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RESEARCH ARTICLE

Tree retention practices in boreal forests: what kind of future landscapes are we creating?

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Tree retention practices promoting biodiversity may reshape future boreal forest production landscapes. Using the Heureka system, scenarios of 0%, 5%, and 20% retained patches at the stand level were projected over 200 years in a 533 ha boreal landscape. Visualizations of future forest states at a landscape scale and a more detailed scale were made based on the projections. The no retention results in no forest >120 years old, and no large trees (diameter at breast height >40 cm for conifers and >35 cm for broadleaved trees) 100 years from now. With retention levels of 5% and 20%, the area of old forest will comprise 7% and 19% of the total area, respectively. The average number of large trees per ha will be 4 and 13, respectively. Deadwood volumes will be 2.5 times higher at 5% retention and 4 times higher at 20% retention compared to no retention. Landscape visualizations indicate that retention patches covering 5% will marginally modify the visual impression, compared to clear-cuts, while 20% cover will create a much more varied landscape. We conclude that the retention approach is essential for restoring natural conditions. Landscape transformation will be slow and depend on starting conditions and retention levels.

Keywords: aesthetic values; biodiversity; deadwood; forest management planning; Heureka; tree retention; visualization

Introduction

Many boreal forests in northern Europe are intensively used for pulp, timber, and forest fuel production. Clear-felling practices became common in Sweden in the 1950s and 1960s to facilitate harvest operations and to make regeneration more effective (Lundmark et al. 2013). The introduction of clear-felling coincided with the start of the mechanization of forest operations and has since then been the dominant management regime (Jansson 2011). More than 90% of the productive forest land has long been used for wood production, which has significantly altered the forest landscape. Compared to natural conditions, areas of old forest have been reduced, tree species composition has changed and stand structure has been homogenized (Bernes 2011). As a consequence, habitats of importance to flora and fauna, such as old forest (Paillet et al. 2010), old trees (Remm & Lõhmus 2011), and dead trees (Stokland et al. 2012), have declined resulting in a number of forest species being added to the Red List, i.e. the list with rare and declining species (Gärdenfors 2010). In addition, the landscape transformation due to forest practices has also influenced aesthetic and recreational values. Thus, it is increasingly important to restore forest landscapes to more natural conditions, in order to deliver targets of the Convention on Biological Diversity (Halme et al. 2013).

Environmental concerns have long been raised about clear-felling (e.g. Keenan & Kimmins 1993), and as a consequence a few decades ago a new approach developed in the Pacific NW of the USA and Canada, in which parts of stands and single trees are retained from felling (Franklin et al. 1997). The main rationale behind this approach was to incorporate natural structures and processes into production forestry in order to maintain biodiversity and ecological functions on a long-term basis (Bauhus et al. 2009). In Sweden this new type of forestry – "retention forestry" (Gustafsson et al. 2012) – has been widely adopted during the last two decades (Bush 2010) and it is also being practiced in other parts of Europe (e.g. Lõhmus et al. 2006), South America (e.g. Martinez Pastur et al. 2009), and Australia (e.g. Baker & Read 2011). Although retention amounts and designs differ widely between countries and regions, it is common to retain a mixture of solitary trees and patches of trees (retention patches). There are many ecological studies relating to retention forestry, e.g. Lindenmayer et al. (2012) report more than 450 studies on the link between retention and biodiversity. In Finland, Norway, and Sweden more than 50 papers have been published on how flora and fauna respond to retention actions (Gustafsson et al. 2010). However, the long-term influence of retention practices on forest structures, wood production, and aesthetic values has been much less studied. Potentially, retention forestry could be an important strategy to restore forest structures such as old trees and deadwood in forests long shaped by production forestry.

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In production forest landscapes where clear-felling is practiced and with a rotation time of about 100 years, 1% of the forest area – given a normal age class distribution of the forest – should be harvested each year to ensure a stable wood supply. When retention is practiced at final felling, live and dead trees will slowly and continually be incorporated into the next generation stands. In due time, this addition will considerably change the structure and composition of forest landscapes. Nevertheless, the long-term consequences of retention forestry on landscape composition including the visual appearance of retention forestry have seldom been studied. To our knowledge, for example, a case study in British Columbia by Meitner et al. (2006) is the only scientific study so far where the long-term visual consequences of retention actions have been examined.

Currently, on average, about 5% of the clear-felled area is retained in Sweden (Swedish Forest Agency 2014), including retention patches and single, dispersed trees. Retention actions are required from all forest owners according to the Forestry Act, without minimum requirements regarding amounts. Retention also forms an essential part of the Swedish implementation of the forest certification standards FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification). In addition to retention actions at harvest, certified forest owners are also obliged to set aside a certain proportion of their productive forest land (5% for FSC certification) for conservation purposes. Such voluntary set-asides are usually >0.5 ha in size and often considerably larger, forming individual forest stands of their own, and they are not linked to final felling, i.e. they are not a retention-forestry component. Consequently, we have omitted them from our analyses.

We used a computerized decision support system (DSS) to project the future state of a boreal forest landscape under different retention level scenarios. The projections were also visualized by producing photo-like computer drawn images. Such images have been used to illustrate the outcomes of different forest management practices, e.g. stand development stages (McCarter et al. 1998), the impact of the location of logging areas (Karjalainen & Komulainen 1999), and the public's preferences for alternative landscape scenarios (Karjalainen & Tyrväinen 2002). Projections for 200 years (to cover 1–2 rotations) were made with respect to factors known to be important for biodiversity, such as old forest, large trees, and deadwood. In addition, volumes and economics of timber production, as well as the visual appearance of the different retention alternatives, were projected. Comparisons were made between three alternatives: no tree retention, and retention patches established during clear-felling operations corresponding to 5% and 20% of the stand area. Five percent equates to the current practices in Swedish forestry, and 20% simulates a potential future increase in retention levels.

Our study has two main aims. First, we aim to evaluate how much the retention approach contributes to the restoration of natural forest characteristics in boreal production forests long shaped by clear-felling. By using a production forest landscape which, although small, is typical of boreal Sweden, our results may be transferable to other parts of boreal northern Europe with a similar forest history and management. In addition, since Sweden is one of the countries in the world with the most intensive harvesting of native tree species, (FAO 2010; Levers et al. 2014) our example could reflect the future development of boreal countries in which more intense management may be introduced in the future. Second, we aim to illustrate the visual impact of stands harvested with retained trees, compared to traditional clear-felling, i.e. an important social aspect of retention forestry. We expect that: (1) retention approaches are essential for the supply of structures such as old forest, large trees, and deadwood in future production landscapes; (2) the number of such structures will largely correlate with retention levels, i.e. the 20% level will contribute considerably more than the 5% level; and (3) the visual impact of retention at the landscape scale and at more detailed scales will differ widely from clear-felled areas but the perception of change will be considerably greater at high than at low retention levels.

Material and methods

Landscape and stand data

The case study involved a 533 ha boreal forest landscape in northern Sweden (64°06′ N, 19°08′ E, 245–320 m.a.s.l.; Figure 1). The landscape is part of a larger forest holding – named Strömsjöliden – owned by the state-owned forest company Sveaskog. The landscape is managed for timber production in line with the company's standard forest management regimes, including consideration of nature conservation and environmental aspects. The management is quite similar to the regimes of large private companies. The forest is dominated by Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). The volume of broadleaved trees is low, mainly made up of birch (*Betula* spp.) and aspen (*Populus tremula* L.) and to a lesser extent rowan (*Sorbus aucuparia* L.) and willow (*Salix* spp). The part of Strömsjöliden used in this study consists of 58 stands 0.14–29.9 (median 7.2) ha in size.

The rotation periods in these boreal forests are typically 100–120 years (steadily decreasing due to plant breeding and improved silvicultural activities and management regimes) including 1–2 thinnings per rotation, each thinning removing 25–35% of the volume. The lowest permissible age for final felling according to the Forestry Act is around 70–80 years depending on site productivity. When establishing the case study the age class distribution was quite uneven – as is often the case

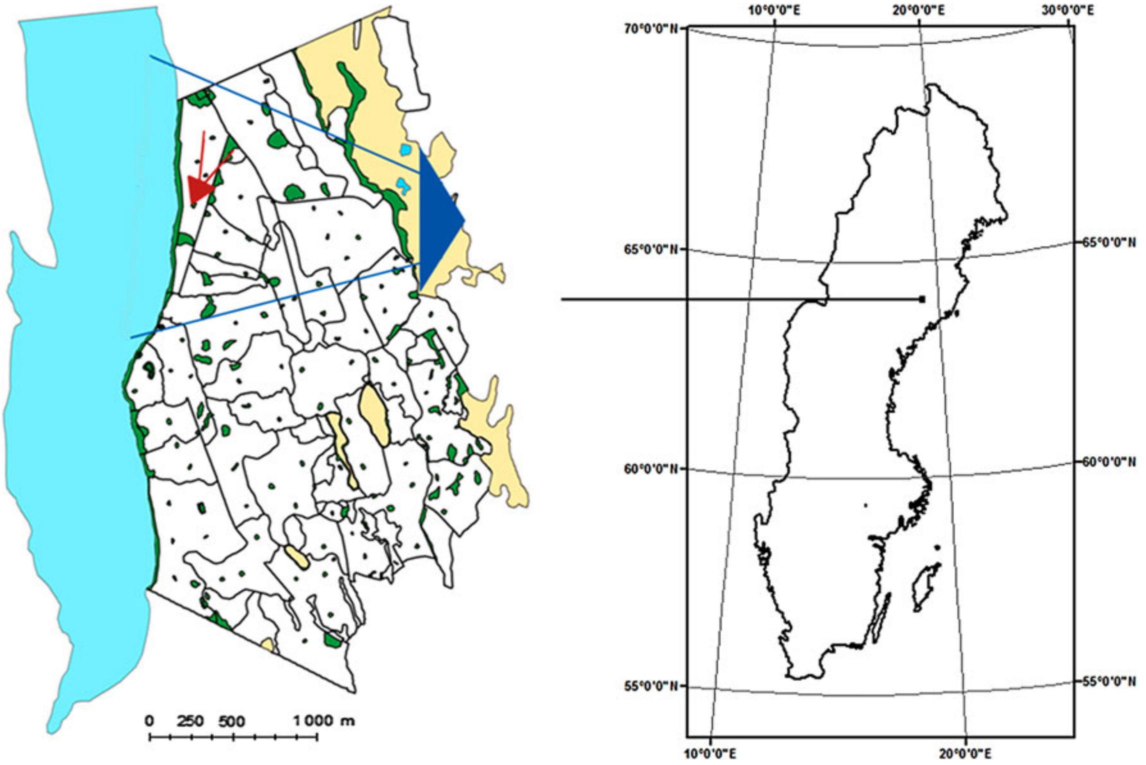

Figure 1. Location and map of the 533 ha landscape studied in Strömsjöliden, with stands (white polygons) and retention patches (169 in total; green polygons). The triangles represent the camera position and view in the visualized images. The blue triangle indicates the landscape view and the red triangle a single stand view with retention patches in Figure 5 and 6. The elongated retention patches in the western and northeastern parts are border zones beside a lake (blue) and mires (yellow), respectively. Zones around mires are also present in the interior of the area.

for a landscape of this size – with a lack of middle-aged forests and a rather high proportion of mature forests (Figure 2).

All forest stands had been surveyed in the field in 2008 and 2009 using ca 10 circular sample plots (radius 4–10 m depending on stand age) per stand, within which tree species and stem diameters at breast height (DBH) were recorded for all trees (middle-aged and old forest) or the number of plants counted (young forest).

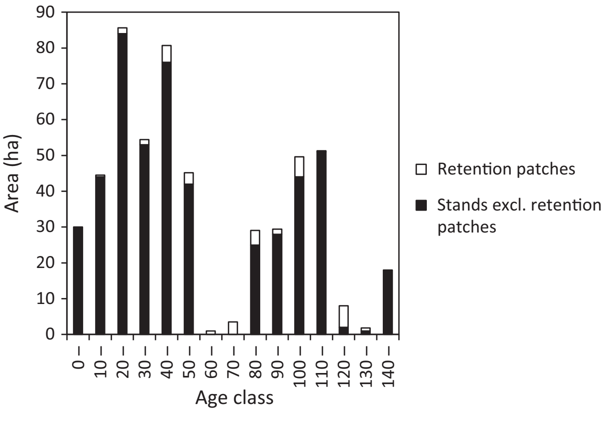

Figure 2. Initial age class distribution for the studied landscape excluding designated retention patches (499 ha) and initial age class distribution for the designated retention patches (34 ha, i.e. ca. 5% retention level).

Mapped retention patches

In the case study area, as is typical in Sweden, retention patches are present in stands up to about 20 years old, i.e. they have accumulated since the introduction of the practice. Moreover, as part of the company's planning procedure for harvest operations, retention patches have been selected and mapped in all mature forest and in some middle-aged forest. A set of current and planned retention patches in the study area (68 out of a total of 169) was field surveyed by recording tree species and DBH for all trees in the retention patch (small patches with less than ca 40 trees) or in 3–9 circular sample plots (larger patches, plot radius 10 m; Jonzén 2011). Mapping of these patches was undertaken in the field using GPS. Retention patches in young and middle-aged stands, where planning of retention had not yet been undertaken by the forest company, were selected as part of this study. The delineation of 101 such patches was achieved by interpretation of color infrared aerial photos (flight altitude 4800 m) using a photogrammetric work station as well as by interpretation of low altitude orthophotos obtained from an unmanned aerial vehicle (UAV). Forest characteristics for the future retention patches in these young and medium-aged stands were obtained by photo interpretation and from stand register information.

Retention is part of Sveaskogs' environmental and nature conservation policy and required for their environmental certification. The practice is described in the Sveaskog handbook for planning of final felling and regeneration operations. When selecting retention patches, large and old trees and, in conifer-dominated stands, broadleaved trees are given priority. This approach was also used in the case study when selecting retention patches by aerial photo interpretation in young and middle-aged forests. The already established retention patches also provided an example when selecting these retention patches. In total, 169 retention patches (minimum 0.01 ha, maximum 5.9 ha, median 0.06 ha) were either field surveyed or selected by photo interpretation, together making up 33.5 ha, i.e. 5% of the forest in the study area.

Forest management scenarios

Three long-term forest management scenarios were applied over a 200-year period. The first scenario – no retention – mimics what could have happened if tree retention practices never had been introduced. Here, all mapped retention patches in the study landscape were excluded and stand areas were expanded to replace the areas of the retention patches. The second scenario – 5% retention – involved the mapped retention patches as described above, i.e. in line with today's practice. For the 20% retention alternative, an additional 15% of the stand area was selected as retention patches in each stand. These patches were assigned the same stand characteristics as the ordinary stand (stand age, tree sizes, tree species distribution, etc.), i.e. criteria used for selecting mapped retention patches were not used. In these examples, the 15% area was located in one or several patches, aiming for a patch size larger than 1 ha since larger patches are more likely to promote biodiversity than smaller ones (e.g. Aubry et al. 2009; de Graaf & Roberts 2009). Consequently, not only the total area of retention patches but also the size of individual patches were larger in the 20% retention alternative compared to the 5% retention alternative.

In the simulations, retention patches were established initially in all stands as described above and the patches were maintained over 200 years, i.e. no retention patches were harvested nor were any new ones established during subsequent harvesting of ordinary stands.

Deadwood

The initial amount of deadwood was simulated based on data from the Swedish National Forest Inventory (NFI). In this region of Sweden the average volume of coarse woody debris (minimum diameter 10 cm) in managed forests is about 10 m^3 ha^{-1} in total for all decay classes and age classes (Swedish Forest Agency 2014). In the forest DSS used for projections, three different initial levels of deadwood could be simulated: low, medium, or high. As the case study area is a well-managed area from a timber production perspective, the initial volume was assumed to be lower than the average for the region and the simulation was set to a medium level of 4.3 m^3 ha^{-1}.

Projection of landscape characteristics

Projections of landscape characteristics given the three management scenarios were made using PlanWise, a software component in the Heureka suite of forest analysis and planning tools (Wikström et al. 2011). Of the many tree layer characteristics that are the output of the PlanWise projections, we focused on characteristics reflecting the persistence of biodiversity: old forest (mean stand age ≥ 120 years), old forest rich in broadleaved trees (less long-lived than conifers; mean stand age ≥ 90 years and proportion of broadleaved trees ≥ 30%), large-diameter coniferous and broadleaved trees (DBH ≥ 40 cm for conifers and ≥35 cm for broadleaved trees, respectively), stocking of broadleaved trees and deadwood. PlanWise has a core of empirical growth and yield models (time-step five years) including models for stand and individual tree growth. These models are based on the Swedish NFI data, have been validated in long-term experimental plots (Fahlvik et al. 2014), and include natural mortality (Fridman & Ståhl 2001) and in-growth, i.e. seedling establishment under the canopy (Wikberg 2004). Deadwood is created by natural mortality and added to the deadwood pool. Decay functions transfer the deadwood between decay classes during the projections. The mortality level depends on stand age, tree species, number of stems, and site index. When practicing tree retention, mortality rates in retention patches increase when the surrounding stand is clear-felled, mainly due to wind throw. Empirical data on mortality rates for retention trees and patches are rare but based on studies in Sweden (Jönsson et al. 2007), Finland (Hautala & Vanha-Majamaa 2006), and Estonia (Rosenvald et al. 2008), annual mortality rate (in terms of number of stems) for the first five-year period after clear-felling was set to 9% and in second five-year period to 4.5%.

In the projections a set of potential management alternatives was first generated for each stand. A management alternative consists of a sequence over time of silvicultural and harvest activities including costs of and incomes from those activities. The management alternative providing the highest net present value at a real interest rate of 2.5% was then chosen for each stand. This mimics forest management (e.g. thinning programs and rotation lengths) performed by economically driven forest companies in the region The retention patches were simulated with a no-management alternative where only growth, natural mortality, and in-growth determined their development.

Visualization

Data on stands and retention patches were transferred from the PlanWise projections to the visualization software Visual Nature Studio 3.0. A set of images was produced for different time points and geographical scales, some of which are presented in this paper. The visualization was performed in a three-level hierarchy: (1) tree layer if any (stands, retention patches, and living and dead solitary trees); (2) field layer including objects like stones; and (3) ground texture. The tree layer was described by the output from the PlanWise projections in terms of stem number, tree species distribution, and mean tree height for each stand and retention patch. These data were linked to a vector forest map including stands and mapped retention patches and then transferred to the visualization software. Tree height variation within stands and retention patches was a parameter set in the visualization software; 2D-billboard model trees used in the visualization were created using the Xfrog software and based on photos of different tree species (pine, spruce, and birch). Field layer vegetation and objects like stones were created by modifying photos (acquired in an earlier project) in the Adobe PhotoShop software and parameters describing the field layer (vegetation height, species, and density) and other objects were set in the visualization software. Standing and fallen dead trees and high stumps were created in the Xfrog software. Low altitude UAV photos were used to create ground textures for different forest and vegetation types (young and old stands, clear-felled areas, mires, etc.) covering a digital elevation model surface (3 × 3 m^2). The different retention levels were visualized at two geographical scales: a medium landscape scale showing a set of stands and a more detailed scale showing a single stand with centered retention patches and adjacent stands. For the landscape view, the camera's height (i.e. viewpoint) was 2242 m above sea level and the horizontal field of view (FOV) was 14.2°. Corresponding values for the more detailed view were 284 m above the sea level and FOV 50.8°.

Results

Landscape characteristics

The initial area of old forest (age ≥ 120 years) was 20.2 ha. After harvesting these stands within a 25-year period no old forest remained in the no retention alternative. Retention successively added old forest as the retention patches grew older and finally all retention patches were older than 120 years at the time points 100 and 120 years for retention of 5% and 20% of forest, respectively (Figure 3, upper left).

Initially there were no stands of old forest rich in broadleaved trees. Occasionally one stand met these criteria before it was harvested, thereby representing this forest type in the no retention alternative for just one five-year period (Figure 3, upper right). As broadleaved trees were given priority when selecting retention patches in the 5% alternative, the amount of old forest rich in broadleaved trees increased at an early stage. Increasing the retention level from 5% to 20% did not initially increase the area of old and broadleaved rich forests. The reason is the 15% additional retention patches had the same stand characteristics as the stands in which they were located and therefore they were rarely rich in old broadleaved trees. The initially young stand retention patches in the 20% alternative were, however, often rich in young broadleaved trees and were left unmanaged, thereby providing a further increase in the amount of old forest rich in broadleaved trees as they aged. After 100 years, the area of old forests rich in broadleaved trees decreased slightly as the proportion of broadleaved trees dropped below the 30% threshold in some patches due to natural mortality.

The initial numbers of large-diameter trees – DBH ≥ 40 cm for conifers and ≥35 cm for broadleaved trees – were 3.0 and 0.2 stems per ha, respectively. Apart from an initial temporary decrease in large-diameter conifers, the number increased in all scenarios as trees grew into these size classes (Figure 3 bottom left). After about 60 years, large conifers declined rapidly in the no retention scenario as they were all harvested and the subsequent generations did not provide such trees. In the 5% scenario there was also a decrease in large conifers after 60 years but they did not completely disappear and thereafter the number slightly increased (maximum of ca 6 ha^{-1}). In the 20% scenario, in contrast, the number of large conifers showed only a minor decline after 60 years and then increased further (maximum of ca 18 ha^{-1}). Apart from a less pronounced initial peak, large broadleaved trees showed a similar pattern (maximum of ca 0.9 and 2 ha^{-1} in the 5% and 20% scenarios, respectively, Figure 3 bottom right). After 100 years all large-diameter trees were retention trees.

The initial stocking was 130 m^3 ha^{-1} and the tree species distribution was 25%, 65%, and 10% for Scots pine, Norway spruce and broadleaved trees, respectively (Table 1). In the no retention alternative, the stocking increased to an average of 155 m^3 ha^{-1} in the first 100-year period and stayed roughly at that level in the second 100-year period. Tree retention increased the stocking further to 169 and 209 m^3 ha^{-1} on average in the second 100-year period for the 5% and 20% retention alternatives, respectively. This included an increase in broadleaved trees, from 12 m^3 ha^{-1} to 20 m^3 ha^{-1} in the 20% retention alternative. The proportion of broadleaved trees in relation to total stocking did not, however, change as it remained at about 10%.

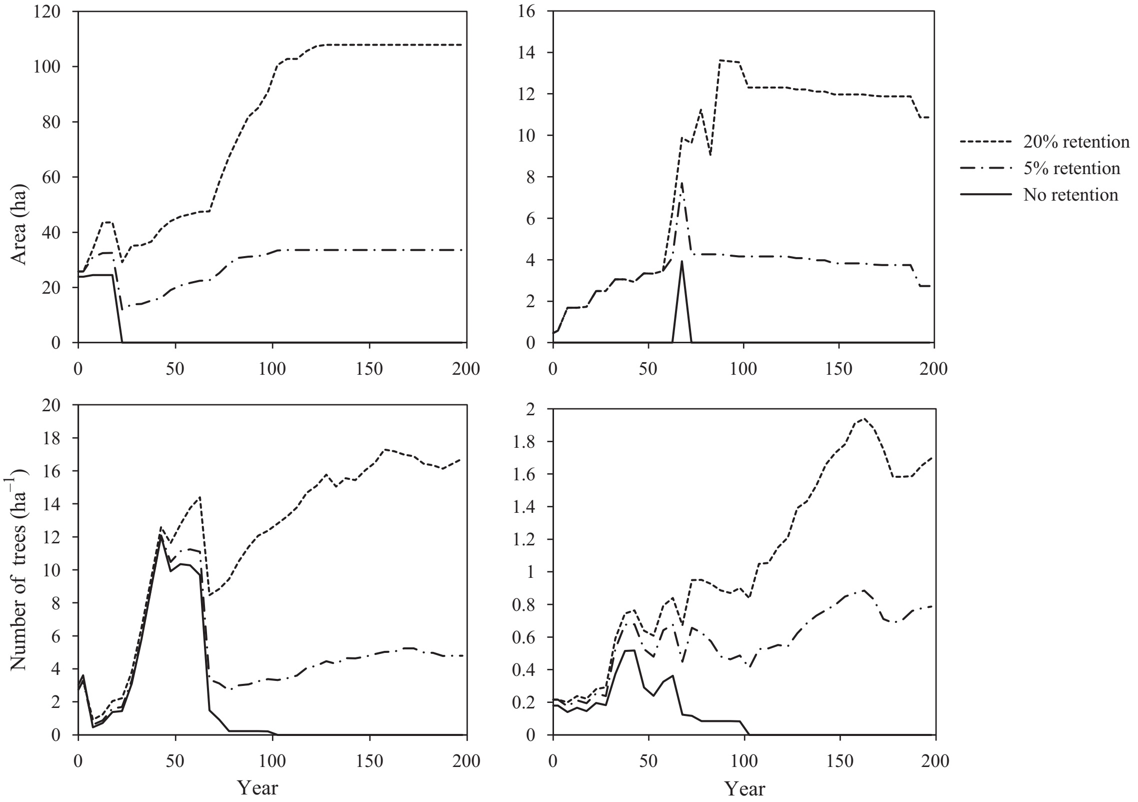

Figure 3. The area of forest ≥ 120 years (upper left) and the area of old forest rich in broadleaved trees (age ≥ 90 years and the proportion broadleaved trees ≥ 30%; upper right) over the 200-year period. The number of large (DBH ≥ 40 cm) conifer trees (lower left) and number of large (DBH ≥ 35 cm) broadleaved trees (lower right) per ha in the 533 ha landscape over the same time period.

As the accumulation of deadwood in late stages of decay is uncertain in long-term projections, we present only results for hard and slightly decayed deadwood (snags as well as downed coarse woody debris, i.e. decay classes 0–2 according to the Swedish NFI; Anon. 2011). In the no retention alternative the volume of deadwood in these decay classes increased slightly to a maximum of ca 4 m^3 ha^{-1} (Figure 4). The 5% retention scenario over the long term provided about 4 m^3 ha^{-1} more than the no retention alternative, peaking at 8 m^3 ha^{-1}. In the 20% scenario the average volume beyond year 70 was ca 14 m^3 ha^{-1}, i.e. more than triple the no-retention alternative. The variation in the 20% scenario was, however, considerable due to pulses of deadwood in periods with high final fellings temporarily causing high mortality in retention patches.

Timber production

Compared to no retention, the 5% and 20% tree retention levels resulted in a reduction in both mean annual harvest and net present value of the same size as the

Table 1. Stocking and tree species distribution, initially and in years 1–100 and 101–200 for the different retention levels in the 533 ha case study area.

		Total stocking and stocking per tree species (m^3 ha^{-1}, percentage of totals in brackets)			
Year	Retention level (%)	Total stocking	Scots pine	Norway spruce	Broadleaved trees
0 (Initial)	–	130	33 (25)	85 (65)	12 (10)
1–100[a]	0	155	43 (28)	96 (62)	16 (10)
	5	163	46 (28)	99 (61)	18 (11)
	20	183	52 (28)	109 (60)	22 (12)
101–200[a]	0	158	60 (38)	88 (56)	10 (6)
	5	169	62 (37)	94 (55)	13 (8)
	20	209	70 (33)	119 (57)	20 (10)

[a] Average for the period.

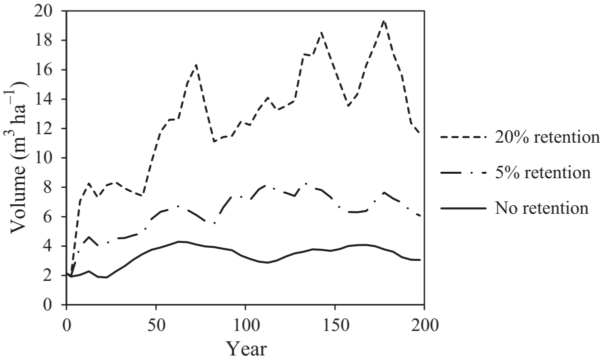

Figure 4. The amount of hard and slightly decayed deadwood in the case study area for the three retention levels.

proportion of the area retained. Mean annual harvest during the 200-year period was reduced by 6.1% and 20.2%, respectively, compared to no retention. Corresponding decreases in net present value for the studied area were 6.5% and 20.5% (Table 2).

Visualization

Several images at the landscape scale as well at a more detailed level, representing different time points and retention levels, were produced, some of these are presented in Figure 5 (landscape level) and Figure 6 (detailed level). Additional visualizations can be viewed at the Supplemental online material.

On the initial landscape scale, retention patches are not visually apparent in the 5% retention alternative. This corresponds to today's situation where retention has been practiced (at about the 5% level) by the forest company for a couple of decades and retention patches are not yet established in all stands (Figure 5 top). After 200 years all stands have been clear-felled at least once and retention patches are found in all stands. The larger retention patches in the 20% retention level scenario show a prominent difference compared to the 5% retention level (Figure 5 bottom and middle, respectively).

On a detailed scale, a sequence of stand level images over one rotation (present, 20, 50, and 100 and 110 years) for the 5% retention level is presented in Figure 6. The retention patches are gradually enclosed in the emerging stand as the patches age. In addition, the changes in surrounding stands are visible. On this scale and from this viewpoint the 5% retention level in year 110 makes a clear difference compared to the no retention alternative (Figure 6 bottom).

Figure 5. Part of the case study area visualized at the landscape scale in its initial state (5% retention, top), and after 200 years with the two different retention levels, 5 and 20%, respectively (middle and bottom).

Discussion

Our analysis shows that retention practices can reshape future boreal production forest landscapes and restore components of natural forests, such as old forest, large

Table 2. Timber production and economic outcome for the three retention levels within the 533 ha study area.

	Retention level		
	No retention	5%	20%
Mean annual harvest (m^3 year^{-1})	2628 (100%)	2469 (93.9%)	2098 (79.8%)
Net present value (MSEK)	18.3 (100%)	17.1 (93.5%)	14.5 (79.5%)

Note: Figures in brackets are values relative to the no retention alternative.

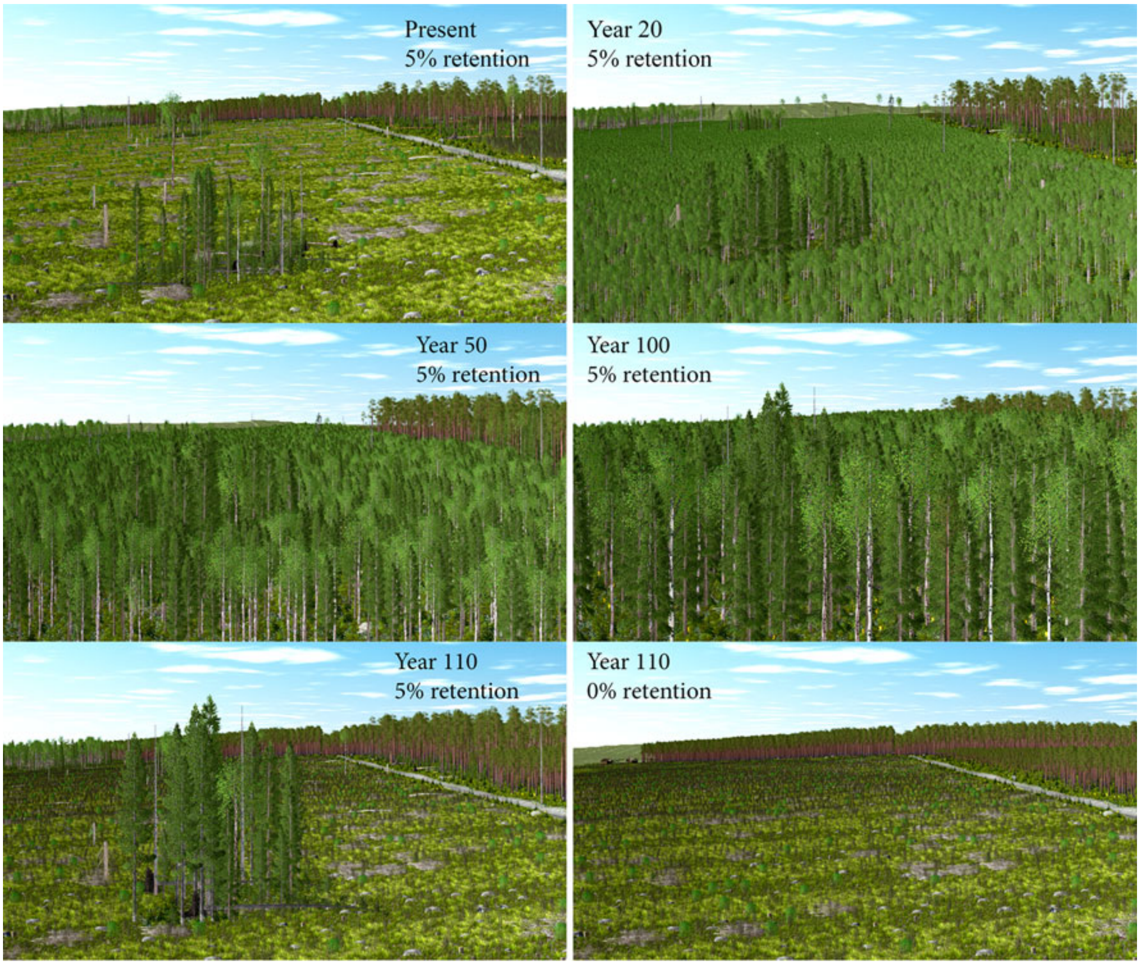

Figure 6. Part of a stand and its retention patches (5% retention level) in its initial state and in years 20, 50, 100, and 110, respectively. For comparison, the alternative without retention (0%) in year 110 is also shown (bottom right).

live trees, and deadwood. In the projections, the outcomes of these ecologically valuable parameters exhibit large variation between different levels of retention. In our study area, 100 years from now there will be no forest ≥120 years old, and no large trees (DBH ≥40 cm for conifers and DBH ≥35 cm for broadleaved trees) if the forest is managed based on economic optimization without retention. For retention levels of 5% and 20%, the area of old forest in a 100 years will comprise 7% and 19% of the total area, respectively, and the average number of large trees per ha will be 4 and 13, respectively (Figure 3). Compared with clear-felling without retention, deadwood volumes will be 2.5 times higher at 5% retention and 4 times higher at 20% retention. The stand visualizations indicate that public perception of the harvested area can be quite different compared to the open surface of a clear-felled area without retention. Thus, retention approaches in boreal production forest landscapes long characterized by clear-felling operations have the potential both to restore qualities of natural forest landscapes and to increase public acceptance.

It is also clear from our simulations that if high retention levels are desirable from an ecological or aesthetic point of view, there will be large economic losses to the forest owner. For biodiversity conservation, one possible way to increase cost-effectiveness could be to improve the knowledge-base on the biodiversity quality as well as on the economic value of retention patches. If patches with low economic value, like low-productive sites in bouldery terrain, steep slopes or paludified spots, have large values to biodiversity, they could be prioritized for selection. In the only study on cost-effective selection of retention patches so far, such solutions were indeed identified, but the recommendation still was that different types of patches should be selected, since they have complementary species compositions (Perhans et al. 2011).

Landscape characteristics

Restoration and biodiversity

Like most northern Swedish forests, the forest landscape used in the study has been transformed from semi-natural vegetation to areas shaped by final fellings of whole stands followed by even aged plantations in less than 50 years. There are still remnants of natural forest characteristics in the few remaining old stands since they have probably never been clear-felled but have been successively high-graded and thinned, implying continuity of some old trees.

The ca. 20% proportion of forest >120 years old after 100 years in the 20% retention alternative represents a rather large step toward more natural forest conditions. Although retention patches often are small, rarely exceeding 0.5 in size, they may have an important function for at least some species classified as old-forest species (e.g. Perhans et al. 2009). It should be noted, however, that our study landscape has younger forest than the average for this part of the country; in the county of Västerbotten where the landscape is situated, about 16% of the forest area is currently >120 years old (Swedish Forest Agency 2014). Thus, although the area of old forest will be considerably larger in our study landscape 100 years from now, it will only marginally exceed current average levels in the surroundings. The projected proportion of old forest is also considerably lower compared to pre-exploitation levels. For instance, Linder and Östlund (1998) in a study of three large mid-boreal landscapes found that before the 1880s, forests >200 years old dominated. The restoration effect on large trees may be more pronounced. Although data on former numbers of large trees are scarce, Nilsson et al. (2002) suggest that densities of 20 trees ha^{-1} with DBH > 40 cm used to be common in north European boreal old-growth forests. The density of large-diameter trees in our study area (DBH > 35–40 cm) at 20% retention 100 years from now was projected to reach about 13 ha^{-1}, i.e., not dramatically less than reported for natural conditions. On the other hand, Linder and Östlund (1998) reported greater densities, varying between 38 and 77 trees ha^{-1} but with a slightly smaller DBH, 33 cm. The amounts of deadwood in pristine forest conditions have been estimated to average 90–120 m^3 ha^{-1} in spruce-dominated old-growth forests in south and middle boreal Fennoscandia (Siitonen 2001). The starting volumes in our study landscape were very low; only 4 m^3 ha^{-1}, and with 20% retention would increase to about 14 m^3 ha^{-1}, i.e. a large change but still an order of magnitude lower than in natural forest landscapes. Deadwood has been shown to increase rapidly following the introduction of retention forestry, e.g. Kruys et al. (2013), analyzing Swedish NFI data, reported an increase in volume of 70% over a 10-year period in forests 0–10 years old.

A key question is how biodiversity might respond to the retention levels of 0%, 5%, and 20% in our projections. Even with extensive habitat modeling it would be hard, or even impossible, to project the effect on biodiversity in general from one threshold, since threshold responses are species-specific (Ranius & Fahrig 2006). For Sweden alone with more than 20,000 forest species (Gustafsson & Ahlén 1994), the range in habitat thresholds most likely is very large. The response will also vary greatly depending on species pool, habitat, and region (Müller & Bütler 2010). Nevertheless, a recent meta-analysis concluded that there is an overall positive response of biodiversity to retention and that the number of forest species increases with the number of trees retained (Fedrowitz et al. 2014). Further, Gustafsson et al. (2012) in a global overview of retention practices suggest 5–10% retention as a strict minimum, and Halpern et al. (2012), drawing on data from a large retention research experiment, conclude that at least 15% is needed to maintain the abundance of the species characteristic of old forests. This indicates that 5% retention might be at the lower end for a positive biodiversity response. Still, our projections show that retention even as low as 5% is a prerequisite for future availability of certain structures like large-diameter trees, and thus may still play a role in maintaining populations of certain species.

Delivery time

Our projections indicate that the effect of retention actions will be rather slow; it may take 80–100 years to reach higher numbers of large trees, and it will also take a long time for the area of old forest to increase. One potential reason for the long delivery time is the uneven age class distribution in the study area, in which the proportion of stands aged 60–100 years is low (Figure 2). On the other hand the retention patches contain relatively more forest older than 60 years. In the first decades retention does not contribute to large trees found in the managed stands (Figure 3 bottom; all three curves coincide until about year 30). Thus, if large trees are desirable in the short term, patch retention should be complemented by retention of large solitary trees. Such single-tree retention in combination with retention patches is also the common procedure in Swedish forestry. The main practice of the forest company at the time for the survey of the landscape was, however, retention patches.

Aesthetic values and visualization techniques

Computer visualization of forecasted landscapes is an excellent tool for illustrating the future consequences of present forest management alternatives. Figures 5 and 6 show that the overall impression of a cut area will only be marginally modified at a retention level of 5%, whereas a much more varied landscape will take form when 20% retention is practiced. This impression corresponds well with earlier research where panels of respondents have been used which was not the case in this study as it had its focus on forecasting and the comparison of multiple values. Tönnes et al. (2004) used a panel of 373 respondents and found that the scenic quality of clear-felled areas increased significantly with the degree of tree retention and was almost negligible for retention levels below 3 m^3 ha^{-1}. Ribe (2009) also found that tree retention increased the public acceptance of clear-felling, but he identified a threshold retention of 15% of the area. Below this minimum level the cuttings with retention were perceived negatively, as open clear-felled areas. Tönnes et al. (2004) and Ribe (2009) also found that downed wood and trees in poor condition were less well perceived by the general public. Thus, the saving of deadwood by tree retention for maintaining biodiversity on the one hand and for increasing aesthetic values on the other hand tend to contradict each other. However, studies show that deadwood is more accepted by an educated panel that understands its ecological value (e.g. Kardell 1990). On the other hand, large old trees, the amount of broadleaved forest, and variations in the production landscape managed in stands are qualities that tend to increase the public preferences for a given forest (Gundersen & Frivold 2008).

Visualization is a potential tool for designing and evaluating different landscape management scenarios, including tree retention, and in landscape preference research (Karjalainen & Tyrväinen 2002). In our case study it seems that the detailed visualization is probably easier for a viewer to perceive and interpret than those at the landscape scale. The detailed scale is probably suitable for studying people's preferences, for example.

The computer visualization technique is a rapidly evolving area and should be evaluated continuously regarding usability in landscape and forest management planning. It has the potential to be further developed in terms of both working procedure and the final result. For example, the method used here required much work for creating ground vegetation, deadwood, etc. In addition, 2D-billboard trees were used which might be less suitable if trees grow very close together and a combination of 3D and 2D (from a distance) models are probably more appropriate.

Data on landscape characteristics and projection models

The case study was based on much better data than are normally available in stand registers and forest maps. Stand registers typically contain only mean values, without information about tree-size distributions. Data on less frequent tree species – like aspen, which is of interest for nature conservation – are also lacking or uncertain. In the case study, all stem diameters were recorded within sample plots in the stands and retention patches (in small retention patches, a total tally), and thus tree size distributions were known. In the future, the combination of field surveys and remote sensing, for example LIDAR, has the potential to improve forest data for analyses and planning of multipurpose forestry. Long-term forest management planning typically concerns one rotation; in this region approximately 100 years. Especially for the unmanaged forests in the retention patches, the 200-year projection implies the use of tools such as growth and mortality models outside the range of the empirical data on which the models are based, thereby making the projections uncertain. When using net present value as a criterion in forest management planning the rotation period is related to the interest rate used. A higher interest rate leads to shorter rotation periods and vice versa. This also affects the relative impact of tree retention. For example, if short rotation periods are used no large-diameter deadwood will be created among the managed trees and large-diameter deadwood will depend solely on tree retention. Thereby the contrast between no retention and retention will increase with shorter rotation periods compared to longer rotation periods.

Conclusions

Retention approaches at clear-felling are a powerful way to restore boreal production forest landscapes to more natural conditions and are also more acceptable to the public than traditional treeless clear-cuts. The transformation, however, is slow and will depend on long-term and continual retention actions at final harvest. Starting conditions and retention levels will be decisive for the speed and direction of change. For small forest landscapes, like the one studied here by us, stochastic events like storms and wildfire may create unpredictable patterns that are hard to project. Visualizations are a good way to communicate and exemplify landscape changes due to retention actions. Future challenges for projections similar to ours include modeling the responses of plant and animal species, and further investigating stakeholder preferences regarding future states of forest stands and landscapes. In future projections, it will also be important to include different types of set-asides in the modeling, to be able to assess the contribution of retention actions to the restoration of natural forest characteristics, relative to other conservation areas.

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Supplemental data

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