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Tree growth response at stand edges in gap cutting in Finland

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ABSTRACT

This study provided the models to quantify the edge effect of gap cuttings on surrounding trees growth for pine, spruce, and birch. The developed models predict tree level growth as a function of tree distance from the gap edge with other commonly used growth factors. The models were based on data from 21 gap cutting experiments of pine and spruce dominated stands located in Central and Eastern Finland. Gap cutting had a significant positive effect on tree diameter growth for all tree species in the remaining edge stand. The trend was nonlinear, i.e. the growth acceleration was greatest in the immediate vicinity of the gap, diminishing rapidly towards stand interior, and was virtually extinguished 10 m away from the edge. The effect of distance from the gap edge on height growth showed to be negative for birch and positive for pine and spruce. Despite the large range of gap size (0.1–0.6 ha) in the study material, the growth response showed to be insensitive to gap size. The detected diameter growth response means also increased stand basal area growth of nearby the gap edge. If the edge effect is not addressed basal area growth of the surrounding trees are underestimated. In our study this underestimate was on average by 7 % and 11 % for pine and spruce stands. Although natural regeneration is the most essential aim in gap cutting, the edge effect on the surrounding trees growth needs to be considered especially when assessing profitability of whole management chain for long run. Lack of suitable growth models for gap cuttings has caused challenges for predicting reliably stand developments in Finland.

1. Introduction

In the contemporary Nordic context, gap cutting is a silvicultural harvesting method that systematically opens small gaps. Its main use is in selection management, which is the key management paradigm in continuous cover forestry (CCF) (Brunner et al., 2025). A key contemporary application in Finland is to establish gaps simultaneously with single-tree harvesting in a stand in order to boost regeneration and the growth of existing advance regeneration, particularly for shade-intolerant tree species (Äijälä et al. 2019). One variation of the theme is the gradual transformation of even-aged stands towards greater structural complexity aiming at the adoption of selection management. Gap cutting may also be applied in rotation forest management (RF) when aiming at natural regeneration of a stand in a more rapid succession (Brunner et al., 2025).

The tree growth response to the creation of a sharp stand edge through gap cutting is probably mostly attributable to changes in basic resource availability (see e.g. Oliver and Larson, 1990). The edge trees enjoy a much higher intensity of direct sunlight than before (Canham et al., 1990; Gray et al., 2002). The depth and intensity with which it penetrates into the stand is dependent on aspect, slope, latitude tree height, crown length, and species. Root systems expand into the released growing space in the gap (Biber and Pretzsch, 2022). A temporal lag in growth response is usually involved, pertaining to gradual progress in the physiological and morphological adaptation and root expansion. Its magnitude and duration depend on preharvest stand density, and tree species age, size, and vigor (Maguire et al., 2006; Thorpe et al., 2007, Garber et al., 2011; Gray et al., 2012, Biber and Pretzsch, 2022). Additionally, negative effects to tree vitality and growth at or near the edge may emerge due to intensified exposure to radiation, temperature, drought and wind (Harrington and Reukema, 1983; Garber et al., 2011). They are often visibly manifested as sun scald, leaf loss, and wind breakage or tipping for instance. Most of the positive and negative edge effects are restricted to trees on or near the edge, while progressively farther into the stand, conditions become more like those in the stand interior (Pedersen and Howard, 2004, Thorpe et al., 2007, Gray et al., 2012, Biber and Pretzsch, 2022).

Until now, silvicultural research on gap cutting in the Nordic

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countries has focused on regeneration (review by Lula et al., 2024) and elsewhere (Yamamoto, 2000, Muscolo et al., 2014, Zhu et al., 2014)). As it involves a major degree of tree retention over long periods of time, development and productivity of the remaining trees is an essential part of the system, constituting a great knowledge gap. This knowledge gap causes a challenge for forest management and planning systems. There have been published only few studies focusing directly on the effect of gap cutting or partial cutting on the growth of surrounding trees with at least some relevance to Fennoscandian boreal forests (Pedersen and Howard, 2004, Thorpe et al., 2007, York and Battles, 2008, Gray et al., 2012, Hartikainen, 2022, Biber and Pretzsch, 2022). The previous studies concluded that gap cutting increased diameter growth of trees located nearby the gap edge and the gap effect fades out towards the stand interior. Pedersen (2004) concluded also that part of increment lost caused by gap cutting was offset by the growth response of trees at gap edge and this growth lost is considerably less than the gap area indicates. These facts should be accounted for when predicting stand development in gap cutting. Traditional growth models for the rotation forest are not suitable under these conditions (Biber and Pretzsch, 2022). There is an urgent need for tools and models to quantify the edge effect on surrounding tree growth. In the Nordic area there are neither any suitable growth models nor studies directly focusing on tree or stand growth on gap cutting (cf. Bianchi et al., 2024). The previously published studies are not either directly applicable in Finland due to different species or growth conditions. Lack of suitable growth models for gap cuttings causes challenges for predicting reliably stand developments obtained by commonly used stand simulators (e.g., MOTTI, MELA).

The purpose of this study was to analyze the tree growth response to gap cutting as a gradient from the gap edge into the interior of the remaining stand based on data from a permanent experiment in Central and Eastern Finland, also accounting for other major growth factors like site, tree species, stand density in terms of empirical modeling. The study aims to constitute a major step forward in creating a model and simulation basis for exploring tree and stand development and productivity of gap cutting-based regimes for practical purposes.

2. Materials and methods

2.1. Study stands

This research was carried out in the state-owned Isojärvi and Ruunaa experimental forest areas in southern and eastern Finland, which have been designated for research and development purposes under the DISTDYN project (Koivula et al., 2014) and are managed by Metsähallitus.

The Isojärvi experimental area is situated near Jämsä (61°40 N, 25°00 E) and covers an area of 700 ha. The predominant forest site types at Isojärvi are the submesic *Myrtillus* type and the mesic *Oxalis–Myrtillus* type (Cajander, 1909). Subxeric *Vacciunium* types also occur representing a quarter of the area. Some drained peatlands with similar or lower fertility levels are also present. The dominant tree species are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Mixed species stands also occur, most commonly with silver birch (*Betula pendula* Roth) and pubescent birch (*Betula pubescens* Ehrh.), and occasionally with European aspen (*Populus* tremula L.), rowan (*Sorbus aucuparia* L.), common alder (*Alnus glutinosa* L.), and grey alder (*Alnus incana* Moench). Norway spruce and birch make up the primary commercial species on the mesic and submesic sites at Isojärvi, constituting 84 % of the standing volume.

The Ruunaa area is situated near Lieksa (63°26 =N, 30°22 =E) covering 1200 ha. It consists of Scots pine-dominated forests on xeric (*Calluna* type; Cajander, 1909) and subxeric (*Vaccinium* type) sites on mineral soils. The dominance of pine is overwhelming with admixture species constituting just some 15 % of standing volume in the area. The stand structures are quite monotonous, mostly including just a single canopy layer of trees of uniform size and age. Old stands dominate the landscape which has been managed as a hiking area with limited forest management for commercial purposes for decades.

Since 2009, the forests in the experimental areas are managed according to the principles of natural disturbance emulation (Attiwill, 1994; Bergeron et al., 2002; Long, 2009); please see Kuuluvainen and Aakala (2011), Kuuluvainen and Grenfell (2012), Kuuluvainen et al. (2021) for typical natural forest dynamics in this region, and their emulation in forestry and Koivula et al. (2014) for their application in the DISTDYN project. In that context, four different harvesting treatments are applied in the DISTDYN forests, of which those belonging the silvicultural system of group selection were relevant for this study. The harvest treatments of “gap felling” and “partial felling” involve harvesting small irregular clearcut gaps with areas of ca. 0.1–0.3 ha and diameters of approximately 10–60 m with 10–50 m wide buffers of residual forest between the gaps, either thinned or un-thinned in the same entry, depending on stand density at that point. The properties of the gaps produced by both treatments were essentially no different in respect to factors influencing tree growth and were therefore merged and referred to as “gaps” in this study. The effect of gap size was focused on in the analyses as an explanatory variable among other factors.

At Isojärvi, gap and partial felling was carried out in 40 stands during January and February of 2010 and 2011. Stand areas vary between 0.5 and 9 ha, and each harvested stand contains one to seven gaps, depending on the availability of stand area, establishing a total of 86 gaps. The first harvesting round at Isojärvi failed to produce the smallest gap sizes prescribed in terms of “gap felling”, and the final diameter range was 30–60 m (vs. the intended range of 10–60 m).

At Ruunaa, gap and partial harvesting was carried out in 20 stands during January and February of 2011 and 2012. Stand areas vary between 2.5 and 30 ha, and each harvested stand contains one to 16 gaps.

2.2. Sampling and measurements

The material for this study was sourced from the permanent plots established in conjunction with the first harvest entry in 2010–2012. The experimental sample of stands was designed to cover the variation in the forests by geographic extent, treatment (gap felling and partial felling), site (mineral soil vs. peatland; xerix, subxeric, submesic, and mesic site types), and site preparation (no/yes). The sample gaps were selected among viable candidates, i.e. gaps with middle-aged or mature edge stands surrounding the gap on at least three sides with sufficient extent to accommodate a full-fledged sampling strip in each. Originally 1–4 gaps were placed in each stand, but some were discarded from this study due to heterogeneity of site or stand properties within and between the sampling strips. The experimental setup thus comprises 20 gaps in 12 stands at Isojärvi, and 17 gaps in 9 stands at Ruunaa (Table 1).

The sample plots were initially designed to yield data both on regeneration within the gaps as well as tree growth and mortality and stand characteristics and dynamics in the edge stands. Four baselines were established in each gap outward from the gap midpoint with east–west and north–south orientations (Fig. 1). Each baseline continued into the residual stand for some 21–23 m from the gap edge (as is seen in Fig. 1). The gap edge was defined as the point where the baseline crossed the imaginary line that connected the bases of the two nearest trees, as per Runkle (1981). The sampling strip for trees was centered on the baseline and constituted a width of 21 m.

For all standing trees on these sampling strips that were $\geq$ 4 m in height, the coordinates, species, health and vigor, and diameter at breast height (1.3 m) from two perpendicular directions were recorded at plot establishment in 2010–2013. The diameter measurement point was marked with paint. A set of 20 sample trees per gap was measured for height. The sampling was stratified by tree diameter classes (at 10-cm intervals), and systematic sampling (every n^{th} tree) was applied within the classes. The measurements were repeated with the same protocol in the late summer of 2019. Tree characteristics by tree species at plot

Table 1
Stand characteristics at plot establishment (2010–2013).

Stand and Gap No	Gap size	Site	Sp	T	H_{dom}	H_{100}	G	V	Sp proportion SP/NS/Birch
Isojärvi									
40.2	0.19	MT	NS	72	25	31	27	250	0,15, 0.55, 0.25
40.3	0.15	MT	NS	73	25	31	25	256	0.15, 0.67, 0.18
41.1	0.21	MT	NS	86	28	31	40	482	0.28, 0.67, 0.05
65.1	0.14	VT	SP	59	21	27	20	169	0.60, 0.14, 0.23
65.2	0.11	VT	SP	60	21	27	21	178	0.72, 0.07, 0.20
73.1	0.17	OMT	NS	76	24	29	24	221	0.23, 0.61, 0.13
73.3	0.05	OMT	NS	78	24	29	26	265	0.26, 0.16, 0.53
73.5	0.13	OMT	NS	80	24	29	28	303	0.06, 0.83, 0.08
77.2	0.12	MT	NS	86	24	26	31	312	0.04, 0.48, 0.46
77.3	0.13	MT	NS	87	24	26	31	319	0.10, 0.87, 0.03
89.1	0.09	MT	NS	60	22	31	21	183	0.23, 0.58, 0.18
89.2	0.15	MT	NS	61	22	31	24	215	0.23, 0.58, 0.18
100.3	0.31	MT	NS	121	28	25	31	307	0.43, 0.28, 0.26
115.2	0.17	MT	NS	74	25	30	25	232	0.25, 0.62, 0.03
117.5	0.11	MT	NS	62	21	29	26	223	0.08, 0.73, 0.15
117.6	0.13	MT	NS	63	21	29	23	201	0.33, 0.55, 0.11
130.1	0.22	CT(pe)	NS	93	21	22	20	182	0.83, 0.14, 0.03
148.1	0.21	VT(pe)	SP	72	21	25	21	175	0.66, 0.20, 0.14
148.2	0.13	VT(pe)	SP	73	21	25	26	218	0.51, 0.20, 0.29
151.2	0.15	MT	NS	67	21	28	20	175	0.26 0.62, 0.08
Ruunaa									
4.11	0.10	VT	SP	143	24	21	34	319	0.94, 0, 0.06
4.19	0.06	VT	SP	151	24	21	37	380	0.95, 0, 0.05
25.2	0.10	VT	SP	135	24	21	23	233	0.98, 0, 0.02
25.5	0.12	VT	SP	136	24	21	23	216	0.87, 0.10, 0.03
25.11	0.13	VT	SP	138	24	21	28	269	0.98, 0.01, 0.01
25.14	0.11	VT	SP	139	24	21	27	267	1, 0, 0
30.11	0.58	VT	SP	120	22	20	21	193	0.88, 0.07, 0.05
78.6	0.51	VT	SP	120	21	19	24	208	1, 0, 0
79.5	0.11	VT	SP	100	21	21	20	165	0.96, 0.01, 0.03
79.13	0.18	VT	SP	106	21	21	18	150	0.86, 0.09, 0.05
81.5	0.24	CT	SP	111	23	22	23	194	0.97, 0, 0.03
81.6	0.19	CT	SP	112	23	22	28	242	0.85, 0.06, 0.09
111.7	0.25	VT	SP	156	25	21	24	237	0.96, 0, 0.04
124.4	0.11	VT	SP	111	22	21	23	183	1, 0, 0
124.6	0.12	VT	SP	113	22	21	19	146	1, 0, 0
154.3	0.17	VT	SP	98	19	19	13	103	0.99, 0, 0.01
154.9	0.24	VT	SP	104	19	19	14	101	0.90, 0, 0.10

Gap size = Surface area (ha); Site = Site type by Cajander (1909): OMT = *Oxalis-Myrtillus* type, MT = *Myrtillus* type, VT = *Vaccinium* type, CT = *Calluna* type; (pe) = peatland (others mineral soil); Sp = main species: NS = Norway spruce, SP = Scots pine; T = stand age (years), H_{dom} = dominant height: average height of the 100 thickest trees ha^{-1} (m); H_{100} = site index: H_{100} at T = 100 years (m) according to Gustavsen(1980); G = basal area (m^2ha^{-1}); V = stem volume (m^3ha^{-1}), Sp proportion = Tree species proportion of basal area.

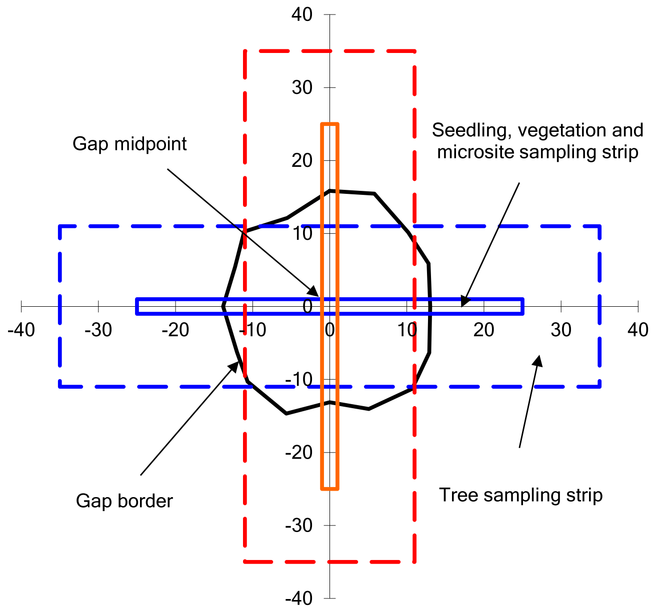

Fig. 1. Experimental setup for gap and edge stand analysis.

establishment (2010–2013) are summarized in Table 2.

Trees that were dead in either of the measurements were discarded from the data. Stand-level increment was calculated as the difference between the two measurements, representing net growth in terms of live trees. Tree mortality during the period thus decreased net growth. Tree-level increment was calculated as the difference between the two measurements. The periodic increment between the two measurements comprised 6–10 growing seasons, depending on their benefits and applicability the timing of the first measurement. It was converted into annual increment by simply division.

Table 2
Tree characteristics at plot establishment (2010–2013). Range is given in parenthesis.

Tree species	Number of trees	Diameter, cm Mean Std	Height, m Mean Std	Distance from gap edge, m Mean Std
Scots pine	1690	19.9 7.3	17.4 3.8	9.8 6.3
	438 *	(4.8–50.6)	(6.0–30.8)	(0–22.8)
Norway spruce	1566	16.3 7.8	15.9 5.3	9.8 5.9
	258 *	(4.5–79.0)	(3.3–30.8)	(0–21.0)
Birch	796	13.6 7.9	14.2 4.6	10.0 6.4
	74 *	(2.0–42.4)	(4.0–26.8)	(0–23.0)

*Number of sample trees whose height has been measured.

2.3. Statistical methods

To analyze the effect of gap cutting on growth of the surrounding trees, models for tree annual diameter (i_d) and height growth (i_h) were developed. To analyze the effect of gap cutting on growth of the surrounding trees in addition to tree location (tree distance from the gap edge) the factors which generally have impact on tree growth were accounted and used as covariates in the models. Only variables that are normally measured in forest inventories, or which can be estimated easily and reliably from inventory data, were used as covariates.

The models were constructed separately for the tree species of pine, spruce, and birch. The material had a hierarchical structure with stand, gap, and within-gap levels. In order to simplify the model structure, the sampling trips of a gap were not separated as an own level, but it was included at gap level. To account for this spatially correlation and to obtain efficient parameter estimates the linear mixed model (Searle 1987, Parresol 1999) with both fixed and random effects was formulated as follows:

$$y_{ijk} = \boldsymbol{\beta}\boldsymbol{X}_{ijk} + u_i + v_{ij} + e_{ijk} \tag{1}$$

where i, j, and k refer to stand, gap, and tree, y_{ijk} is the response variable (annual diameter or height growth), $\boldsymbol{\beta}$ is a vector of fixed effects parameters, $\boldsymbol{X}_{ij}$ is the vector of independent variables indicating tree distance from the gap edge, tree size (diameter or height), between-tree competition (basal area, basal area of trees larger than the target tree, tree diameter divided by stand mean diameter), stand treatment (gap cutting or partial cutting), gap size, site fertility (site types) and area (Ruunaa or Isojärvi), u_i is the random stand effect, v_{ij} is the random gap effect, and e_{ijk} is the residual error. The random effects (u_i, v_{ij}) and residuals errors (e_{ijk}) were assumed to be uncorrelated and to be identically distributed Gaussian random variables with a mean of 0 and follow constant variances at each level.

The maximum likelihood (ML) method in the MIXED procedure of SAS (SAS Institute Inc. 1999) was used in the estimation of the models. The selection of the independent variables was based on inspections of residuals and the values of the $-2 \times$ log-likelihood, and only variables with a significance of p-value < 0.05 were accepted in the model.

2.4. Model application

To evaluate the edge effect of gap cutting on the annual basal area growth of the surrounding stand, the compiled tree growth models were applied to the trees of each sampling strip. To access the magnitude of edge effect diameter growths were predicted to the trees on the plots in two ways: with and without the edge effect as follows:

- With edge effect: Tree distance from the edge of gap cutting (*Dist*) was used as it was in the study material
- Without edge effect: Tree distance from the edge of gap cutting (*Dist*) were set at 20 m

Annual basal area growth (m^2ha^{-1}) was calculated by the study plots (gap) in both ways i.e., with ($iBA_{edge\ effect}$) and without ($iBA_{No\ edge\ effect}$) the edge effect. The difference of the obtained basal area growth (iBA_{diff}) was calculated with Eq. (2). This can be interpreted as bias if the edge effect was not accounted for in the model.

$$iBA_{diff} = \frac{iBA_{Edge\ effect}}{iBA_{No\ edge\ effect}} \tag{2}$$

3. Results

3.1. Stand level growth

The average annual net volume increment at Isojärvi was 9.3 m^3ha^{-1} and 4.4 m^3ha^{-1} at Ruunaa, respectively. Site fertility level was a key growth factor. Compared to the mesic OMT type, the average volume increment was 81 % for the submesic MT type and 43 % for the subxeric VT type respectively. Average annual natural mortalities were 0.8 m^3ha^{-1} at Isojärvi and 0.3 m^3ha^{-1} at Ruunaa, respectively.

3.2. Tree diameter growth

Tree diameter at breast height (*d*) was a significant predictor of diameter growth for all tree species. For pine and spruce the relationship was nonlinear, i.e. a combination of linear and logarithmic transformed variables included, proved to be the most suitable expression of *d* (Table 3). For birch only linear form of *d* was needed.

The effect of between-tree competition on diameter growth was described with stand basal area (*BA*) and, alternatively, basal area of trees larger than the target tree (*BAL*). They represented a broad stand-level measure of competition a high value of *BA* was associated with lower diameter growth for spruce (Table 3). For birch and pine, *BAL* showed a closer correlation with growth. For pine, site location and fertility had significant effects on the diameter growth level. The stands located at Isojärvi and the site types of MT and OMT indicated higher diameter growth. For other tree species, site fertility was not significant as a main effect nor within interaction effects. Silver birch had a higher diameter growth level than downy birch (Table 3).

The gradient in diameter growth from gap edge into the stand interior was described with tree distance from the edge (*Dist*). The effect of *Dist* showed to be nonlinear and it was expressed as $Dist\ /\ (Dist + n)$, where n is 1 or 2 depending on tree species (Table 3). This transformation of *Dist* was a highly significant predictor ($p < 0.0001$) for all tree species. For pine, also the interaction term combining *Dist* and fertile site types (MT, OMT) was significant, representing a steeper gradient on the more fertile sites (Table 3).

The increment gradient showed a decreasing trend with increasing distance from the gap edge, and it was highest when distance to edge was < 5 m (Figs. 2 and 3). The edge effect was greatest for spruce trees located at the gap edge with a 0.15 cm higher annual diameter growth compared to trees located in the stand interior (distance with over 10 m). For pine the edge effect was at the same level on fertile sites but clearly lower (0.05 cm y^{-1}) on poorer sites (CT, VT). For birch the trees located at the gap edge had some 0.1 cm y^{-1} greater annual diameter

Table 3

Parameter estimates of models for annual diameter growth (i_d, cm y^{-1}) for pine, spruce, and birch. Standard error of the estimates in parentheses.

	Pine i_d, cm	Spruce i_d, cm	Birch i_d, cm
Variable	*Estimate*	*Estimate*	*Estimate*
Intercept	−0.088 (0.050)	0.041 (0.055)	0.298 (0.224)
d	−0.009 (0.001)	−0.004 (0.002)	0.003 (0.001)
ln (d)	0.173 (0.024)	0.222 (0.028)	
BAL	−0.002 (0.000)		−0.004 (0.001)
BA		−0.005 (0.001)	
$\frac{Dist}{Dist + n}$	−0.060 (0.011)	−0.200 (0.018)	−0.128 (0.017)
n	1	2	2
Fertile	0.295 (0.085)		
$Fertile * \frac{Dist}{Dist + n}$	−0.309 (0.089)		
Area	0.128 (0.037)		
Silver birch			0.046 (0.012)
var(u_i)	0.0004	0.005	0.0003
var(v_{ij})	0.0002	0.002	0.0001
var(e_{ijk})	0.010	0.021	0.011

d, tree breast height diameter (cm); *BAL*, basal area of trees larger than the target tree (m^2); *BA*, basal area (m^2ha^{-1}); *Dist*, tree distance from the edge of the gap cutting (m); *Fertile*, dummy variable for site types OMT and MT; *Area* dummy variable for Isojärvi area; *var(u_i)* variance of random stand effect; *var(v_{ij})*; variance of random gap effects; *var(e_{ijk})* error variance; *Silver birch* dummy variable for silver birch.

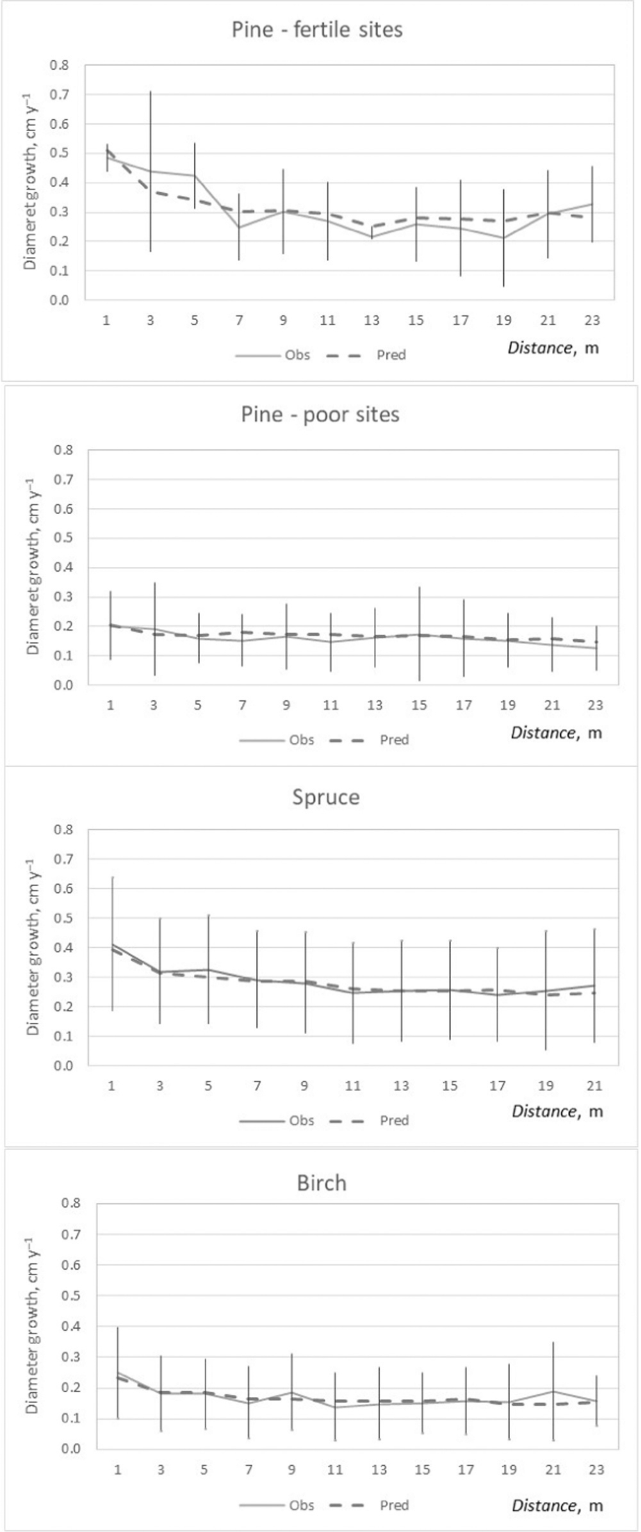

Fig. 2. Observed and predicted annual diameter growth values (cm) by distance from gap edge. Mean for 2-m wide distance classes and standard deviations for observed values are shown. For pine both fertile (OMT, MT) and poor (CT, VT) sites are presented.

growth compared to trees further away (distance from gap edge > 10 m).

To illustrate more reliably the distance effect on tree diameter growth the effect of other factors than distance needed to be eliminated from the predictions. This was done by using the mean values of the study material as constant values for the covariates (d = 20 cm, BA = 26 m^2ha^{-1}, BAL =13 m^2) and the different $Dist$ values. The predicted growth values confirmed that the edge effect in absolute scale on diameter growth seemed to be quite small (Fig. 3). Despite this the relative difference in diameter growth between trees growing near the gap edge and the stand interior appeared more clearly (Fig. 4). When tree diameter growth along the distance gradient was compared with trees at a 20-m distance, the edge effect was manifested in faster growth near the edge (< 2 m) by 18 – 56 % depending on tree species and site fertility (Fig. 4). Especially for pine, site fertility had a clear impact, and the edge effect was significantly higher on fertile site types (OMT, MT) (Fig. 4). The edge effect decreased deeply and in the distance of 5 m and 10 m the edge effect was < 20 % and < 10 %.

3.3. *Tree height growth*

In addition to distance from the gap edge, similar covariates were used also in the models for annual height growth. Tree diameter at breast height (d) was a significant regressors for all tree species, and additionally tree height for spruce (Table 4). Between-tree competition with a minor effect of BA was significant only for spruce. For pine the stands located in Isojärvi indicated a higher height growth than at Ruunaa, as well as the treatment of partial felling over gap felling.

The edge effect was significant for all species, though the statistical significance was low for conifers due to substantial variation in height growth (Table 4). In contrast to diameter growth, the parameter estimate for $Dist$ was positive for pine and spruce, indicating slightly higher height growth with increasing distance from the edge into stand interior (Table 4, Fig. 5). However, the effect of $Dist$ was rather small, and differences in annual height growth at difference distances were mainly less than 0.05 m (Fig. 5). For birch, this effect was converse, i.e, $Dist$ showed a negative height growth with increasing distance, and trees located near the edge had about 0.1 m y^{-1} higher annual height growth compared with trees in the stand interior at a 20-m distance.

To illustrate the distance effect on tree height growth the predictions were obtained with constant covariates (d = 20 cm, BA = 26 m^2ha^{-1}, BAL =13 m^2) and the different $Dist$ values. The predicted growth values confirmed that the edge effect in absolute scale on height growth was quite small and effect was either negative or positive depending on tree species (Fig. 6). Model predictions showed that there was a significant positive edge effect, as the relative difference in height growth between trees in the edge zone and those in the stand interior (20 m) for birch. Height growth was 30 % greater near (< 2 m) the gap edge and still some 5 % 10 m into the stand. (Fig. 7). On the contrary, a minor negative edge effect was detected for pine and spruce (Fig. 7).

3.4. *Stand basal area growth*

To demonstrate the magnitude of the edge effect at the stand level, plot basal area growth was calculated by applying the diameter growth model (Table 3) to the observed trees by two alternatives: 1) using the observed tree distance; 2) using a constant distance of 20 m to represent growth with null distance effect. For pine stands the edge effect produced on average 7 % (range 5–13 % by plots) higher annual basal area growth compared with the case when this effect was not accounted for (Fig. 8). For spruce stands the edge effect was higher yet, on average 11 % varying from 7 % to 18 % (Fig. 8).

4. Discussion

Gap cutting had a significant positive effect on tree diameter growth in the remaining edge stand. The trend was nonlinear, i.e. the growth acceleration was greatest in the immediate vicinity of the gap, diminishing rapidly towards stand interior, and was virtually extinguished 10 m away from the edge. Positive edge effects on diameter growth have been reported also in previous studies (Jones and Thomas, 2004,

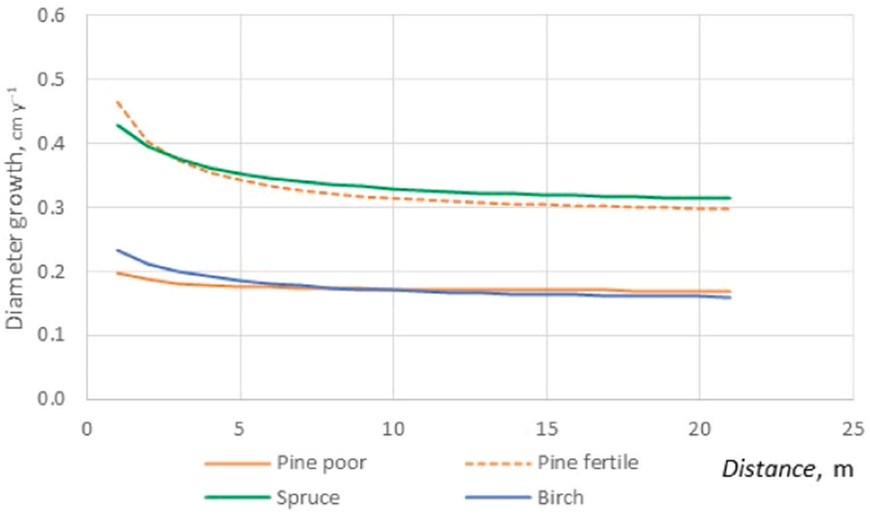

Fig. 3. Predicted diameter growth as a function of the distance from the gap edge. The growth values were obtained with the model (Table 3) with the constant values of the covariates (d = 20 cm, BA = 26 m^2ha^{-1}, BAL =13 m^2).

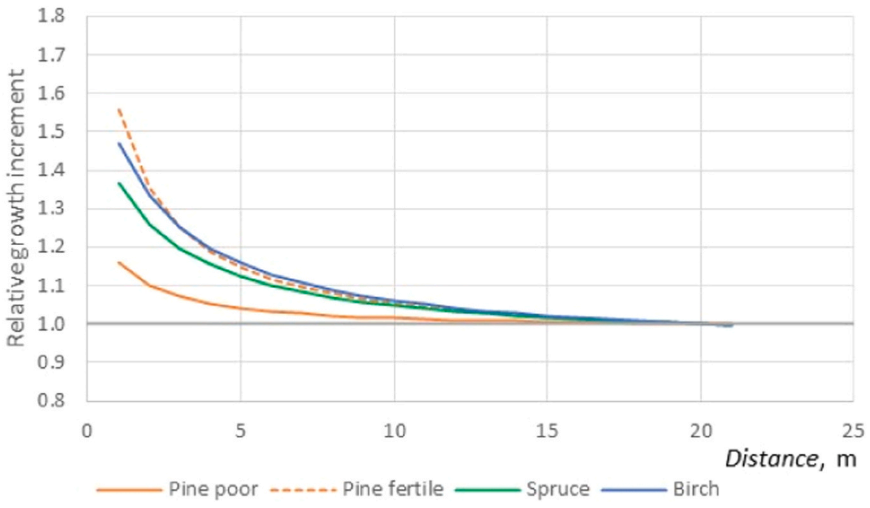

Fig. 4. Relative diameter growth increment as a function of the distance from the gap edge. The comparison level was tree growth located at a 20-m distance from the edge. The diameter growth was obtained with the model (Table 3) with using the mean values of the study material as the covariates (d = 20 cm, BA = 26 m^2ha^{-1}, BAL =13 m^2).

Pedersen and Howard, 2004, Thorpe et al., 2007, York and Battles, 2008, Gray et al., 2012, Hartikainen 2022, Biber and Pretzsch, 2022). However, the distance gradient from the gap edge has been rarely addressed directly. York and Battles (2008) reported that mature conifer trees within 10 m of gaps grew more than trees in stand interior in central Sierra Nevada, California. Despite the different area and tree species, their results are in line with our results.

In this study, the diameter growth response was higher for spruce and birch, than for pine. It seems that the pattern was not fully attributable to pine as a species only but partly to the fact that a great majority of the pines in the data were growing on clearly poorer sites. The growth response for pine was substantially greater on fertile sites (OMT, MT) than that on infertile sites (CT, VT). This assumption is supported by York and Battles (2008) who pointed out that the edge effect was independent on tree species. The effect of site fertility on the growth reaction in a gap cutting has not been previously reported but Mäkinen and Isomäki (2004a) reported similar results on the effect of site fertility on the diameter growth reaction for pine after the thinning in rotation forests. In our material the fertile sites were spruce-dominated stands where pine appeared only as mixed tree species when poorer sites were pine dominated. A higher edge effect of pine on fertile sites probably didn't result solely from site fertility but also from mixed stand structure (species mixture) when gap cutting decreased between tree species competition near the gap edge. No such response was detected for tree height growth in this study. In fact, the coefficients for the edge effect variables were mostly negative but insignificant for height increment in candidate models.

The dependent variable, annual diameter and height growth were based on the subsequent measurements i.e., at the beginning and at the end of the monitoring period. Tree diameter was measured of all trees of the plot (sector) and height only on the sample trees. For this reason, the models for diameter growth were based on clearly a larger number of observations than the height growth models. This meant also that the response of the edge effect to diameter growth could be estimated more reliably than that of height growth. For all tree species the edge effect (negative response) was also highly significant (p-value <0.0001) on diameter. Instead, the response of edge effect on height was negative for birch (p-value 0.005) and positive for pine and spruce (p-value 0.033 for both). Lower significance of parameter estimates can cause unreliability on the effect of gap cutting on height growth of the surrounding trees.

Table 4
Parameter estimates of models for annual height growth (i_h, m y^{-1}) of pine, spruce and birch. Standard error of the estimates is presented in parenthesis.

	Pine i_h, m	Spruce i_h, m	Birch i_h, m
Variable	*Estimate*	*Estimate*	*Estimate*
Intercept	−0.099 (0.005)	−0.300 (0.101)	−0.020 (0.063)
d	−0.005 (0.001)	−0.012 (0.003)	
ln (d)	0.112 (0.026)	0.433 (0.102)	0.109 (0.023)
ln (h)		−0.161 (0.070)	
BA		−0.002 (0.001)	
$\frac{Dist}{Dist+n}$	0.029 (0.013)	0.074 (0.034)	−0.115 (0.038)
n	1	3	2
Area	0.065 (0.022)		
Partial cutting	−0.044 (0.022)		
$var(u_i)$	0.000	0.000	0.000
$var(v_{ij})$	0.002	0.001	0.001
$var(e_{ijk})$	0.004	0.014	0.010

d, tree breast height diameter (cm); *h*, tree height (m); *BA*, basal area (m^2ha^{-1}); *Dist*, tree distance from the edge of the gap cutting (m); *Area* dummy variable for Isojärvi area; *Partial cutting* dummy variable for partial cutting; $var(u_i)$ variance of random stand effect; $var(v_{ij})$; variance of random gap effects; $var(e_{ijk})$ error variance; *Silver birch* dummy variable for silver birch.

However, the effect of gap cutting on height growth has not previously reported but the results from thinning effect in rotation forest have shown that height growth was relatively independent of increased growth space (thinning intensity) of pine and spruce in Finland (Mäkinen and Isomäki, 2004b, 2004a). These results from rotation forest are not directly comparable to our results.

Dynamics of tree growth response to cuttings have been studied in rotation forests but only few in gap cuttings stands (Jones and Thomas, 2004, Thorpe et al., 2007, Gray et al., 2012). Generally, diameter growth response to the changes in growth space (e.g. thinning, partial cutting) will start one to three years after thinning and last several years. Maximum growth last up to four to six years before growth response start to decrease (Holgén et al., 2003, Thorpe et al., 2007, Burkhart, Tomé, 2012). Hynynen (1995) concluded that pine trees reacted without any delay to thinning in rotation forest in Finland and the response reaches its maximum within period of 5–10 years after thinning. The dynamics of growth response could not be analyzed in our data because trees growth during the monitoring period was based on two repeated measurements not on the increment cores enabling annually growth determination. In our data the length of growth period varied by the stands from six to ten years the growth values between stands and they are not totally comparable. Therefore, annual growth values were used as a response variable, but this didn't eliminate totally the problem caused by the different growth period. In stands with shortest growth period (6-years) the response to gap cutting haven't maybe totally reached the highest growth response contrary to the stands with longest growth period (10-years). The length of growth period was also test as an independent variable, but it was not significant. Despite this the study provide realistic viewed of the edge effect on tree growth 6–10 years after cap cutting but the length and possible delay of growth response could not be analyzed. Based on the result of the previous studies it can be assumed that the length of growth response is more than 10 years. Biber and Pretzsch (2022) suggested that an exposition to a gap edge enables trees to improve their individual crown and root architecture in a way they can profit from on the long run, even after the original gap has closed again. Gray et al., (2012) showed that the growth response of Douglas-fir dominated forest to gap cutting last whole 16-year monitoring period in USA. Hynynen (1995) concluded that the growth response of pine trees in rotation forest leveled off by 30 years after thinning in Finland.

In our study material contained different gap size from 0.1 to 0.6 ha. Despite the large range of gap size, it did not have an impact on diameter growth. Also, other studies have shown that growth responses are relatively insensitive to gap size (York et al., 2004, York and Battles, 2008, Gray et al., 2012). The previous studies have concluded also that trees orientation (cardinal direction) in the surrounding stand hadn't any impact on growth response (Pedersen and Howard, 2004, York et al., 2004, York and Battles, 2008, Gray et al., 2012). This finding was detected also in our study when the sectors in the cardinal directions were tested as an independent variable with no significance. This may result from the fact that in addition gap area, also the shape of the gap varied. This could not be addressed in the model specifications because such information was not available.

The gap cuttings increased the diameter growth of the surrounding trees especially located nearby the cap edge. There was not information of history of the previous thinning or whether the surrounding stand was thinned at the same time when cap cuttings were carried out. In that case growth response can be partly resulted from the thinning of the surrounding stand and the edge effect can remain weaker. Also, location of strip road can have own edge impact on the trees growth which was not accounted in the analysis.

The detected diameter growth response means also increased stand basal area growth of nearby the gap edge. This should account when predict stand growth in stand where gap cutting has been applied. In our study stands basal area growth of the sample plots was underestimated on average by 7 % and 11 % for pine and spruce stand if the edge effect were not addressed. The increased tree growth at gap edge partly compensated growth loss of trees removed in the gap cuttings. Pedersen and Howard (2004) showed that nearly two-thirds of the stand basal area increment lost because of gaps was offset by the enhanced growth of trees at gap edges. This offset was not determined in our study. It is also highly dependent on the number, area, and spatial configuration of gaps in a stand. This needs to be accounted when the offset effect is assesses e.g. for practical forestry purposes.

Our models were based only trees which were alive in the second measurement, and trees which had died during the growth period were not included into the analysis. When assess the edge effect of gap cutting at stand level in addition to the tree-level growth response, also the influence of mortality on productivity needs to be addressed. Compared to the preharvest situation, mortality rate near the edge may increase directly due to greater wind exposure, or indirectly through increased susceptibility to disease and damage if tree vitality declines due to intensive exposure to light, temperature, or drought near the edge (see Oliver and Larson (1990). In principle at least, mortality may decrease if tree vitality tends to improve along with the greater resource availability (Oliver and Larson, 1990, Gray et al., 2002, Gray et al., 2012). However, mortality was very low in the study stands during the observation period. Average annual mortality in basal area at Isojärvi was 0.07 m^2 ha^{-1} y^{-1}. That was only about one tenth of the rate observed in spruce-dominated stands managed with single-tree selection in Southern Finland (Valkonen et al., 2020). Furthermore, the respective mortality was only 0.02 m^2 ha^{-1} a^{-1} in the pine-dominated forests with gaps at Ruunaa (Hartikainen 2022).

An anticipated pattern of climatic and site-dependent difference emerged in stand-level volume growth results. The pine-dominated stands on less fertile sites at the more northerly (by 200 km) location at Ruunaa grew much slower than the spruce-dominated stands at Isojärvi. There were too few observations of similar site-species combinations for a direct comparison. Focus on the observed stand-level growth was not further pursued in this study. Stand growth is a result of a complex web of interdependent factors like climate, soil, stand age, density, spatial patterns of gaps and remaining stand elements, among other things. The projected simulation system with integration of the distance-dependent increment gradient is devised as a tool for such analyses.

5. Conclusions

This study provided tools to quantify the edge effect of gap cuttings on tree diameter and height growth for pine, spruce, and birch, which

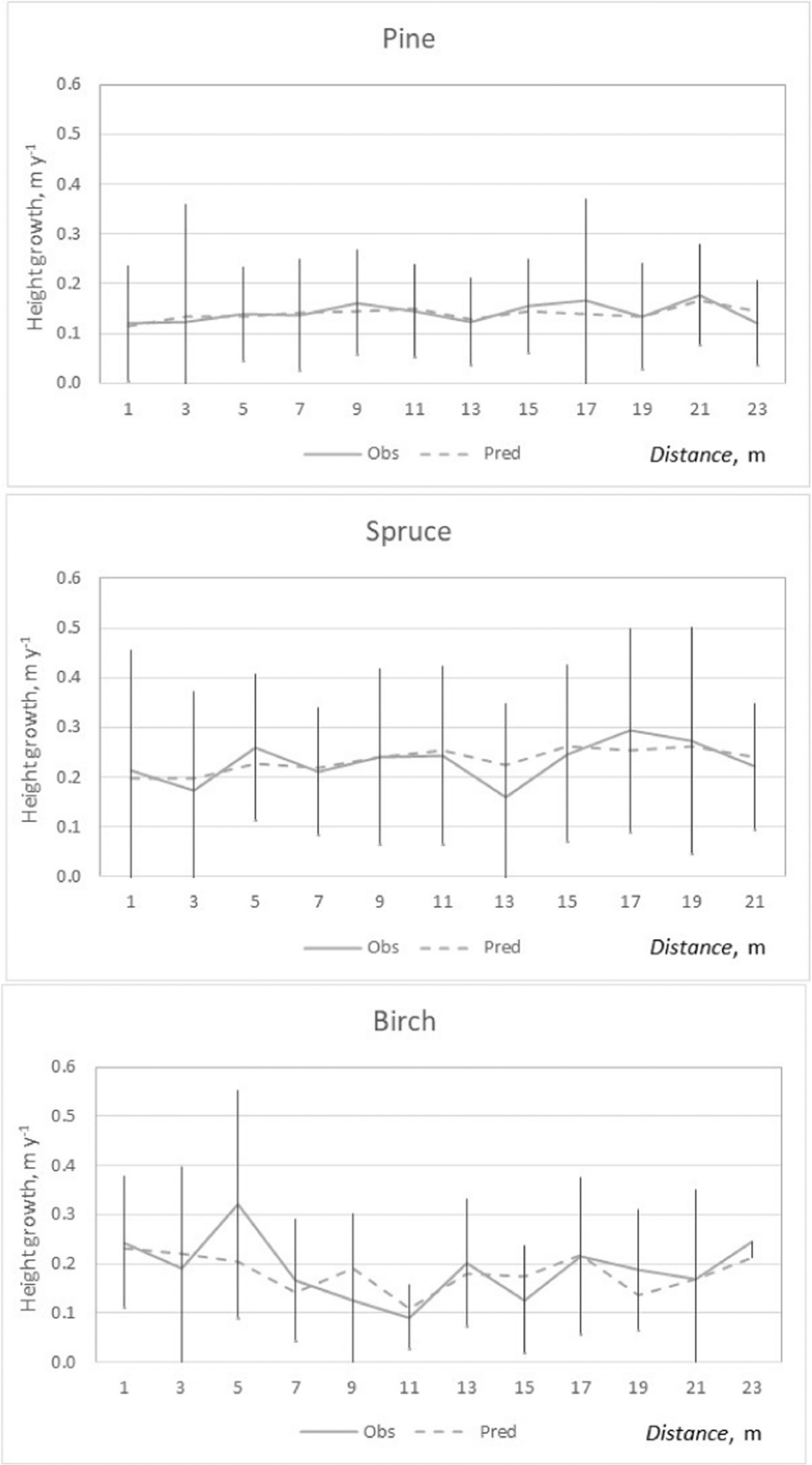

Fig. 5. Observed and predicted mean annual height growth values (m) in the study material. Standard deviations of observed values are shown.

have been not previously available in Finland. The developed models predict tree level growth as a function of tree distance from the gap edge with other commonly used growth factors. In practice there are very rarely available tree level data with spatial information. Therefore, the compiled models are not directly applicable e.g., in stand simulator such MOTTI. For this purpose, the models can be applied e.g., to predict mean response of edge effect with 10 m distance and use this value to generalize the area of surrounding stand affected by edge effect. Although natural regeneration is the most essential aim in gap cutting, the edge effect on the surrounding trees growth needs to be considered especially when assessing profitability of whole management chain for long run and when comparing it with that of rotation forest management (RF). To assess more broadly the importance or magnitude of the edge effect on a stand growth the simulations of the stand development with

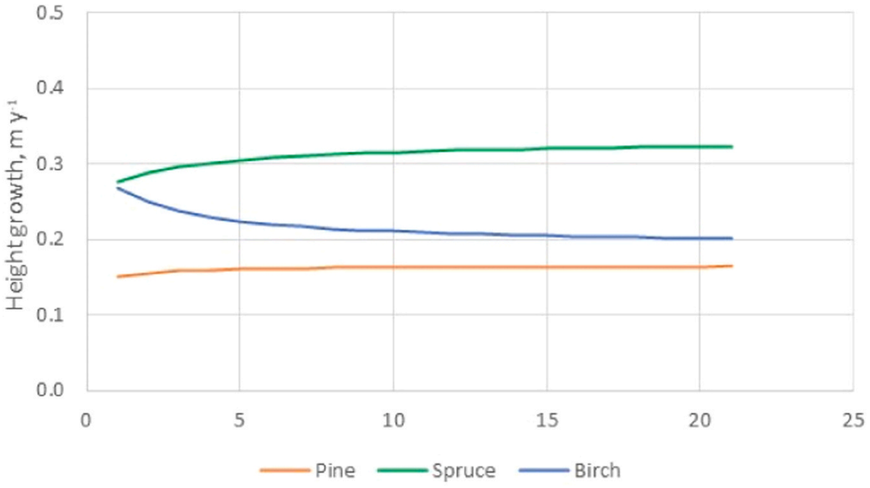

Fig. 6. Predicted height growth as a function of the distance from the gap edge. The growth values were obtained with the model (Table 4) with the constant values of the covariates (d = 20 cm, BA = 26 m^2ha^{-1}, BAL =13 m^2).

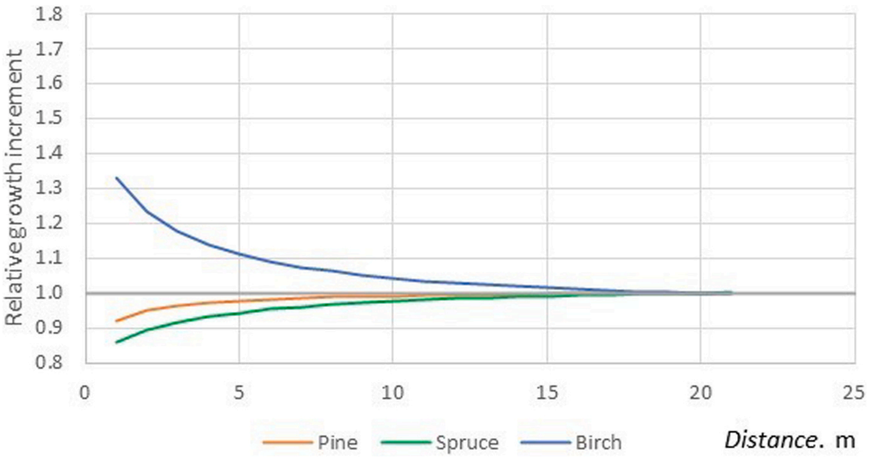

Fig. 7. Relative height growth increment as a function of distance from the gap edge. The comparison level (1) was growth of a tree growth at 20 m distance into the stand interior. Height growth was obtained with the model (Table 3) with using the mean values of the study material as the covariates (d= 20 cm, BA = 26 m^2ha^{-1}, BAL = 13 m^2).

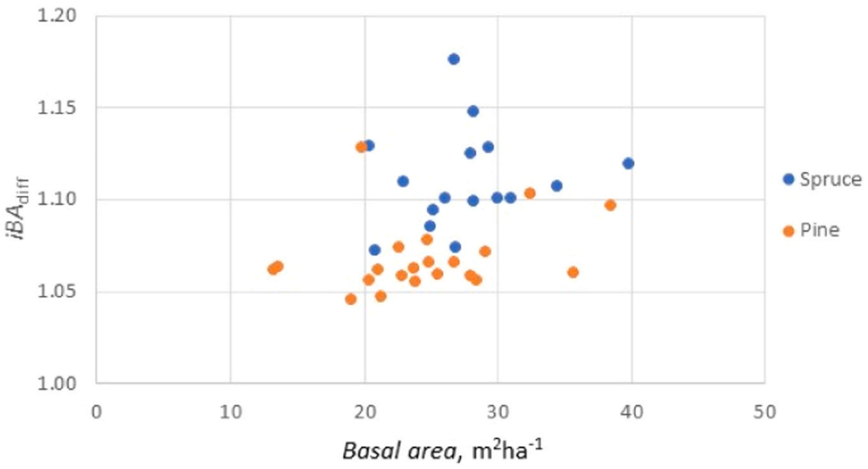

Fig. 8. Relation between stand basal area growth (iBA_{diff}) predicted with and without the edge effect of the gap cutting.

varying number of gaps and gap size are needed.

CRediT authorship contribution statement

Sauli Valkonen: Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition. **Jaakko Repola:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122862.

Data availability

I have share the link to my data at the attach file step

Tree growth response at stand edges in gap cutting in Finland (Zenodo)

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