. As the size of an opening increases, the amount of light reaching the centre of the gap

26　also increases as a function of both the diameter of the gap and the height of the surrounding stand,

1   i.e., the sky view factor. At night, the sky view factor is related to radiation loss to the sky and the

2   occurrence of summer frosts (Lieffers et al. 1999).

3   The practical application of this study requires the determination of sapling growth-rates in Scots

4   pine stands within regeneration cores for the new silvicultural treatments based on gaps. This must

5   then be linked to observations of field light regimes. The studies have revealed a significant

6   relationship between gaps and regeneration core of saplings. Decreased canopy cover had a

7   significant positive effect on sapling growth and this has been found by most studies in the past

8   (Pamay 1962; Valkonen et al. 2002; Genç 2004; Odabaşı et al. 2004; Çoban et al. 2016). In this

9   study, appropriate gap size classes and sapling growth in relation to the position within the

10 regeneration cores were determined (Tables 1 and 2). Similar responses were found by Pukkala et

11 al. (1993) with the correlation between the radiation parameters and Scots pine sapling growth

12 significantly positive. As stated by Tegelmark (1998), regeneration core of naturally-occurring

13 Scots pine saplings is potentially important in future stand development and sapling properties

14 change with the evolving stages of the stand. Like Çoban et al. (2016), this study also found, that

15 compared with saplings in the middle of regeneration cores (crop saplings), those at the edge were

16 always reduced in terms of mean height. In this respect, other key factors except light were

17 intraspecific competition (Kuuluvainen & Juntunen 1998; González-Martínez & Bravo 2001),

18 sapling position in the regeneration cores (Pamay 1962), and root competition with mature trees

19 (Valkonen 2000; Siipilehto 2006; Montes & Cañellas 2007). Examination of the positions of

20 previously removed trees indicated that root system shape and extent resulted from past

21 competition prior to regeneration works (Valkonen 2000).

22 Research on shade tolerance suggests that there are species-specific physiological and growth

23 adaptations which influence the ability to survive and grow at different levels of light. For example,

24 in low light, shade-tolerant *Abies* species exhibit reduced height and diameter growth without

25 mortality, but this is not true for pine species (Kobe & Coates 1997; Mason et al. 2004). Scots pine

26 is a typical shade-intolerant pioneer (Coates & Burton 1999; de Chantal et al. 2003; Ewald 2007;

27 Kowalska et al. 2016) for which regeneration is practically restricted to open, non-forest

1 vegetation. Its behaviour in native pinewoods in Scotland certainly reflects this (Ewald 2007).

2 While the broad classification of species as 'shade tolerant', 'intermediate', or 'light demanding'

3 appear to be consistent between regions (Mason et al. 2004). However, the behaviour is not totally

4 fixed and shade tolerance within species may be affected by site quality (Carter & Klinka 1992).

5 Consequently, the magnitude of the competition effect may vary between geographical areas along

6 with differences in site productivity. However, there is little published research available to

7 evaluate or quantify this hypothesis (Valkonen 2000). Sapling establishment and development

8 continues out of the dense groups of the younger cohort, under the protection of the low density

9 groups of remaining mother trees. This semi-shade tolerant behaviour found in the southern

10 distribution of Scots pine, i.e. the Sistema Central range, the Iberian Mountain Range, and other

11 enclaves in Spain, is quite different from the poor shade tolerance shown by the species in the rest

12 of its distributional area (Montes & Cañellas 2007). Although Scots pine is generally considered a

13 shade intolerant species (de Chantal et al. 2003), with increasing site quality it can survive for long

14 periods under a dense forest canopy (Odabaşı et al. 2004; Çoban et al. 2016). Species-specific

15 growth responses show little difference under high available light conditions, but performance at

16 low light levels is generally consistent with shade tolerance rankings in the literature. The

17 exception was that Scots pine shade intolerance was higher than expected (Claveau et al. 2002).

18 Some previous studies suggest that Scots pine saplings cannot survive long under a dense forest

19 canopy (Ata 1995; Genç 2004). However, the results of stem sapling analyses and inspection of the

20 age-height graph showed that naturally-occurring saplings of Scots pine in the gaps have

21 intermediate shade-tolerant characteristics (Figure 5; Table 2). Scots pine saplings as a shade-

22 intolerant species act as intermediate shade-tolerant saplings in the gaps, that are able to thrive in

23 the intermediate shade and do not require full sunlight (Figure 3 and 5; Table 2). It seems that for

24 the time-periods considered, naturally-occurring Scots pine saplings in the gaps are intermediate-

25 tolerant even though they are suppressed. Pamay (1962) described this situation as the "semi-shade

26 type" of Scots pine. This is important since a more detailed understanding of species response to

27 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.

Acknowledgements

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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.

Number of sample plots	Regeneration core in sample plots (Figure 3)	Gap sizes (m^2)
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).

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		

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			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	L_7	1
7	S_7	0	I_{15}	1	L_8	0
8	S_8	0	I_{16}	1	L_9	0
9	S_9	0	I_{17}	1		

Frequencydistribution					
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.		$p < 0.001$

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.

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

	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.

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

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.

| Plots	Altitude (m)	Aspect	Inclination (degree)	Nr of trees	*/ha	Basal area (m^2)	CE	Index TD	Index TH	Index TCl	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
											x̄		40.68	33.09
											S^2		226.92	31.25
											S		15.06	5.59
											SE$_{x̄}$		5.02	1.86
											n		9	9
											μ		40.68± 11.57	33.09± 4.29
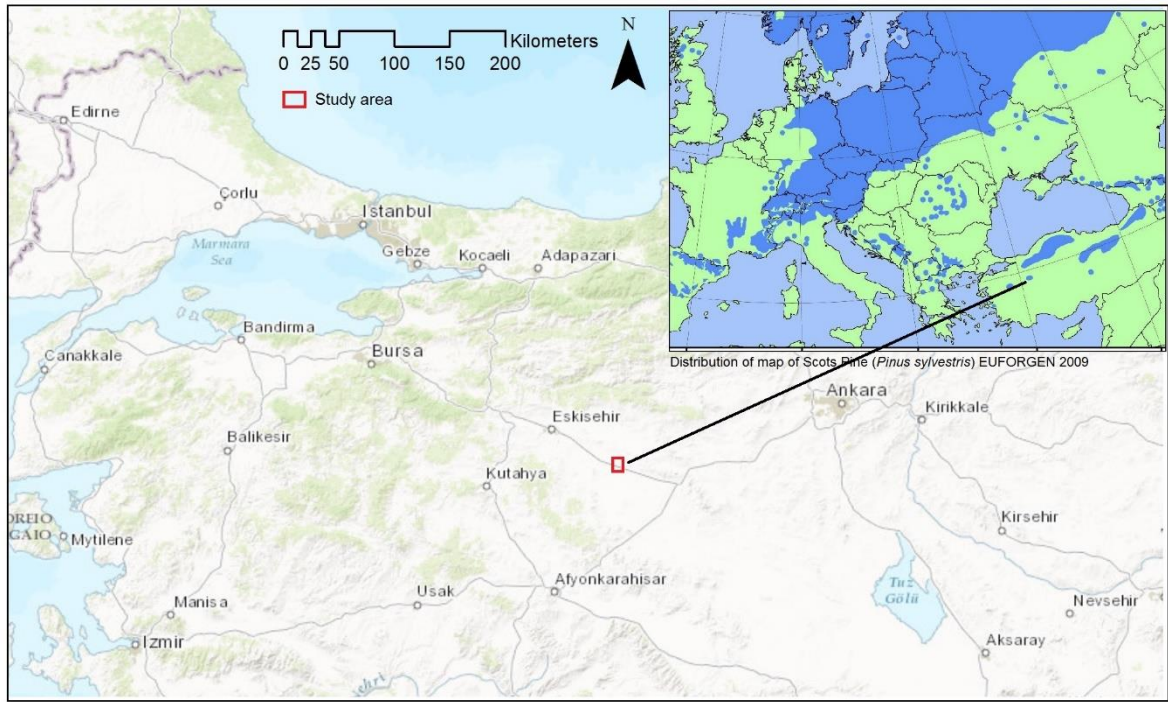
Figure 1. Natural distribution range of *Pinus sylvestris* L. (EUFORGEN, 2009) and location of sample plots.
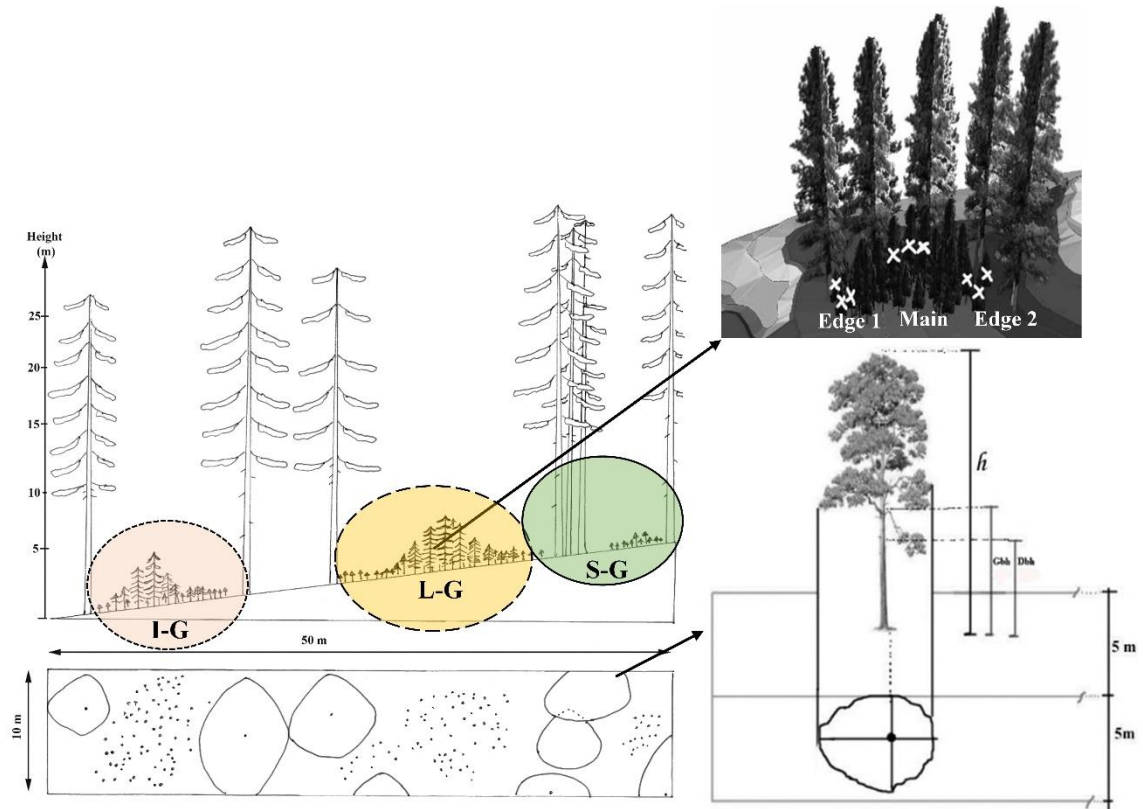
Figure 2. The gap size gradient models of Scots pine stands with three gap gradients (Zhang & Zak 1995): Small gaps (S) with a diameter of < 5 m (< 20 m^2); Intermediate gaps (I) with a diameter of 5 - 15 m (20 - 177 m^2); Large gaps (L) with a diameter of 15 - 30 m (178 - 707 m^2) (longitudinal and vertical projection of stands from (Coban 2007, Coban et al. 2016).
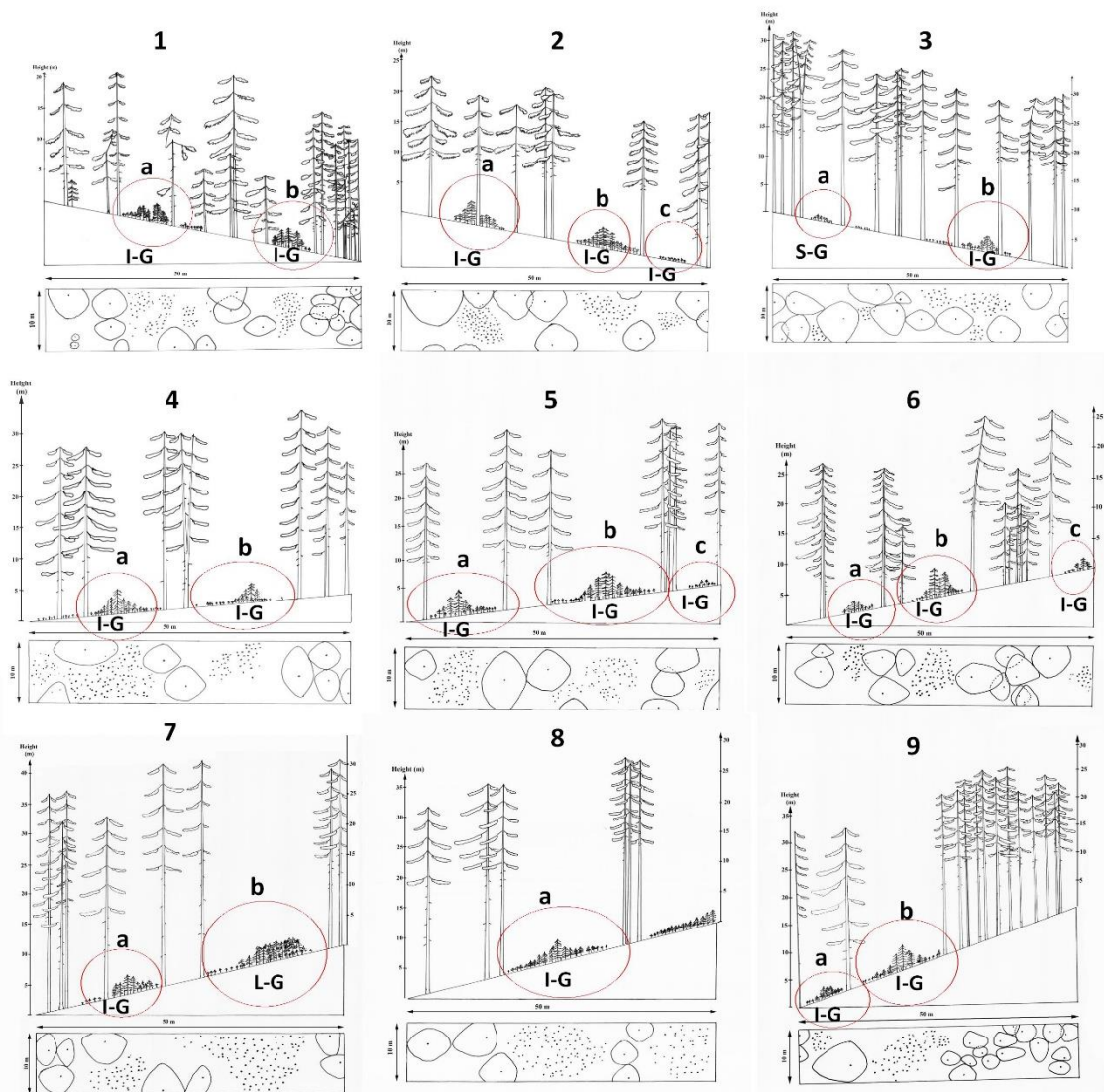
Figure 3. Longitudinal (profile) and vertical stand projection of 20 sample plots with different gap size gradients within the regeneration cores (S-G: Small gaps; I-G: Intermediate gaps; L-G: Large gaps) in pure Scots pine stands.
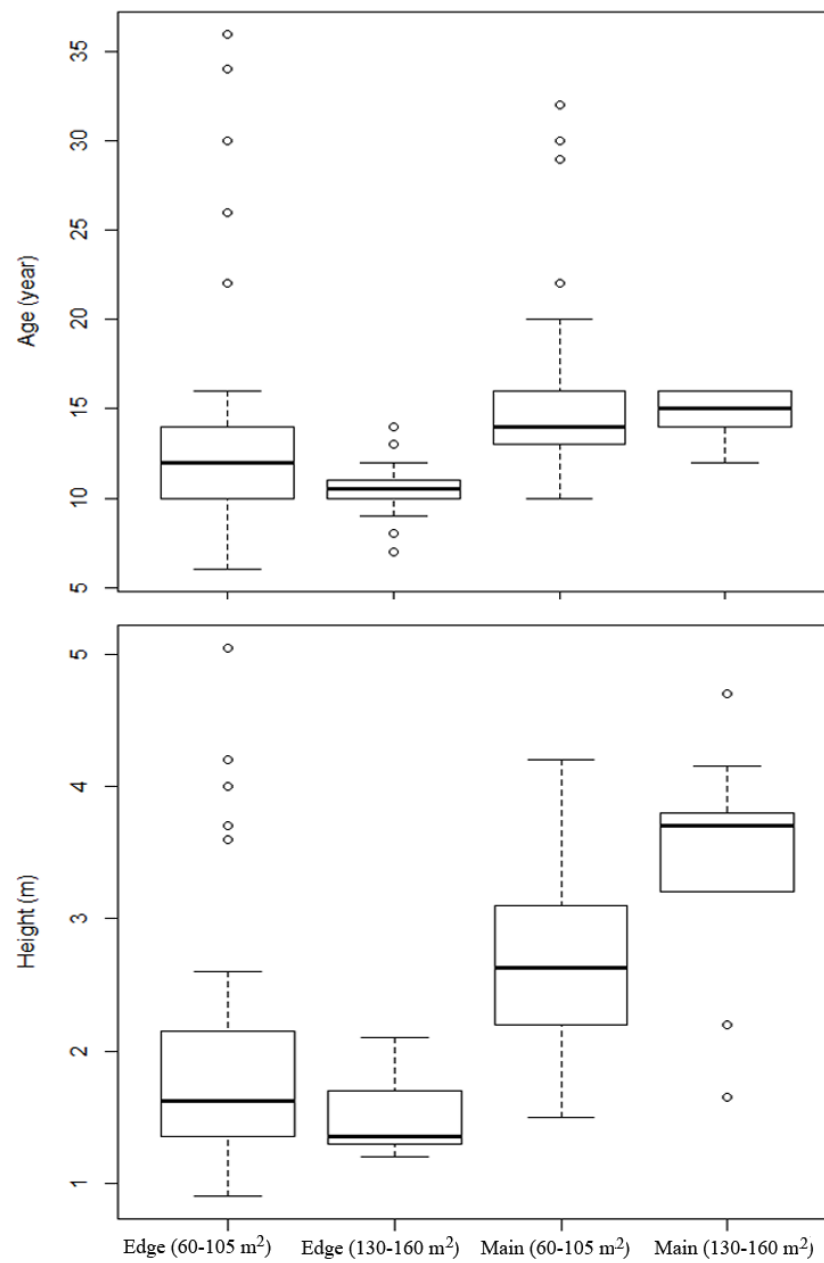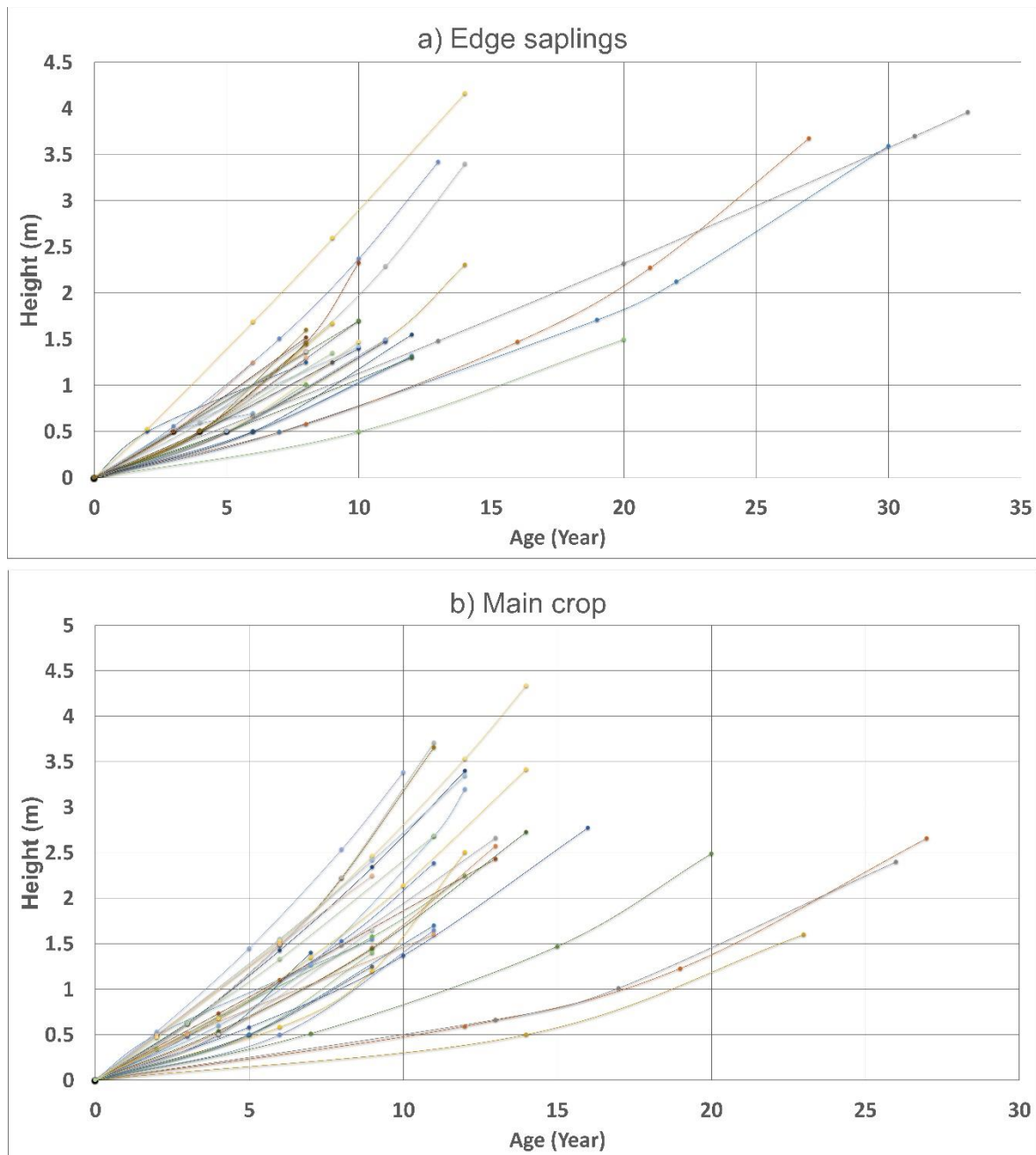
Figure 4. Boxplots of sapling age (above) and height (below) in relation to their position in the regeneration core and sizes of intermediate gaps.

Figure 5. 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).