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Radial growth changes in Norway spruce montane and subalpine forests after strip cutting in the Swiss Alps

Valentina Vitali[a,b], Peter Brang[a], Paolo Cherubini[c], Andreas Zingg[a], Petia Simeonova Nikolova[a,*]

[a] Forest Resources and Management, Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland
[b] Institute of Silviculture, University of Freiburg, Tennenbacherstr. 4, 79106 Freiburg, Germany
[c] Landscape Dynamics, Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland

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ABSTRACT

New forest edges are continuously being created by forest management. In the Swiss Alps, silvicultural treatments have partly changed from the selection cutting widespread two decades ago to a more intensive strip cutting. However, little is known about the impact of such harvesting on tree growth and on the structural development of Alpine forest stands dominated by Norway spruce (*Picea abies* (L.) Karst.), which have high economic and protective value.

We therefore investigated the effect of strip cutting in four Alpine spruce stands differing in site and stand conditions through a dendrochronological analysis of 134 tree stems. The change in growth rate was assessed for the 10-year period before and after the cutting year, and rate changes in edge and non-edge trees were compared. The relative change in Hegyi's competition index before and after the cut was used as a proxy for the change in space and related resources. A linear model was developed to assess the effects of biotic and abiotic variables on changes in growth after strip cutting.

Radial growth responses varied greatly between the stands, with a significant increase only in edge trees in the two north-facing sites, i.e. 12% and 60%. Changes in tree competition had the strongest impact on tree growth, followed by site effects. With the same relative change in competition index, the radial growth of edge trees increased more strongly in reaction to cutting than that of non-edge trees. Additionally, small-diameter trees growing near edges benefited more from the strip cutting than larger trees.

Our results suggest that strip cutting on north-facing slopes can boost the growth of trees on the east and north-east-facing forest edges. Small spruce trees growing along newly created forest edges can be kept to enhance stand yield. As cutting often leads to long forest edges and may thus affect the growth of a significant proportion of the forest area, such effects should be considered in planning cutting layouts.

1. Introduction

Norway spruce (*Picea abies* (L.) Karst.), which we refer to as "spruce" hereafter, is one of the most important tree species for timber production in Europe temperate forests (Spiecker, 2003) and in Alpine protection forests (e.g., for Switzerland, Duc et al., 2010). In Switzerland alone it accounts for nearly 45% of the growing stock and almost half of the timber harvest, with even higher proportions in the Swiss Alps (58% and 60%, respectively) (Swiss National Forest Inventory NFI 4, data shown for the period 2009–2013). To initiate natural regeneration in Norway spruce forests, a cutting layout with narrow strips seems to work well (Imbeck and Ott, 1987). The creation of slit-shaped gaps, increased the solar radiation (Bischoff, 1987; Imbeck and Ott, 1987; Trepp, 1955) and successfully stimulated natural regeneration (Streit et al., 2009; Wunder and Brang, 2001). Gap dimensions of around 20 m in width and 50–70 m in length have been recommended (Bischoff, 1987; Imbeck and Ott, 1987) to provide sufficient direct sunlight (Brang, 1996, 1998; Vandenberghe et al., 2009), while at the same time maintaining the protective effect, especially against snow avalanches (Cunningham et al., 2006).

Implementing small strip cutting in practice is, however, costly. The trend has therefore shifted in the last two decades toward cutting larger strips 40–100 m wide to allow more timber extraction and make the operations more profitable. This new approach is increasingly being practiced, although not in protection forests, where management guidelines prescribe smaller gaps to preserve

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* Corresponding author.
E-mail address: petia.nikolova@wsl.ch (P.S. Nikolova).

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the protective effect (Frehner et al., 2005). How these intensive silvicultural operations influence tree growth and the forest structure of the remaining stands is, however, unclear.

Many recent studies have looked into tree growth changes after thinning in spruce stands (Bachofen and Zingg, 2001; Laurent et al., 2003; Mäkinen and Isomäki, 2004; Sohn et al., 2013) or after retention cutting (Dieler et al., 2008; Pretzsch et al., 2014). Only a few, however, have focused on their effects on the growth reactions of trees newly exposed to edges, i.e. following one-sided exposure. A study of the edge effects in North Carolina Piedmont across a range of tree species with different light requirements (McDonald and Urban, 2004) found the tree radial increment considerably improved in the first seven to ten m from the edge, with the highest growth increase in light-demanding species. This suggests solar radiation is the limiting resource for the light-demanding tree species, although other factors, e.g. water ability, appeared to also play a role near edges (McDonald and Urban, 2004).

Releases related to light changes have similarly been detected in sub-alpine spruce stands in trees growing along edges on a north-facing slope in the Swiss Alps (Bräker and Baumann, 2006). The radial increment at the tree stem base was greater than at breast height (dbh), possibly because the root system had adapted to stabilise the border trees (see also Pretzsch et al., 2014). Another study in boreal Scots pine (*Pinus sylvestris* L.) forests in Sweden found that the greater radial increment in trees along the north-facing edge was related to them consuming more water than non-edge trees (Cienciala et al., 2002). In a modelling approach, growth releases in edge trees were explained by the reduced competition after cutting, with effects being greater in young than in old stands apparently due to the greater stand density (Sandoval and Cancino, 2008). This finding suggests that younger trees are more sensitive to changes in growing space than older trees.

The great variability in the edge-tree growth patterns reported may arise from a number of interacting biotic and abiotic factors, such as species-specific differences, site-specific characteristics related to elevation, aspect, soil and climatic conditions as well as to tree age and size (Mäkinen and Isomäki, 2004). The response of forest trees to new edge conditions is not yet, however, well understood, and not enough research has been conducted to estimate the magnitude of these effects and to support associated management decisions, particularly in those mountain and sub-alpine forests that have a crucial protective function.

Radial growth changes can be quantified and dated with dendrochronological methods (Nowacki and Abrams, 1997; Rubino and McCarthy, 2004), and the radial growth analyzed to elucidate a stand's disturbance history (Cherubini et al., 1998). The reaction of trees to a specific event can be assessed with a yearly resolution. Disturbances usually induce growth releases in the surviving trees in a stand, but they are often difficult to distinguish from releases induced by climatic trends and events (Fraver and White, 2005). To identify a release or suppression of radial growth retrospectively, dendrochronological methods have been widely used, adjusted and tested (Black and Abrams, 2003, 2004; Trotsiuk et al., 2012). In our study, we used tree-ring width as a proxy for annual tree radial growth, focusing on radial increment before and after a known event, i.e. the year of strip cutting. Non-edge trees, which grew in an interior environment, were compared with edge trees, which experienced one-sided release from competition following strip cutting. Tree-ring growth patterns were analyzed and correlated with site and tree characteristics, and the following questions addressed:

1. How large is the mean growth change in reaction to a change in competition, i.e. in growing space?
2. How is this reaction related to site conditions?
3. Does the growth reaction depend on tree size?

2. Materials and methods

2.1. Study area

Three study sites were selected in the Upper Rhine Valley and one in the Lower Engadine (Canton of Grisons, Switzerland) (Fig. 1) according to four criteria: (1) stand composed of at least 80% spruce; (2) a minimum of 10 years since last strip cutting; (3) a clear border along the cutting area, 20–70 m in width; and (4) not actively managed or naturally disturbed during the last 30 years prior to strip cutting. The sites are located at elevations ranging from 1215 to 1680 m a.s.l. on slopes with an inclination between 50% and 70%. Two sites have a south- and two a north-west aspect (Table 1), with winds predominantly from the west.

The spruce stands differed in stand age, density and growing stock. Furna is the oldest stand with trees up to 266 years old, but with the lowest tree density (332 trees ha^{-1}), and the highest growing stock and basal area (1029 m^3 ha^{-1} and 71.2 m^2 ha^{-1}, respectively) (Table 1). The youngest stand is Jenins, its oldest trees having a mean age of 59 years, with a relatively high stand density and growing stock. The stand in Siat is similar to Furna, but with a lower growing stock, while Sur En has the smallest growing stock (400 m^3 ha^{-1}) and lowest basal area (34.6 m^2 ha^{-1}). According to Keller's site index (Keller, 1978), Furna is the most productive site (site index 22), and Sur En the least (site index 16; Table 1).

Three stands originated from natural regeneration, but the stand at Jenins was planted. Strips of variable size were cut between 1997 and 2006 (Table 1) but with a similar east to south-east orientation. Forest management plans (Cantonal Forest Office, Chur, Switzerland), available for all the stands, were used to reconstruct the stand's history.

Daily means of temperature and precipitation for each site were interpolated using the DAYMET software (Thornton et al., 1997) on the basis of meteorological data recorded at the MeteoSwiss meteorological stations closest to each study site during the period 1991–2013. Average temperatures varied from 3.6 °C to 5.7 °C, with the largest intra-annual variation in Sur En, located in Lower Engadine, characterized by a continental climate (Table 1). The average annual precipitation sum (P) ranged from 811 to 1481 mm at the four different sites, with Sur En receiving the lowest amount of precipitation per year. The Lower Engadine is one of the driest regions in Switzerland, although, according to the climatic classification of de Martonne (1926), the annual aridity index DMI (De Martonne Index) still places Sur En in the "humid" climate class, whereas Siat, Furna and Jenins (with a DMI over 60) are classified as "very humid" (Fig. 2). At each study site, a strong decrease in the DMI was observed during the extremely dry year 2003 (Ciais et al., 2005), but the DMI did not recover to pre-drought levels until 2008 (Fig. 2).

2.2. Sampling design

A rectangular 40 m × 20 m plot inside the forest stand was set up at the edge of each cutting area and as an inlay in the permanent plot. In each plot all living trees with a stem diameter at breast height (dbh), i.e. at 1.3 m height above ground, larger than 7.5 cm were mapped and cored for tree-ring analysis. Trees with crown perimeters exposed to the cutting area were defined as edge trees and the remaining trees as non-edge trees. The plot size was chosen to ensure a minimum sample size of 20 trees with variable dbh. The plot width was chosen to cover a range of tree reactions to the cutting, from trees fully exposed to the cutting area to trees unaffected by the cutting, and set at 20 m according to the results of a similar study in conifer plantations in North Carolina. In this

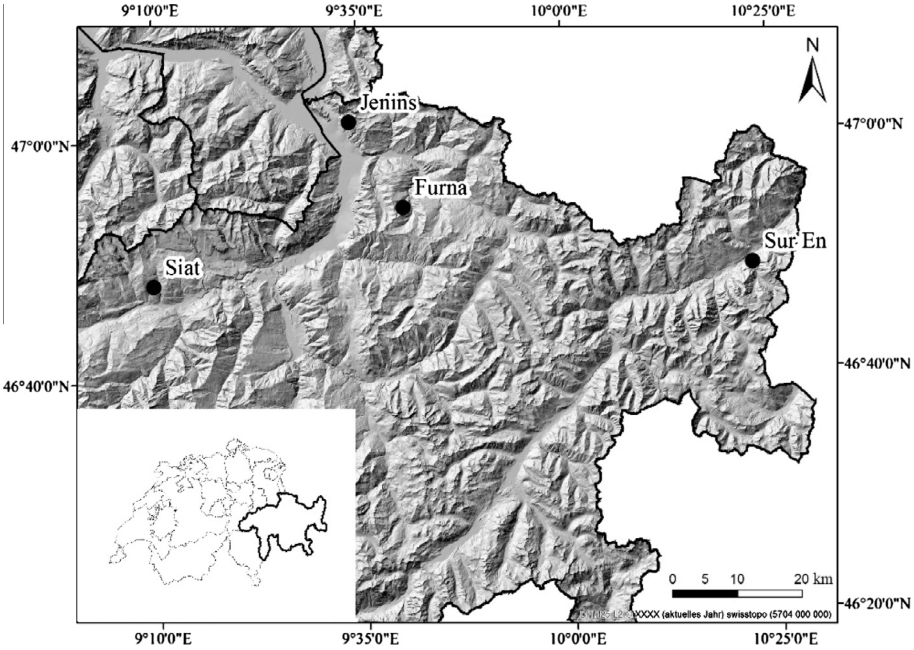

Fig. 1. Location of the four study sites in the canton of Grisons, Switzerland, with the position of the canton shown in the small map (reproduced with the permission of swisstopo, JA100118).

Table 1
Stand and site description.

Site	Furna	Jenins	Siat	Sur En
Latitude and longitude	46°54′07″N 9°40′16″E	47°01′21″N 9°33′54″E	46°47′58″N 9°09′40″E	46°48′43″N 10°22′35″E
Elevation (m a.s.l.)	1680	1215	1615	1500
Aspect	North-west	South	South	North-west
Edge orientation	North-east	East	East	North-east
Climate (1991–2013)				
Mean annual temperature (T, °C)	3.6	5.7	3.6	4.4
Min/Max annual temperature (°C)	−0.1/8.0	1.9/10.1	0.1/7.8	−0.4/10.1
Mean summer temperature (°C)	11.7	13.9	11.6	13.3
Annual precipitation sum (P, mm)	1322	1472	1481	811
Summer precipitation sum (mm)	493	546	481	323
Annual De Martonne index (DMI)	97	94	109	56
Stand characteristics				
Year of the cut	2004	1997	2004	2006
Average width of the cut (m)	70	55	70	35
Stand density (n ha^{-1})	332	749	363	644
Growing stock (m^3 ha^{-1})	1029	795	668	400
Basal area (m^2 ha^{-1})	71.2	62.9	47.6	34.6
Dominant tree height (h_{dom}, m)[a]	35.6	31.4	33.1	28.4
Stem diameter of dominant trees (dbh, cm)	61.5 ± 0.5	50.7 ± 0.4	56.3 ± 0.4	41.2 ± 0.9
Site index[b]	22	18	20	16
Characteristics of the cored trees				
Sampling size	32	73	29	46
Average age of the 5 oldest trees (years)	266 ± 6	59 ± 2	249 ± 9	174 ± 10
Average stem diameter (dbh, cm)	50 ± 2.3	34 ± 1.5	48 ± 2.1	30 ± 1.7

[a] Average height of the 100 largest trees per hectare (modelled according to Zingg, 1999). Climatic data were averaged over the period 1991–2013. The summer period is defined as June 1 to August 31. The annual de Martonne index was calculated as DMI $= \frac{P}{T+10}$ (Maliva and Missimer, 2012). Tree age was assessed on the longest complete cores ($n = 5$ per site) and is thus a proxy for the maximum tree age. The tree parameter data are given with the mean ± standard error.

[b] Site index was defined for forest stands in Switzerland according to Keller (1978). Low values indicate low site productivity.

study, the edge effects on tree growth rates were restricted to a strip 5 m in width (McDonald and Urban, 2004).

The coordinates and diameters of the remaining stumps in the cutting area were recorded in order to be able to reconstruct the stand before the cutting. As the stump heights varied greatly, the dbh was extrapolated from a form factor equation calculated from 10 still standing trees per site. Their stem diameters were measured at five heights (10, 40, 70, 100 and 130 cm), and stump height-dependent correction equations were then estimated for each site.

For the retrospective tree-growth analysis, each living tree with dbh > 7.5 cm in the permanent plot was cored at 1.0 m stem height, which is lower than the usual extraction height of 1.3 m, to avoid stem damage at the point of future dbh measurements.

Cores were collected with an increment borer (0.5 cm in diameter, Suunto, 400 mm, Finland). All trees were cored twice from two opposite directions perpendicular to the slope direction to minimize any potential bias should there be any reaction wood. The coring position was adjusted to avoid stem sections with scars. Some rotten trees could not be sampled.

2.3. Dendrochronological analyses

2.3.1. Ring-width measurements

Each core was glued on a wooden holder and sanded using a sanding machine with sandpaper of different coarseness. Ring width was measured with the LINTAB™ device and the Software TSAP (RINNTECH, 2003). Single-core chronologies were then built and crossdated in pairs for each tree before crossdating each tree ($p \leqslant 0.05$) with all other trees in the stand using the COFECHA software (Grissino-Mayer, 2001). Ring-width measurements were then detrended and indexed using the non-exponential function of the R software (detrend.series with ModNegExp, dplR package; Bunn, 2010; Cook and Kairiukstis, 1990) to minimize the ring-width variation associated with age trends.

2.3.2. Quantification of growth changes

We quantified the abrupt growth releases induced by the strip cutting in terms of the percentage change in growth rate (PGC, %), calculated as the relation between the growth prior to (G_p) and after (G_a) the year of cutting (York et al., 2004). We applied the approach of Nowacki and Abrams (1997) and Trotsiuk et al. (2012), who quantified the growth release as the change in the mean annual increment in percentage between two intervals using the formula:

$$\mathrm{PGC} = \frac{G_a - G_p}{G_p} \times 100 \quad (1)$$

where G_p is the mean growth during the 10 years before the cutting, and, G_a that during the 10 years after the cutting. Both parameters G_a and G_p are calculated with raw undetrended ring widths. Raw data were used for these analyses because detrended data did not show any trend induced by stand disturbances or remove the low-frequency variability attributable to stand growth dynamics (Cherubini et al., 2003; Tognetti et al., 2000).

In Sur En, where the cutting was in 2006, only 8 years were averaged in calculating G_a, which could lead to a small overestimation of the growth reaction there. The period of 10 years is preferable for averaging tree radial growth because it has proved to be the most suitable in smoothing short-term growth responses to climate (Leak, 1987), while still capturing the growth responses related to canopy disturbance. A shorter interval of 5 years after harvesting as in Pretzsch et al. (2014) and York et al. (2004) was considered too short because spruce in the present study appears to have a more lagged response (Fig. 3).

2.4. Calculating Hegyi's competition index

The Iterative Hegyi's competition index (CI), which is based on the dbh and the distance away from directly competing trees (Lee and von Gadow, 1996), was used to characterize the growing space for each sample tree. Tree coordinates were used to calculate the distance between the trees. CI was calculated for each sampling tree as:

$$\mathrm{CI}_i = \sum_{j=1}^{n} \frac{\mathrm{dbh}_j/\mathrm{dbh}_i}{d_{ij}} \quad (2)$$

where CI_i is the Hegyi's competition index for tree i, dbh_i the diameter at breast height of the target tree i (cm), dbh_j the diameter at breast height of the competitor j (cm), d_{ij} the distance between the target tree and the competitor (m), and n the number of trees within the competition zone with a dynamic radius (for more details, see Lee and von Gadow, 1996).

The CI was first calculated for the dataset that represented the stand before the cutting ($\mathrm{CI_b}$), which included the measured dbh and coordinates of the stumps, and the dbh of standing trees corrected by the post-cut increments. A second competition index ($\mathrm{CI_a}$) was calculated with the dbh measured in 2014, but without the trees in the gap, to represent the growing space after the cut ($\mathrm{CI_a}$). The resulting relative change in CI after cutting (CCI) was calculated for each sampling tree according to the formula:

$$\mathrm{CCI} = \frac{\mathrm{CI_a}}{\mathrm{CI_b}} \quad (3)$$

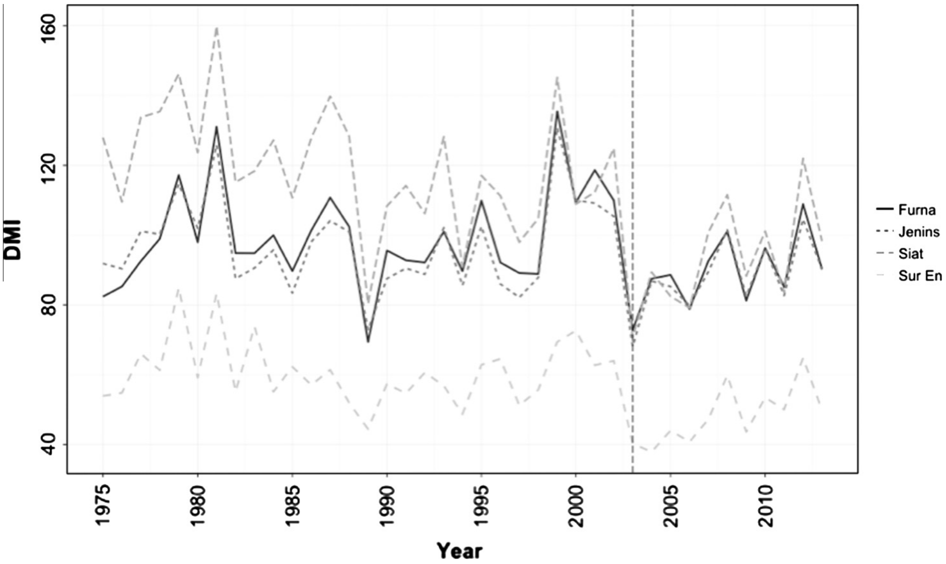

Fig. 2. Aridity index DMI (de Martonne, 1926) for the period 1975–2013 in the study sites Furna, Jenins, Siat and Sur En. The vertical line indicates the extremely dry and hot year 2003.

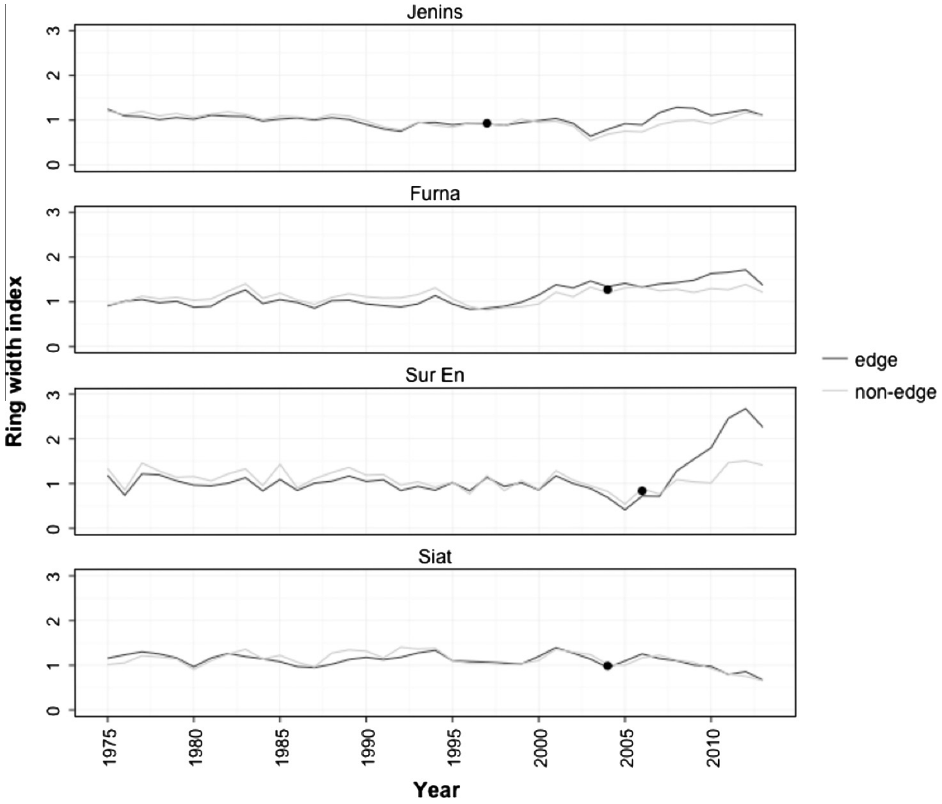

Fig. 3. Mean chronologies of the ring-width index for edge and non-edge trees in the four study sites for the period 1975–2013. Black dots indicate the cutting year.

This variable was then used as a continuous explanatory variable to link the reaction of each tree with the effective liberation it experienced, where CCI < 1 indicated enlarged growing space after cutting. Only trees with dbh > 10 cm in 2014 were included in the quantification and analysis of growth change as the dbh reconstruction did not provide reliable values for smaller trees.

2.5. Statistical modelling

Analysis of covariance was done, and multiple regression models were built to explain the change in growth PGC, applying linear model fitting functions (Crawley, 2005). We fitted each model separately, with PGC as the response variable and CCI a continuous explanatory variable describing the change in competition status of the trees. As we were interested in the growth reactions of trees both at the stand edge and within the stand, as well as their dependency on site conditions, we included the tree group (edge, non-edge) and site (Furna, Siat, Jenins, Sur En) as categorical variables. The dbh assessed for the cut year was also included for testing the growth dependency on tree size within the tree groups and sites. Outliers with Cook's distance > 8/*N* (*N* = dimension of the dataset) were excluded from the analysis and the models then refitted (Crawley, 2005). Outlier ($n = 3$) exclusion did not change the model outcome, but did slightly improve model fit. The model with the lowest Akaike Information Criterion (AIC) was retained, and parameter coefficients and fit (adjusted R^2) were used to evaluate model effects and suitability (Crawley, 2005). For multiple comparisons, subsequent Tukey's post hoc tests and contrasts were performed. All computations were performed using R version 3.1.2 (R Development Core Team, 2014).

3. Results

3.1. Effects of strip cutting on the radial growth of edge and non-edge trees

A total of 134 ring-width chronologies were built for edge and non-edge spruce trees in the four sites. The year-to-year variation and the overall trend of indexed ring widths before the strip cutting were similar in all four stands for edge and non-edge trees (Fig. 3). At Jenins, the youngest stand, which was planted and thus even-aged, the growth of the two groups was almost identical. Strip cutting accelerated the radial stem growth of edge trees in Jenins, Furna and Sur En, whereas no increase was detected in Siat. Distinct differences in the growth patterns of edge and non-edge trees began three (for Furna and Sur En) to seven (for Jenins) years following the cutting, and flattened out or disappeared seven to ten years after it.

In Jenins, trees from both groups experienced on average a reduction in radial growth of up to 30% during the extremely dry year 2003, whereas trees growing at all the other sites showed no drought impact (Fig. 3). A differentiation in the increment of edge and non-edge trees was detectable in Jenins during the post-drought period from 2004 to 2012.

3.2. Stem growth of edge trees before and after strip cutting

Cutting lead to a significantly lower CCI (Fig. 4A) in edge trees in comparison to trees from the stand interior in Sur En ($p < 0.001$; Wilcoxon rank sum test) and Furna ($p < 0.05$; Wilcoxon rank sum test), whereas no change in competition index was detected in Jenins and Siat. Most non-edge trees experienced increased competition in the period after cutting (CCI > 1, Fig. 4A). Competitive pressure within the stand interior increased most markedly in

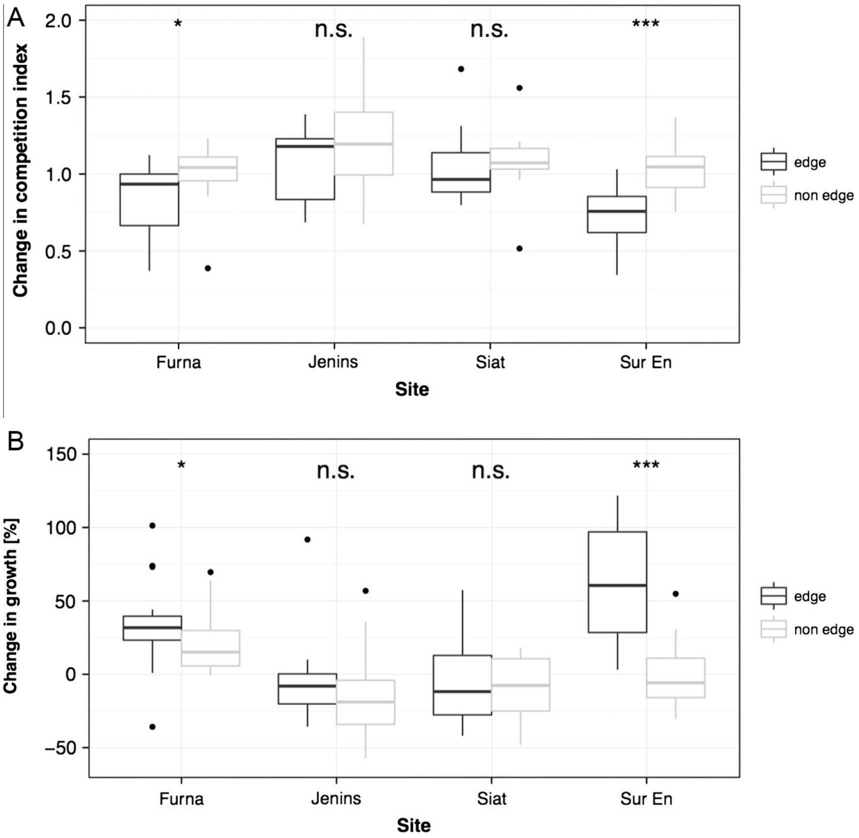

Fig. 4. Changes in the competition index CCI (A, Eq. (3)) and percent changes in growth PGC (B, Eq. (1)) of edge and non-edge trees after strip cutting. Within a box-plot, the line is the median value of the percentage change in growth rate (PGC). The middle 50% of the values are within the box, and 95% of values are within the error bars. Individual points represent outliers. Significance levels are as follows: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, n.s. (= not significant, $p > 0.05$), Wilcoxon rank sum test.

Table 2
Statistical characteristics of the model for predicting PGC (adjusted $R^2 = 0.53$) in relation to change in growing space (CCI), tree group (edge, non-edge), site (Furna, Jenins, Siat and Sur En) and tree diameter assessed for the cut year (dbh, cm). The final model had the lowest AIC and was constructed after excluding the outliers ($n = 3$) as described in Section 2.5.

	Estimate	Std. error	Pr (>|t|)
(Intercept)	134.14	19.89	<0.0001***
CCI	−56.56	9.74	<0.0001***
Jenins	−47.54	10.03	<0.0001***
Siat	−37.47	8.18	<0.0001***
Sur En	−23.43	10.01	0.0209*
Non-edge trees	−39.96	13.74	0.0043**
dbh	−0.95	0.37	0.0119*
Non-edge trees:dbh	0.70	0.35	0.0482*

Significance levels are as follows: $^*\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$.

the youngest stand Jenins, whereas in the three older stands this change was only marginal, with a median CCI value only slightly over 1.

The percentage change in growth rate (PGC) of edge and non-edge trees was reciprocally related to CCI, with significantly more growth in edge trees than in non-edge trees in Furna and Sur En ($p = 0.043$ and $p < 0.001$, respectively; Wilcoxon rank sum test) (Fig. 4B). The differences between both tree groups were not significant in Jenins ($p = 0.08$) and Siat ($p = 0.89$) (Fig. 4B).

3.3. Factors affecting the changes in tree growth

In general, PGC differed significantly between the edge and non-edge trees ($p = 0.0016$, analysis of covariance). The growth reaction was tightly related to CCI ($p < 0.0001$) and varied across sites ($p < 0.0001$). The dbh tended to influence the tree growth response ($p < 0.0829$), whereas the interaction of the tree group and dbh had a significant impact on the PGC ($p = 0.048$).

Table 3
Characteristic values for the percent change in growth (PGC) of spruces growing in Furna, Jenins, Siat and Sur En.

Site	Percent change in growth [%]	
	Edge trees	Non-edge trees
Furna	34.34 ± 7.74^{ab}	22.64 ± 5.72^{bc}
Jenins	-12.19 ± 5.56^{cd}	-24.25 ± 4.80^{d}
Siat	-5.58 ± 9.70^{cd}	-9.23 ± 5.82^{cd}
Sur En	61.26 ± 14.47^{a}	-1.23 ± 4.53^{cd}

Data are shown with the mean ± standard error and are calculated according to the variation among trees. Letters indicate significantly different values between the study sites and two groups (Tukey post hoc test, $p < 0.05$).

Our final model with the lowest AIC was thus based on the variables tree group, CCI, dbh, site and the interaction of the tree group and dbh. It explained 53% of the variation in PGC (Table 2). Trees in an edge position increased their radial growth after strip cutting more strongly than non-edge trees, with a somewhat larger effect in smaller trees (significant interaction of tree group and dbh; Table 2). Larger trees, in contrast, changed their growth only slightly, although the opposite effect was found in trees in the stand interior. The change in CCI was the single most important factor affecting the PGC (Table 2), explaining alone 37.5% of the variance in the tree growth reaction (linear regression model, data not shown). Overall, PGC increased with decreasing CCI, i.e. the trees whose growing space was most enlarged increased their radial growth most after cutting. The growth releases of edge trees were most important in Sur En, the PGC being, on average, 60%

higher than in non-edge trees (Tukey Kramer's post hoc test, $p < 0.05$; Table 3). In contrast, the effects in Furna and Jenins were weak but still significant (approx. 12% in both sites) and not significant in Siat (approx. 3%).

4. Discussion

4.1. Timing and magnitude of the growth responses

Spruce trees have been shown to react to thinning with enhanced radial growth (Bachofen and Zingg, 2001; Laurent et al., 2003) due to the availability of more light and soil resources (Pretzsch, 2006; Sohn et al., 2013), with somewhat greater effects in smaller trees (Mäkinen and Isomäki, 2004). In our investigation, we extended the study of spruce reactions to enlarged growing space to the edge situation, where trees are subjected to a one-sided alteration in growing conditions. Our findings suggest that the radial stem increment of a spruce tree following strip cutting largely depends on the enlargement of its growing space (CCI) (Table 2). In general, the radial increment increased in edge trees after strip cutting, and somewhat declined in undisturbed adjacent stands (Fig. 3). However, these effects varied in space and time between stands: the reaction time was three years after cutting in the two north-west-facing sites (Sur En and Furna), and seven years in one south-facing site (Jenins), while no response was found in the other south-facing site (Siat). In a subalpine Norway spruce forest managed with strip-cutting in the Italian Dolomites (Eastern Alps), growth releases in the edge trees were delayed by one to five years, with the reaction times of the different trees, and even of different parts of the trees, varying (Cherubini et al., 1996).

The radial growth during the first two to three years after cutting seems to be related to stress-induced adaptive reaction patterns, such as short-term changes in tree root-shoot allometry (Nikolova et al., 2011; Pretzsch et al., 2014). How the trees adapt to the new environment is species-specific. Radial stem growth in Douglas-fir (*Pseudotsuga menziesii*) increased in the year immediately following harvest (York et al., 2004), and in two to five years after cutting in other coniferous trees (Pretzsch et al., 2014; York et al., 2004). Such growth changes may result from the trees becoming mechanically more stable in the face of increased wind loading (Coutts, 1983), and/or acquiring more belowground resources (Coutts et al., 1999), and from aboveground canopy reorganization (Cienciala et al., 2002; Juodvalkis et al., 2005). In edge trees in a subalpine Norway spruce stand in the Swiss Alps, strip cutting induced a stronger radial growth increase at the stem base than at dbh height. This was interpreted as adaptation of the trees' root systems to enhanced wind forces (Bräker and Baumann, 2006). The delayed aboveground effect in our study may be due to a similar initial allocation of tree growth resources to the roots and stem bases.

Significant release effects in edge trees, expressed as relative changes in stem radial growth (percentage change in growth rate, PGC), amounted, on average, to 60% in Sur En, and 11% in Furna (Table 3). The significant radial growth releases detected in Sur En and Furna are in line with previous studies (Bräker and Baumann, 2006; Cienciala et al., 2002; Matlack, 1994), which report increased edge-tree radial growth on north-facing sites. In Jenins, the observed growth pattern may have been provoked by the extremely dry summer 2003 (Ciais et al., 2005), which occurred in the study period only here. In other high-elevation forests, the spruce growth response to 2003 depended on elevation (Hartl-Meier et al., 2014; Jolly et al., 2005), with a decrease in montane forests (1200–1400 m a.s.l.) but growth enhancement at sites above 1400 m a.s.l. In the montane forest in Jenins, the strip was cut in 1997, i.e. six years before 2003 (Fig. 2). During the post-drought period from 2004 to 2012, the radial stem increment of spruce trees at this site declined by up to 30% (Fig. 3), with a stronger decline in interior than in edge trees. Edge trees recovered better than stand trees, and even temporarily increased their radial growth over pre-drought levels. This result needs validation in other montane forests, but is in line with the finding that the growth recovery after the droughts in 1992 and 2003 was faster in recently thinned lowland spruce stands in southern Germany than in unthinned ones (Kohler et al., 2010; Sohn et al., 2013).

4.2. Factors driving the growth of edge trees after strip cutting

The change in the competition index (CCI) in trees, as derived from the iterative Hegyi's competition index, explained 37.5% of the variance of radial growth change and was the main factor in the statistical model. Across all sites, growth, as expressed by PGC, increased with decreasing competition strength, i.e. with enlarged growing space around the target trees, which is related to the enhanced availability of resources such as light, soil water and nutrients. The same increase in growing space, however, provoked more mean radial growth in edge than in non-edge trees (Table 3). This means that the CCI related to the growing space did not capture the full extent of the change in resource availability induced by strip cutting.

The edge trees may have experienced additional growth enhancement due to differences in microclimatic conditions in edge environments. Some aspects of a stand's microclimate, e.g. light, temperature, soil moisture and wind appear to respond significantly to edge effects (Cienciala et al., 2002; Matlack, 1993, 1994), with the edge orientation determining the extent of response (Chen et al., 1993). In an old-growth Douglas-fir forest in southern Washington, cutting markedly enhanced short-wave radiation only in south-facing edges. In contrast, the light conditions along east- and northeast-facing edges, such as those in our study, had only slightly improved, but the relative air humidity was considerably higher than along south- and west-facing edges (Chen et al., 1993). As all four edges face north-east in our study, such effects cannot explain the differences in edge-tree growth release we observed.

A recent study in southern Germany (Sohn et al., 2013) showed that Norway spruce, which is an isohydric species, i.e. drought avoider (Lyr et al., 1992), benefits from thinning if the water supply is scarce as the trees can then maintain a more positive water balance. This finding could help to explain the enhanced radial increment of trees in the north-west-facing sites in Sur En and Furna. The strongly enhanced edge-tree growth in the driest and least productive site, Sur En, (lowest DMI, lowest site index; Table 1) may have resulted from the improvement in soil and nutrient availability along the stand edges. Soil water availability can explain much of the variation in edge tree growth, especially since volumetric soil moisture is enhanced at stand edges (Chen et al., 1993; Cienciala et al., 2002). In contrast, in the fertile and moist but high-elevation site, Furna, the higher soil temperatures in the edge zone may have stimulated radial tree growth. Root zone soil temperature limits tree growth in high-elevation forests (Körner, 1998) and is positively related to the direct solar radiation, which is known to be more intense along edges (Chen et al., 1993).

The edge trees in both south-facing stands in our study do not, however, seem to have been able to benefit from warmer temperatures. In Siat, the local climate conditions changed after the year of cutting 2004, and the De Martonne index (DMI) dropped from an average of 120 to nearly 80 (Fig. 2). The lack of growth reactions in the edge trees in Siat may, therefore, be explained by reduction in available soil water together with the changes in the microclimatic conditions in the edge zone, such as warmer temperatures.

As a result, more belowground growth may have been induced in the trees, in particular in those along the edge, to cover the evaporative demands in the altered environment (Cienciala et al., 2002). An alternative explanation for the lack of a release effect along edges in both south-facing sites is that the availability of water did not increase as much as that of light since the zone directly beside an east-facing edge, which is the rooting zone of the edge trees, is largely in the rain shadow in a climate with prevailing westerly winds.

4.3. Dependence of growth reaction on tree size

Across all study sites, trees with smaller diameters growing near edges benefited slightly more from strip cutting than larger trees, whereas the growth effect on those within the stand's interior appeared to be largely independent of tree size (Table 2). Mäkinen and Isomäki (2004) also found large trees to be less affected by thinning than smaller trees in Finnish Norway spruce stands. Processes such as crowding, gap formation and overtopping (Pretzsch and Biber, 2010; Zang et al., 2011) seem to have a greater influence on the growth of smaller trees than of larger ones. Accordingly, Cherubini et al. (1996, 1998, 1999) observed that suppressed small Norway spruce trees grew faster than larger ones after gap cutting. Unlike in non-managed stands, small trees growing along the newly created forest borders in our study apparently benefited most from the improved light and soil water availability as well as from warmer temperatures. If such small spruce trees are present along newly created forest edges, this growth release effect can be exploited to improve the stand's yield.

5. Conclusions

The radial growth of edge trees in Norway spruce stands in the Swiss Alps was temporarily enhanced within the first ten years after strip cutting, with the stems of small edge trees reacting more than those of large edge trees. Growth releases occurred merely in the two stands located in north-west-facing slopes where the edge trees seemed to benefit mainly from the increase in water availability and soil temperature. On the drier south-facing slopes, strip cutting apparently did not improve the growth conditions of the edge trees.

Our four study sites in the montane and subalpine belts of the Swiss Alps have different stand and site characteristics, which make it difficult to generalize the results. The choice of sites was greatly limited by our initial requirement that cutting should have taken place 10 years previously. Follow-up studies with a larger sample would enable our hypotheses to be rigorously tested. A more physiologically oriented research approach would also be worthwhile. Despite these limitations, our results indicate that edge effects on tree growth can be strong, in particular in north-facing sites. Small spruce trees growing along newly created forest edges should not be cut as they benefit most from edge conditions, which enhances stand's yield. Cutting often leads to long forest edges and may thus entail growth effects on a significant proportion of the forest area, thus such effects should be taken more into consideration when planning cutting layouts.

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