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Development of natural regeneration after different regeneration cuttings in a Norway spruce peatland forest in northern Finland

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Abstract

As the clearcutting of peatland forests is known to cause harmful consequences especially for the water environment, there is increasing interest in alternative natural regeneration methods. We studied the regeneration stocking development on a southern Lapland site, where shelterwood cutting, heavy selection cutting, patch clearcutting ($\leq$0.3 ha) treatments, and a non-treated control with three replicates had been established in the winter of 2013. Regeneration stocking was inventoried in the springs of 2013, 2016, 2018, and 2021 from 16 seedling survey plots (size 5 m^2), which were systematically located in each of the 12 treatment plots. The number of small spruce seedlings ($<$ 10 cm height) was largest in 2016 and then started to decrease. The number of large ($>$ 10 cm) spruce seedlings increased two- to three-fold (4,500–9,000 ha^{-1}) towards the end of the study period for all cutting treatments. The number of large birch seedlings also increased especially for heavy selection and clearcutting and was 2–10 times higher than that of spruce. Birch was less abundant in shelterwood cutting. The tallest spruce and birch seedlings were found in clearcuts. Large spruce and birch seedlings were most evenly distributed for heavy selection and clearcut treatments. All cutting treatments showed high average regeneration density for a mixed seedling stand of Norway spruce and downy birch within the eight post-cutting years.

Keywords Advance growth · *Betula pubescens* · Natural regeneration · Peatlands · *Picea abies* · Shelterwood · Selection cutting

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Introduction

Drained spruce mires are common in northern Finland and they are an important Norway spruce (*Picea abies*, L. Karst.) sawlog resource. They have traditionally been treated with even-aged management with clearcutting, ditch cleaning, site preparation, and planting. As recent studies have indicated that such management causes increased nutrient and suspended solids load on water courses (Nieminen et al. 2010; Kaila et al. 2015) and create harmful climate effects (e.g., Korkiakoski et al. 2019), alternative management methods, like continuous cover forestry have been suggested (Nieminen et al. 2018; Juutinen et al. 2021). Avoiding large clearcuts also benefits other forest species like willow tit (*Poecile montanus*) (Kumpula et al. 2023) and capercaillie (*Tetrao urogallus*) (Rolstad and Wegge 1987; Suter et al. 2002; Pakkala et al. 2003), which need canopy cover and prefer older forests to open areas and dense young stands. Furthermore, artificial regeneration is expensive, which is a problem especially in northern Finland, where the expected timber production and economic yield is much less than in central and southern Finland, though the regeneration costs are the same.

As spruce is a shade-tolerant tree species, alternatives for successful natural regeneration without clearcutting exists. The most used method in practice is regular shelterwood cutting (Leinonen et al. 1989; Hannerz and Hånell 1997; Nilsson et al. 2002; Sikström et al. 1997, 2005) in which 150–300 ha^{-1} dominant and codominant trees (Norway spruce, downy birch (*Betula pubescens* Ehrh.) or Scots pine (*Pinus sylvestris* L.) are retained to provide seeds and protect the advance growth seedlings from frost and competition from ground vegetation (Örlander and Carlson 2000; Holgén and Hånell 2000). Regular shelterwood cutting basically aims for even-aged regeneration (Sarvas 1944; Pothier et al. 2003; Groot et al. 2005).

To be successful, advance growth seedlings with reasonable numbers should be found prior to shelterwood cutting (Sarvas 1944; Hagner 1962; Sikström 2005). Shelterwood cutting has resulted in variable regeneration results on mineral soil sites (Leinonen et al. 1989; Sikström et al. 1997, 2005). In a study by Leinonen et al. (1989), the proportion of satisfactory spruce seedling stands was <30% two years after cutting, which was considered unsatisfactory. According to Sikström (1997) the proportion of acceptable seedling stands 2–8 years after cutting varied from 34 to 72%, depending on the minimum requirement for the number of conifer seedlings and the geographical area. In contrast, good regeneration has been reported on peatland sites (Hånell 1993; Holgén and Hånell 2000; Moilanen et al. 2011; Pothier et al. 2003). The method necessitates the retention of valuable sawlog- size shelter trees, that diminish the cutting income. For some years after cutting these are susceptible to windthrows (Sikström 1997; Hånell and Ottosson-Löfvenius 1994; Moilanen et al. 2011; Anderson et al. 2020) and are therefore prone to financial loss. Where ecological aspects are considered, bird species diversity and species richness have been found to be greater in shelterwoods than in mature forests or clearcuts (King and DeGraaf 2000).

Gap cutting has been found to give a satisfactory regeneration result in 10 years in northern Finland (Hökkä and Repola 2018). If larger (0.2–0.3 ha) patches (i.e., gaps diameters 40–60 m) are cut, the regeneration process is significantly slower than in gaps with a diameter of 15–25 m (Hökkä et al. 2012; Hökkä and Repola 2018; Valkonen and Siitonen 2016). The regeneration in gaps and patches is based on both advance growth and the establishment of new spruce seedlings (Hökkä and Repola 2018; cf., Leemans 1991). Gap cutting and patch clear cuts result in a spatially variable forest structure with patches of younger and older trees. As a form of gap cutting, strip clearcuts are also used to naturally regenerate peatland Norway spruce (Lukkala 1946) and black spruce (*Picea mariana* (Mill.) BSP) stands (Pothier 2000).

The third potential alternative is heavy selection cutting using a low retained basal area. This relies on the existing heterogenous stand structure and a seedling bank, which can be considerable in mature spruce peatland stands (Pothier et al. 2003; Moilanen et al. 2011; Hökkä et al. 2011). The retained stems are expected to respond to improved light conditions with improved growth. The resulting seedling-sapling stand is significantly uneven -aged. As the spruce mire stands in Finland are naturally uneven-aged (Gustavsen and Päivänen 1986; Sarkkola et al. 2003). Even in a low retained basal area composed of pulpwood-size and non-commercial stems the stand density may be sufficiently high to serve as a shelter and nurse stand for the seedlings. Such cutting maintains the heterogenous stand structure and provides another benefit: There will be no need to retain the valuable sawlog-size stems.

One problem related to natural regeneration following different kinds of cuttings, in addition to the aggressive regeneration of downy birch (Holgén and Hånell 2000; Moilanen et al. 2011), is the clustered spacing of the established seedlings. Naturally regenerated seedling stands tend to be irregular, not only in terms of seedling size but also in terms of seedlings' spatial distribution (Leinonen et al. 1989; Sikström et al. 2005; Hökkä and Repola 2018). The number of seedling survey plots without crop seedlings varied from 18 to 54% after 10 years from gap cutting depending on gap size (Hökkä and Repola 2018). Holgén and Hånell (2000) found that ten years after shelterwood cutting on spruce peatland the average proportion of empty survey plots was as much as 58%. Uneven seedling establishment (Saksa and Valkonen 2011) and subsequent spatially varying ingrowth (Lappi and Pukkala 2020) are also a problem in continuous cover forestry.

This study aimed to investigate the development of the number of seedlings on a northern Finland spruce mire after alternative harvest methods aiming for natural stand regeneration. The size and spatial distribution of the seedlings were also analyzed. The cutting treatments involved shelterwood cutting, heavy selection cutting, and patch clearcutting, which were compared to non-treated control. We assumed that the different cutting treatments would result in differences in regeneration stocking density, species composition, and seedlings' spatial distribution. The specific hypotheses were: (i) In clearcuts, downy birch establishment would be quicker than in the other treatments, and the regeneration of Norway spruce would be slow; (ii) with heavy selection cutting, spruce regeneration could be significantly promoted; (iii) in shelterwood areas, both species would have equal opportunities to establish; and (iv) the spatial distribution of both species would become more even during the study period.

Materials and methods

Study site and experimental design

The study site was in Tervola, southern Lapland (66° 11', 25° 42'). The site type is classified as a meso-eutrophic herb-rich type spruce mire (Laine et al. 2012), with a peat layer thickness ranging from 0.2 m to 0.8 m. The site was drained with open ditches in the 1960s and

Table 1 Mean stem number (N, ha^{-1}), basal area (BA, m^{2}ha^{-1}) median diameter (DMd, cm), dominant height (Hdom, m), volume (V, m^{3}ha^{-1}) and volume of saw logs (Vsl, m^{3}ha^{-1}) by cutting treatments after cutting (standard deviation in parentheses)

Cutting treatment	Stand characteristic					
	N	BA	DMd	Hdom	V	Vsl
Control	1,681 (521)	26.1 (2.8)	17.4 (4.1)	15.8 (1.0)	159.2 (26.8)	58.4 (35.5)
Shelter- wood	269 (49)	7.8 (0.7)	23.8 (2.6)	16.4 (0.2)	55.0 (5.4)	38.0 (7.3)
Heavy selection	773 (17)	3.7 (0.7)	9.5 (0.7)	10.8 (1.1)	17.7 (4.9)	0.5 (0.9)

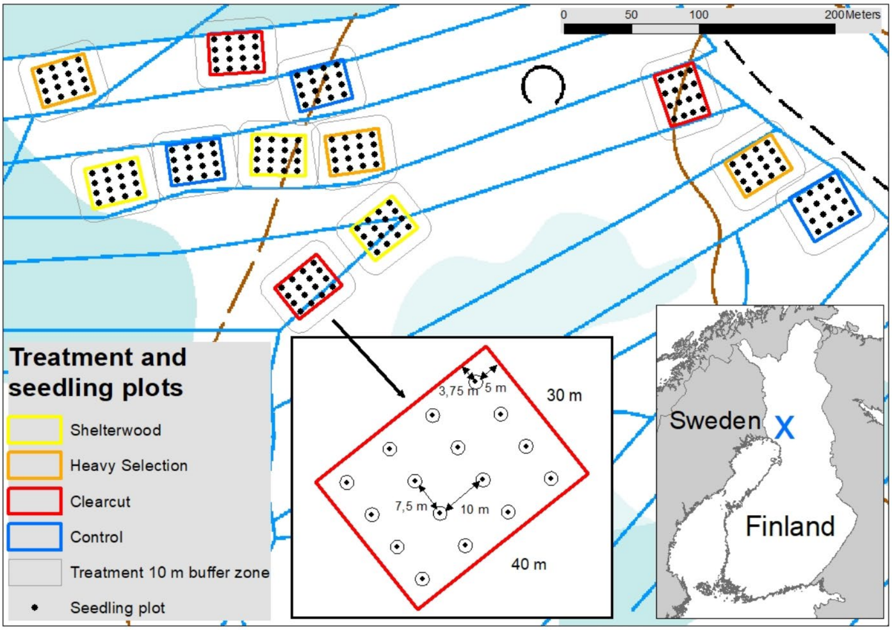

Fig. 1 The site location, the experimental lay-out and the location of the seedling inventory plots in the treatments plots. The radius of each seedling inventory plot was 1.26 m (area 5 m^2). The size of one control treatment plot was 37.5 m X 37.5 m

the ditches were cleaned in the 1990s. The tree stand was a mature, mostly uneven -aged Norway spruce stand with a significant admixture of downy birch and a few scattered Scots pine trees (Table 1). In all plots, variable scattered advance growth of Norway spruce was found before cutting.

In the winter of 2012–2013, the following cutting treatments were completed: small-size patch clear-cutting; shelterwood cutting with ca. 250 ha^{-1} retained shelter trees; and heavy selection cutting that aimed to leave 1000 pulpwood -size or smaller stems (diameter < 15 cm). In patch clearcutting, all trees of commercial size were removed. The fourth treatment was an uncut control. A randomized design was used, with three replicates for each cutting treatment. The size of the treatment plots was 30 × 40 m (or 37.5 × 37.5 m in one control plot), and all the plots had a similarly treated 10 m buffer zone extending to all sides (Fig. 1). The total size (including buffers) of the treatment plots used here was 0.30 ha (one control plot with a buffer 0.33 ha). The 0.3 ha size used corresponds to the maximum of the gap cutting treatment introduced by the 2014 Finnish Forest Act (Forest Act 2014) and has also been applied in practice. In such openings, artificial regeneration actions are not required because they are expected to regenerate naturally.

Before cutting, the trees to be left standing were marked with paint. After cutting, all the retained stems in the treatment plots were measured and mapped. The characteristics of the post-cutting stands varied greatly by treatments (Table 1). However, in the heavy selection treatment, part of the stems that were marked as retained were damaged during cutting operations meaning the average post-harvest stem number was below the target density of 1,000 ha^{-1} (Table 1).

Seedling measurements

The natural regeneration was inventoried from 16 permanent seedling survey plots (radius of 1.26 m; area 5 m^2) set up in the form of a regular grid in each treatment plot (Fig. 1). The inventories were undertaken in the springs of 2013, 2016, 2018, and 2021. All spruce and pine seedlings were counted and classified according to height: small ($h < 10$ cm); and large (10 cm $< h <$ 1.3 m). For birch, only large seedlings (10 cm $< h <$ 1.3 m) were counted. In the 2021 inventory, the tallest spruce seedling was also measured for height in each seedling survey plot. If no spruce seedling was found, the height of the tallest birch seedling was measured.

Statistical analysis

In analyzing the development of the regeneration density, the seedling numbers in the survey plots were averaged at treatment plot level (ha^{-1}). The heights of the tallest seedlings were averaged accordingly. Because the original seedling count distributions were heavily skewed, and the data were hierarchically structured, with four successive inventories repeated in each treatment plot, the generalized linear mixed models (GLMM) approach was used in data analysis. A negative binomial distribution was assumed for the seedling counts. The glmer.nb function of the lme4 package of the R program (R Core Team 2022) was applied to investigate the effect of cutting treatments and the linear and quadratic effects of time and their interactions on the number of small and large spruce seedlings, and the number of large birch seedlings at treatment plot level. In addition to fixed parameters, the treatment plot variance δ_{tp} was estimated.

The impact of cutting treatments on the mean height of the tallest seedling in the last measurement in 2021 was analyzed separately for large spruce and downy birch with the one-way ANOVA model, and Tukey's HSD test was used in pairwise comparisons.

In analyzing the seedlings' spatial distribution, we counted the number of empty survey plots within each treatment plot for the abovementioned seedling height categories (spruce $<$ 10 cm, spruce $>$ 10 cm, spruce combined, and birch $>$ 10 cm) in the 2013 and 2021 survey data. We also calculated the coefficient of variation of the seedling number (CV, %) on each measurement occasion for large spruce and birch seedlings. The number of empty plots and development of the CV indicated whether there was a change in the spatial evenness of the seedlings over the study period, and if there were differences due to different cutting treatments. A mixed ANOVA model with cutting treatments and time as fixed effects, and sample plot as the random effect, was used to test the differences in CVs among the cutting treatments during the 2013–2021 study period. A significance level of 0.05 was used in all analyses to indicate a statistically significant effect.

Results

Mean seedling number

The GLMM model showed that there were no significant differences between the cutting treatments in the number of small spruce seedlings (Table 2), but there was a large temporal variation (Fig. 2). Time since cutting and time squared were the only significant variables and caused first an increasing and then a decreasing trend in seedling numbers for all treatments. Although the statistics could not detect any differences, some interesting trends were observed. The largest seedling numbers were found in the spring of 2016, i.e., after three growing seasons had passed since cuttings. All cutting treatments had about 3–5 times higher seedling numbers (11,000–15,000 ha^{-1}) than those of the control treatment (3,000 ha^{-1}). There was also a marked drop in the density of small spruce seedlings in all treatments in later inventories (e.g., in 2021, from 420 ha^{-1} (control) to 1,570 ha^{-1} (heavy selection cutting) (Fig. 2).

According to the GLMM model, the differences in the number of large seedlings were non-significant (Table 3), although shelterwood cutting showed lower mean numbers than other cutting treatments in all inventories (Fig. 3). The interaction effects of time on the number of large spruce seedlings were significant for all cutting treatments (Table 3). Despite the lower estimate for clearcut (0.162), the test for contrast showed that all interaction effects were similar between cutting treatments (Table 4). For all cutting treatments, seedling numbers increased between the 2016 and 2018 inventories, i.e., in about five to six years after cutting (Fig. 3). For shelterwood cutting, the large spruce seedling numbers increased to around 5,000 ha^{-1} in 2018 inventory and then decreased slightly to around 4,500 ha^{-1} in 2021. For heavy selection, large spruce seedling densities increased to a level of 8,000 between 2016 and 2018 and remained at that level in 2021 as well. For patch clearcut, seedling numbers increased to around 9,000 ha^{-1} in 2018 but decreased to below 8,000 ha^{-1} in 2021 (Fig. 3). For the control treatment, the number of larger spruce seedlings decreased slightly during the study period (Fig. 3).

Table 2 The impact of cutting treatment, time, time^2, and treatment*time interaction on the development of the number of small spruce seedlings according to a GLMM model. The seedling number is divided by 1,000. δ_{tp} is the variance among treatment plots

Variable	Estimate	Std.error	z-value	*p*-value
Intercept	-1.1869	0.860	-1.38	0.168
Shelterwood	-0. 4456	1.144	-0.390	0.697
Heavy selection	-0.4370	1.108	-0.394	0.693
Clearcut	0.891	1.082	0.823	0.410
Time	1.1677	0.275	4.252	***0.000***
Time^2	-0.1433	0.026	-5.453	***0.000***
Shelterwood *Time	0.2408	0.234	1.031	0.303
Heavy Select.*Time	0.3186	0.223	1.427	0.154
Clearcut*Time	-0.0782	0.239	0.327	0.744
δ_{tp}	0.07675			

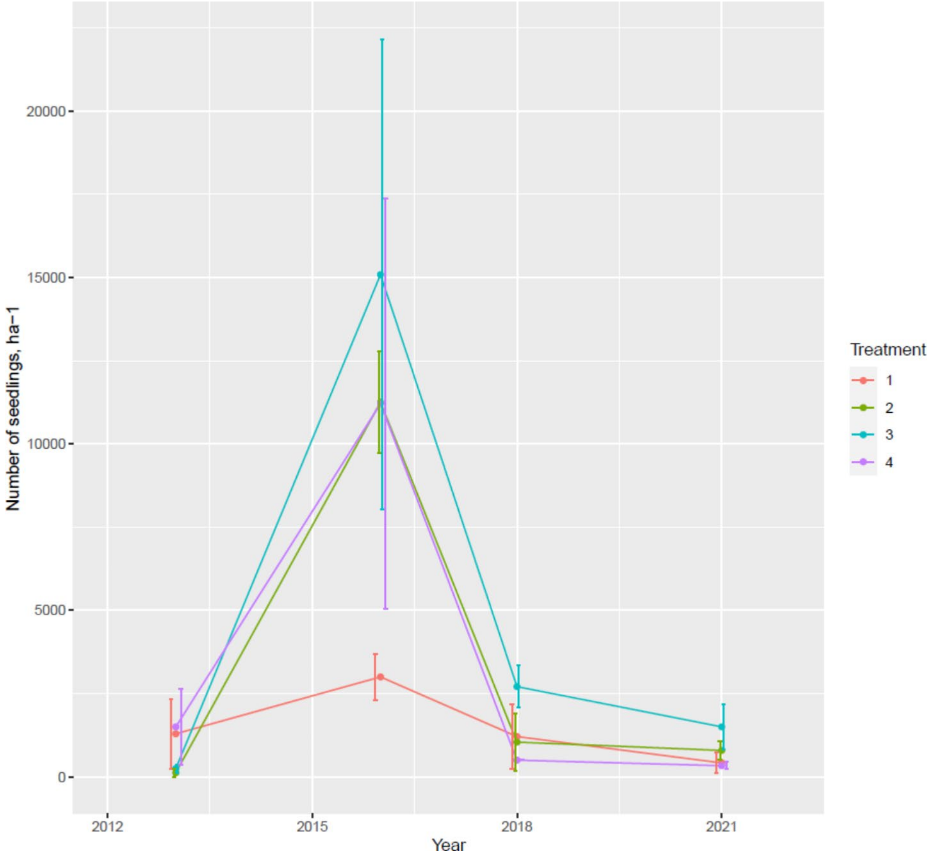

Fig. 2 Development of the number (ha^{-1}) of small (<10 cm) spruce seedlings by cutting treatments (1=control, 2=shelterwood cutting, 3=heavy selection, 4=patch clearcut,) in 2013–2021. Error bars indicate standard error of mean (*N*=3)

Table 3 The impact of cutting treatment, time, time^2, and treatment*time interaction on the development of the number of large spruce seedlings according to a GLMM model. The seedling number is divided by 100. δ_{tp} is the variance among treatment plots

Variable	Estimate	Std.error	z-value	*p*-value
Intercept	3.304	0.428	7.712	***0.000***
Shelterwood	-0.897	0.575	-1.560	0.119
Heavy selection	-0.444	0.573	-0.775	0.438
Clearcut	-0.007	0.563	-0.012	0.991
Time	0.028	0.099	0.280	0.780
Time^2	-0.009	0.009	-1.068	0.286
Shelterwood *Time	0.225	0.068	3.309	***0.001***
Heavy Select.*Time	0.224	0.068	3.308	***0.001***
Clearcut*Time	0.162	0.065	2.475	***0.013***
δ_{tp}	0.2617			

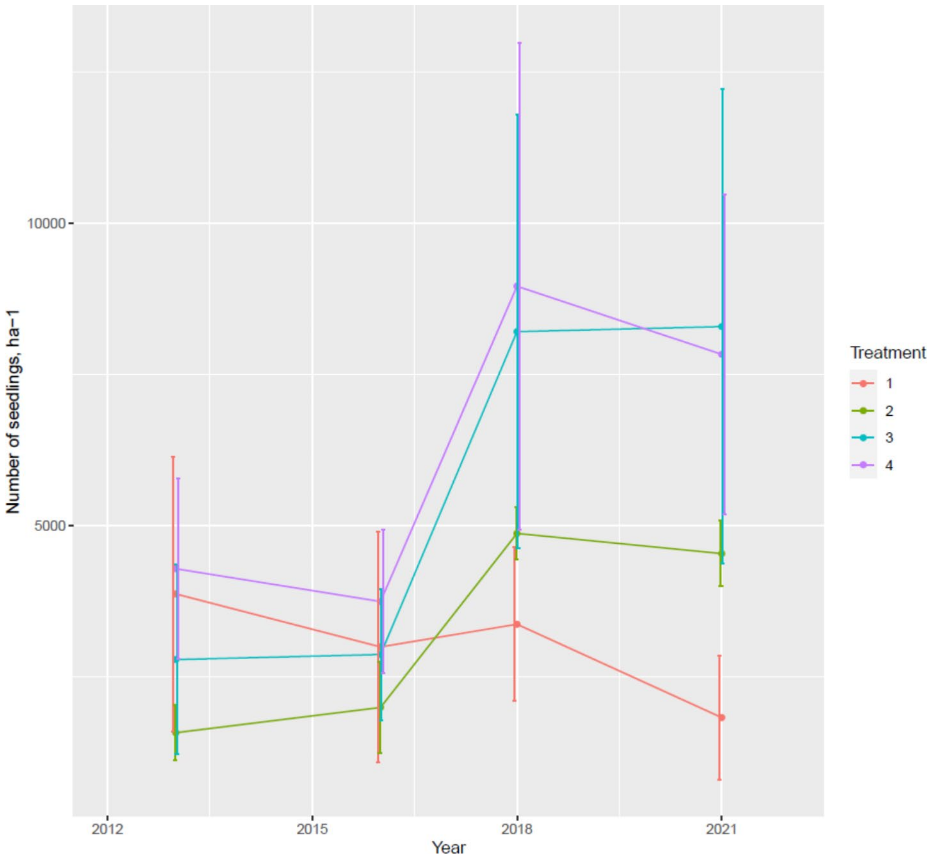

Fig. 3 Development of the number (ha^{-1}) of large (10 cm < h < 130 cm) spruce seedlings by cutting treatments (1 = control, 2 = shelterwood cutting, 3 = heavy selection, 4 = patch clearcut,) in 2013–2021. Error bars indicate standard error of mean (N = 3)

Table 4 Test for contrast effects of different cutting treatments and time in the models for the large spruce seedlings (Table 3)

Contrast	Estimate	*p*-value
Shelterwood – Heavy selection	4.08×10^{-6}	1.000
Shelterwood – Clearcut	6.29×10^{-2}	0.764
Heavy Selection – Clearcut	6.29×10^{-2}	0.764

The relationship between the number of large birch seedlings and time was quadratic in the GLMM model and it differed for the control compared to the cutting treatments, which did not differ greatly (Table 5). For the cutting treatments, the birch seedling numbers observed in 2013 were very low but started to increase in 2016. The highest birch densities (>70,000 ha^{-1}) were observed for patch clearcut in 2018, and significantly lower numbers in 2021 (about 40,000 ha^{-1}). For heavy selection, birch seedling numbers increased to around 25,000 ha^{-1} in 2018 and remained at that level in 2021. For shelterwood cutting, the number of birch seedlings in 2018 was about 15,000 ha^{-1} decreasing to a level of about 12,000 ha^{-1} in 2021 (Fig. 4).

Table 5 The impact of cutting treatment, time, time^2, and treatment*time interaction on the development of the number of large birch seedlings according to a GLMM model. The seedling number is divided by 1000. δ_{tp} is the variance among treatment plots

Variable	Estimate	Std.error	z-value	*p*-value
Intercept	-1.863	0.911	-2.043	***0.041***
Shelterwood	-0.620	1.112	-0.558	0.577
Heavy selection	-0.207	1.062	-0.195	0.846
Clearcut	1.031	0.993	1.038	0.299
Time	0.875	0.219	3.997	***0.000***
Time^2	-0.077	0.016	-4.715	***0.000***
Shelterwood *Time	0.390	0.168	2.318	***0.020***
Heavy Select.*Time	0.390	0.160	2.438	***0.015***
Clearcut*Time	0.343	0.152	2.254	***0.024***
δ_{tp}	0.1601			

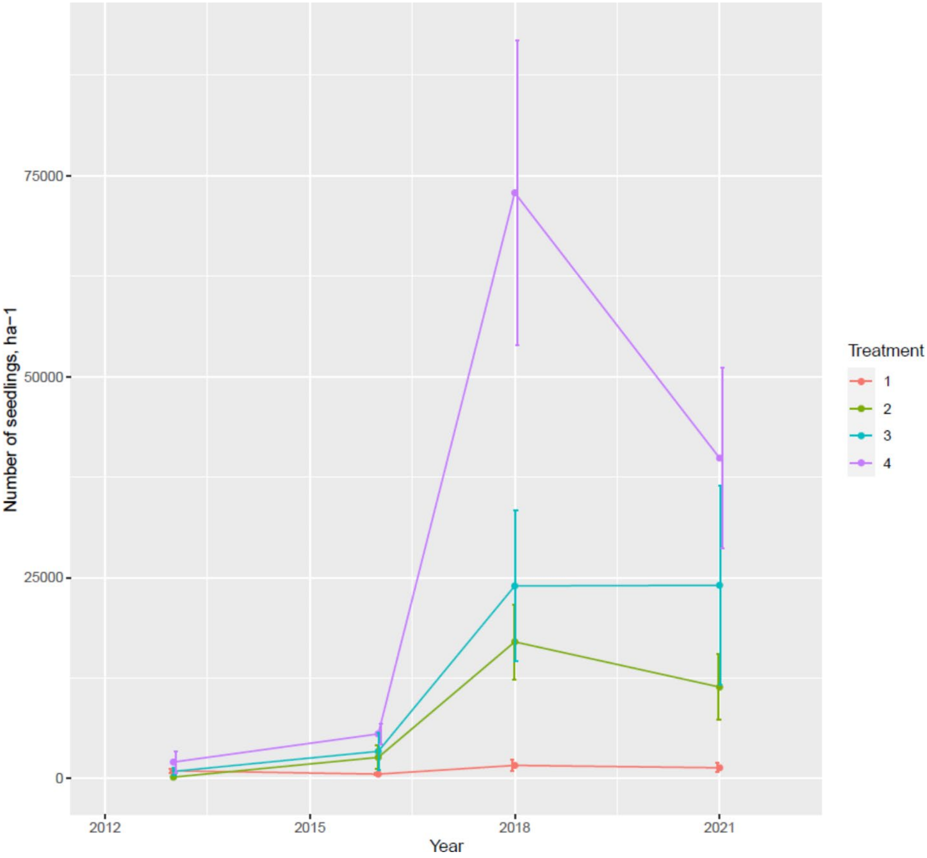

Fig. 4 Development of the number (ha^{-1}) of large (10 cm < h < 130 cm) birch seedlings by cutting treatments (1 = control, 2 = shelterwood cutting, 3 = heavy selection, 4 = patch clearcut,) in 2013–2021. Error bars indicate standard error of mean (N = 3)

Mean height of tallest seedlings

The mean height of the tallest spruce seedling in 2021 was compared by cutting treatments. The mean heights were 12.7 cm, 9.1 cm, and 20.3 cm taller for shelterwood cuts, heavy selection cuts, and clearcuts respectively than for the control (Fig. 5). However, due to the high variation and small number of replicates, the effect of cutting treatments was non-significant in the one-way ANOVA ($p=0.208$, $F_{(3,8)}=1.899$).

For the tallest birch seedling, the effect of cutting treatment was highly significant in the ANOVA ($p=0.001$, $F_{(3,8)}=17.21$). Pairwise comparisons showed that all cutting treatments deviated significantly from the control, and there was also a difference between shelterwood cuts and clearcuts (Table 6). In terms of mean height, the difference between the control and clearcut was 56.2 cm, and those between the control and shelterwood cuts and control and selection cuts were 27.1 cm and 35.1 cm respectively (Table 6; Fig. 5).

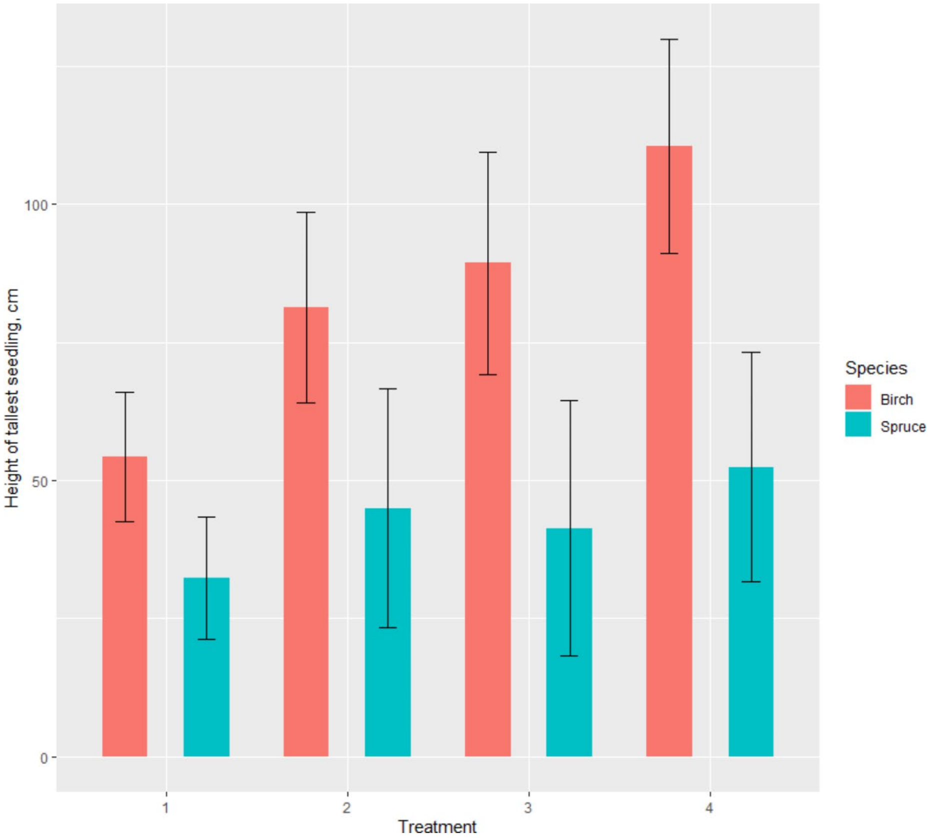

Fig. 5 Mean height (averaged at treatment plot level) of tallest spruce and birch seedlings in 2021 by cutting treatments: 1 = control, 2 = shelterwood, 3 = heavy selection, 4 = clearcut. Error bars indicate standard error of mean ($N=3$)

Table 6 Multiple comparison (Tukey's HSD test) of average height of tallest birch seedling between different treatments

	Difference, cm	Adjusted *p*-value
Control – clearcut	56.167	***0.000***
Shelterwood – clearcut	-29.12	***0.026***
Heavy selection – clearcut	21.100	0.106
Shelterwood – control	27.061	***0.037***
Heavy selection – control	35.065	***0.009***
Heavy selection – shelterwood	8.000	0.748

Table 7 Average proportion of empty survey plots by cutting treatments and seedling classes in 2013 and 2021 seedling surveys

Treatment	Proportion of empty sample plots, %									
	Spruce < 10 cm		Spruce > 10 cm		Spruce combined		Birch > 10 cm		All seedlings	
	2013	2021	2013	2021	2013	2021	2013	2021	2013	2021
Control	81	90	52	63	48	58	85	79	42	50
Shelter-wood	96	75	73	40	69	35	92	42	65	35
Heavy selection	88	69	60	29	56	29	83	19	31	19
Clearcut	79	85	44	29	35	27	77	6	38	4

Seedlings' spatial distribution

Immediately after cutting in the spring of 2013, the proportion of empty survey plots ranged from 35 to 96% among cutting treatments and seedling categories, which suggested an uneven spatial distribution (and small number) of seedlings (Table 7). In 2021, the highest proportion of empty surveys plots of larger spruce and birch seedlings was found in the control plots, while for small spruce seedlings in control and patch clearcut treatments, the proportions were almost equally high (90% and 85%, Table 7). For shelterwood and heavy selection cuttings, no small spruce seedlings were found in 75% and 69% of the survey plots, respectively. Concerning larger spruce seedlings, the number of empty survey plots was equal in heavy selection and patch clearcut treatments (29%). In shelterwood cutting, the proportion was somewhat higher (40%).

For large birch seedlings the number of empty sample plots decreased from the control (79%) to clearcut (6%) (Table 7) and appeared to be related to the amount of the retained stand volume (see Table 1).

For larger spruce seedlings the mean CV showed a decrease between the first two measurement occasions for shelterwood and heavy selection cuttings (Fig. 6). For patch clearcuts, there was no trend in the mean CV. For shelterwood cutting, the CV further decreased during the last period, but for heavy selection, the mean CV increased slightly (Fig. 6). In the mixed ANOVA model, the mean CV values were evaluated against the clearcut treatment (Table 8). The model for large spruce seedlings showed that the average CV was 143%, and there were no statistically significant differences among the treatments or temporal trend in the CV. However, the shelterwood treatment showed a slightly higher CV and a slightly faster decrease in the CV ($p = 0.069$ and $p = 0.089$, respectively), which were both indicatively significant (Table 8).

The mean CV of large birch seedlings decreased for all cutting treatments throughout the study period (Fig. 6). For shelterwood and clearcuts, the biggest decrease in birch seedling numbers occurred between 2013 and 2016, but in later inventories, the CV decreased only

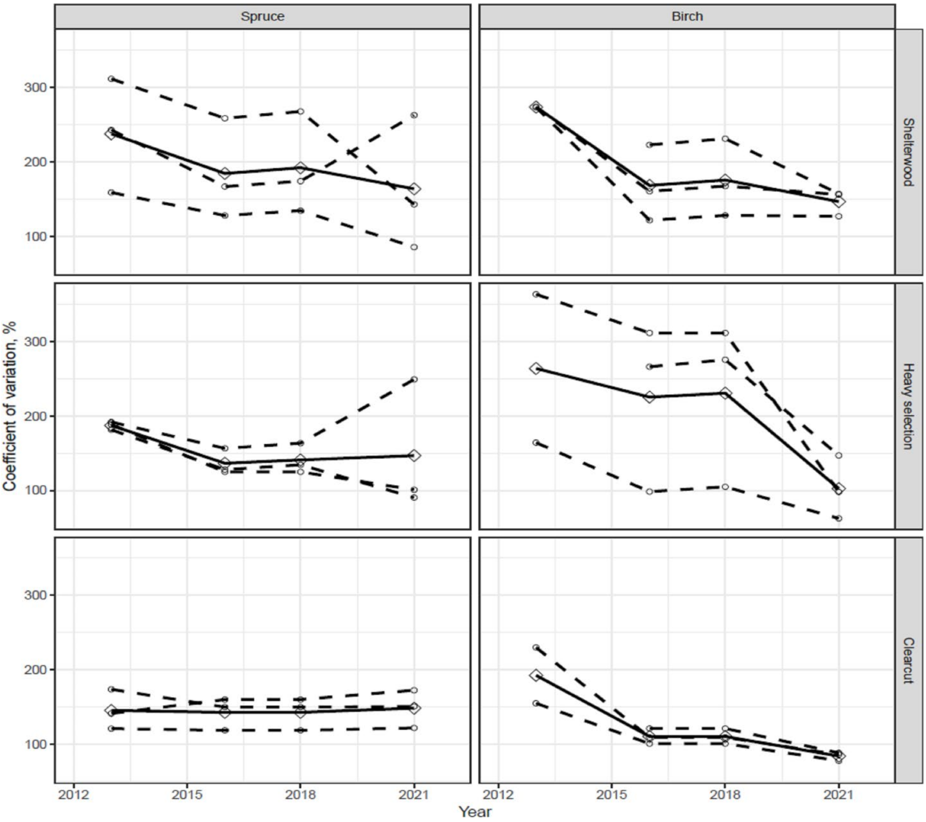

Fig. 6 Treatment plot-wise development of the large spruce and large birch seedling number coefficient of variation over the study period by cutting treatments. Dashed lines with a circle represent different treatment plots and the thick solid line with a diamond represents their mean. Note: One plot in every treatment had no large birch seedlings in 2013

Table 8 Mixed ANOVA models for the effects of cutting treatments and time on the coefficient of variation (%) of large spruce and birch seedlings. S = standard deviation between the sample plots

Fixed effects	Spruce			Birch		
	Estimate	Std. error	*p*-value	Estimate	Std. error	*p*-value
Intercept	143.291	29.841	0.000	183.064	40.479	0.000
Shelterwood	93.344	42.201	0.069	82.458	57.245	0.199
Heavy selection	32.548	42.201	0.469	136.908	57.245	0.054
Time	0.357	3.521	0.920	-12.006	4.431	***0.013***
Shelterwood*Time	-8.825	4.916	0.089	-2.859	6.267	0.653
Heavy selection*Time	-4.981	4.916	0.327	-9.692	6.267	0.137
s	37.856			52.93		

slightly (Fig. 6). In the heavy selection treatment, the average CV also strongly decreased between 2018 and 2021. Based on the mixed ANOVA model, the mean CV of large birch seedlings was higher (183.06) than that of large spruce seedlings (Table 8). For heavy selection, the CV was also at an almost significantly higher ($p = 0.054$) level than for other cutting treatments, which was also seen in Fig. 6. The decrease in the CV of large birch seedlings over time was statistically significant ($p = 0.013$, Table 8).

Discussion

The flush of small (< 10 cm) spruce seedlings in the third spring after cutting proved that all the investigated cutting treatments significantly improved the regeneration conditions of spruce compared to the control. This enabled the establishment of larger spruce seedlings in the coming five years, which suggests that all the cutting treatments significantly enhanced the natural regeneration of spruce on the site.

Considering the whole study period, shelterwood cutting and heavy selection cutting might provide some benefits in relation to patch clearcutting. Although the patch clearcut developed into a seedling stand dominated by birch in the eight post-cutting years, downy birch was less abundant in the shelterwood and heavy selection treatments. These results accorded with our hypotheses that different cutting treatments would result in differences in the composition of regeneration stocking.

The number of small spruce seedlings peaked three years after cuttings and was manifold compared to the situation immediately after harvest. In later inventories, the number of small spruce seedlings decreased close to the pre-harvest level. In a study by Hökkä et al. (2012), the number of small spruce seedlings remained at a high level (~ 10,000 ha^{-1}) for five years after the cutting of small canopy gaps in spruce mire stands. Seedling emergence after cutting is conditional on the occurrence of the peak seed year at the time of cutting or soon afterwards. In northern Finland, abundant flowering of spruce took place in 2010 and 2012, i.e., one and three years before the establishment of the experiment (results not shown). Such a coincidence mostly explains the large numbers of small spruce seedlings found in 2016. A modest increase of small spruces in the control treatment in 2016 also proves that the peak seed years had a positive impact on the number of new seedlings in the 2016 inventory. The next good flowering was nine years later in 2021, so the post-cutting emergence of new seedlings observed here is probably higher than can be expected of the long-term average.

The decrease in the number of small spruce seedlings and the concurrent increase of that of large spruce seedlings between 2016 and 2018 indicated that a significant proportion (2000–17000 ha^{-1}) of the germinated small spruce seedlings had established and achieved a height of > 10 cm within five years of cutting. This change was quickest for heavy selection and patch clearcutting (Fig. 3) but was significant for all cutting treatments (Table 3). This result is better than that observed by Hökkä et al. (2012), who reported only a slight increase of large spruce seedlings in five years after gap cutting on spruce mires in the same region. The results of this study also showed a large variation among treatment plots (for heavy selection and clear-cut) (Fig. 3). In a study by Holgén and Hånell (2000), the average densities of > 10 cm spruce seedlings exceeded 10,000 in ten years, but they also reported large numbers of empty sample plots.

As a light-demanding pioneer species, downy birch establishment and growth is known to be best in clearcuts or large gaps (Moilanen et al. 2011; Hökkä et al. 2011, 2012; Valkonen and Siitonen 2016; Holgén and Hånell 2000). This was also the case here, as seedling numbers between 20,000 and 120,000 ha^{-1} for large birch were found in 2018 and 2021 in the patch clearcuts. Roy et al. (2000) pointed out that conifer seedlings were established in a peatland clearcut in Québec three years after cutting, but the abundant establishment of pioneer hardwood species limited their growth. A similar development was also observed in this study, as spruce regeneration was good in patch clearcuts, despite the strong establishment of birch. This was against our hypothesis of slow spruce regeneration in clearcuts. However, downy birch establishment requires pre-commercial thinning to control birch in the ensuing years. Heavy selection and patch clearcut tended to result in a larger number of large spruce seedlings than shelterwood cutting, but the differences were non-significant. Shelterwood cuttings appeared to be a slightly better method than heavy selection for controlling birch establishment. Holgén and Hånell (2000) also found that under shelterwood, birch regeneration was less abundant than in clearcuts. However, in heavy selection, there is no need to retain large shelterwoods, which is likely to increase cutting income. Shelter trees significantly enhance their growth after cutting for at least ten years (Holgén et al. 2003; also Anderson et al. 2020), which increases their value, but some windthrows are to be expected (Hånell and Ottosson-Löfvenius 1994; Anderson et al. 2020). The net present value of retained shelter trees may not increase during the retention period, but in situations where the seedling cohort needs shelter, and the number of seedlings is insufficient, such a risk is necessary.

In general, seedling height is also an important characteristic in assessing regeneration success. The mean height of the spruce seedlings in all cutting treatments approached the 50 cm target height defined for successful regeneration in northern conditions (in 20 years) in the Finnish forest management guidelines (Äijälä et al. 2014). The tallest spruce seedlings were found in patch clearcuts, but the seedlings in shelterwood and heavy selection were not more than 10–15 cm shorter on average. As downy birch early growth is faster than that of spruce, the birch seedlings were about twice the height in the last inventory of that of the spruce seedlings in all treatments. This result emphasizes the need for precommercial thinning, whatever cutting treatment is used, if the aim is to achieve a spruce-dominated stand (see also Roy et al. 2000). If either the number or height of birch, or both is high, even two treatments may be needed.

The proportion of empty sample plots in all seedling categories was lower in 2021 than immediately after cutting in 2013, suggesting that the seedlings' spatial evenness had increased for all cutting treatments during the study period. In terms of the CV, the spatial evenness of large spruce seedlings slightly increased for shelterwood and heavy selection, but there were no statistically significant differences between the cutting treatments or with respect to time. Especially for patch clearcuts, no change took place during the study period. For large birch seedlings, the decreasing trend in the CV of all cutting treatments during the study period was statistically significant. According to Leemans (1991), the most even regeneration of spruce may be related to cuttings providing the highest light intensity. However, as light intensity increases, it benefits birch more than spruce, which is likely to affect spruce regeneration, and this was also observed in this study. The clumped spatial distribution of spruce seedlings and high proportion of empty sample plots have been regarded as significant risks for shelterwood regeneration on mineral soil sites in the Nordic countries (Leinonen et al. 1989; Sikström et al. 1997, 2005).

When the Forest Act was modified in 2014 in Finland (Forest Act 2014), it became legal to cut up to 0.3 ha gaps without any regeneration actions. The regeneration result of the patch clearcuts can give some idea of the regeneration result of about 0.3 ha patches or in gap cuts (below 0.3 ha) in spruce peatlands. According to this study's results, roughly 7,000 ha^{-1} of spruce seedlings of a height of 10 cm tall or more were found eight years after cutting, as well as 3–12 times more downy birch seedlings that were twice the height of the spruces. Hanssen (2003) reported that in 0.25 ha patches cut on mineral soil sites in southern Norway, the number of spruce seedlings was also largest near the edges, and up to 65% of the sample plots (1 m^2) were empty further than 10 m from the edge stand. The impact of edge distance in the patches was not studied here in detail. In this study, the regeneration of spruce seedlings was significantly higher than that reported by Hökkä and Repola (2018) from the largest (0.25–0.3 ha) gaps cut in 2005. The two good seed years close to the cutting year may explain the larger number of spruce seedlings in this study (also in Hanssen 2003). Peak seed years should be utilized in all cutting treatments that aim for natural spruce regeneration. This is important if a heavy selection cut or a patch clearcut is applied because large seed-producing trees will mostly be removed in cutting.

In a traditional clearcut harvest, the removal of the tree stand stops tree stand evapotranspiration, which may significantly increase the water table in drained peatlands (Pothier et al. 2003). This watering up causes chemical reactions in the rewetting surface peat, followed by increased nutrient loads to the runoff water (Kaila et al. 2015), which is an important reason for finding alternative regeneration methods for large clearcuts in spruce peatlands. As no measurements were carried out on water table changes, we cannot say whether the cutting treatments caused watering up after cutting. Previous studies have shown that shelterwood cutting limits watering up. According to Pothier et al. (2003), a 40–60% removal of basal area significantly reduced the rise in the water table and enhanced water table recovery compared to a clearcut on a natural peatland forest site in Québec. A study by Leppä et al. (2020a) showed that a 10 m^2ha^{-1} retained basal area could prevent the water table rising too high in a drained spruce peatland in southern Finland. In this study, the retained basal area in the shelterwood cutting was slightly less (~8 m^2ha^{-1}) and probably had less impact on the water table due to the northern location (Leppä et al. 2020b). Pothier et al. (2003) also pointed out that in addition to the retained shelter trees, regeneration stocking significantly contributed to the water table through evapotranspiration within five years of clearcutting. This suggests that heavy selection, where significant number of non-commercial and pulpwood -size stems is retained, would help attenuate the post-cutting water table rise.

It should be kept in mind that this is a case study – the data represented only one site, with all cutting treatments repeated three times. The small number of observations and rather high variability reduced the strength of the statistical analyses. Nevertheless, our results underlined the high potential for the natural regeneration of drained spruce mires and therefore confirmed the results of previous studies (Lukkala 1949; Holgén and Hånell 2000; Hökkä et al. 2011, 2012). The potential is based on both the existing advance growth and good emergence of new seedlings after cutting. In our study, the average number of large (> 10 cm) spruce advance growth seedlings in control plots was several thousand, which is in line with the observations of Moilanen et al. (2011) and Hökkä et al. (2011). The emergence of new seedlings is favored by the generally moist ground surface and dominance of *Sphagnum* moss vegetation, which has been found to be a good substrate for the germination of conifer seeds (Heinselman 1957; Place 1955; Jeglum and Kennington 1993; Saarinen 2002; Hanssen 2003).

Conclusions

All the cutting treatments investigated in this case study showed a high average regeneration density for a mixed seedling stand of Norway spruce and downy birch within the eight post-cutting years and can be recommended as alternatives for clearcut regeneration. The number of established birch seedlings was much larger than that of spruce. Shelterwood cutting appeared to constrain birch regeneration better than other treatments. Large spruce and birch seedlings were most evenly distributed for heavy selection and patch clearcut treatments. In peatlands, both spruce and birch are considered suitable tree species for regeneration (Äijälä et al. 2014), but because the production of valuable sawlogs by downy birch is negligible, the target in financially viable regeneration is the establishment of a Norway spruce-dominated stand. In general therefore, precommercial thinning(s) will be needed to develop a spruce-dominated stand, especially after patch clearcutting.

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Author contributions HH planned the study and the experimental design and was responsible for data collection. HH wrote the first draft of the manuscript. JK and JM contributed to the data analysis and commented on the previous versions of the manuscript. All the authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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