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Prioritizing the retention of border zones in production forests: The projected benefits for Swedish broadleaf habitats

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ABSTRACT

Swedish forestry is characterized by relatively intensive silvicultural practices primarily focused on the rotational even-aged management of Norway spruce and Scots pine. The diversification of these management practices, via the increased use of mixed forests and broadleaves, is a recommended means of promoting biodiversity conservation and reducing climate change-related risks. One complementary and underexplored pathway to diversifying production forest landscapes is to increase the ecological quality of retention patches at final felling. Recent studies indicate that border zones towards water, arable land and other land uses have a higher share of broadleaves and, together with other functions, should be prioritized for retention. This study investigates the benefits of prioritizing the retention of these ecological transition zones at final felling in a typical southern Swedish region, focusing on the amount of broadleaves retained. With input from a key regional actor in nature conservation (the County Administrative Board), two different retention scenarios were simulated: Retention patches representative of average stand conditions (AveCOND) and border zones (BORDER). The forest data, sourced from remote sensing, indicated that border zones towards open land and water had a higher volume share of broadleaves than the average found on productive forestland (> 1 m^3/ha/year) in the study region. Simulating the development of the landscape over a 100-year period and prioritizing the retention of border zones increased the share of broadleaves over time. Since only a limited share of the total forest area is subject to retention, 8% in our study, the advantage of BORDER over AveCOND is not dramatic; BORDER yields 50 m^3 broadleaves per ha compared to 47 m^3 for AveCOND after 50 years and 47 compared to 43 after 100 years. In the study, retention patches and border zones were left with no management. Active management to promote broadleaf trees using targeted thinning regimes could add to the ecosystem's provision of border zones relative to no management. The economic outcome suggests that allocating retention to border zones could be advantageous compared with allocation to the harvesting site. However, this result hinges very much on what, in reality, is attained in the BORDER case. Another aspect refers to the unevenly distributed border zones among forest properties. Thus, retaining all border zones would require some landscape approach. We discuss various barriers and opportunities to implementing this retention strategy, for which our findings suggest multiple conservation benefits exist.

INTRODUCTION

Growing demand for natural resources (Steffen et al. 2015) and anthropogenic climate change (IPCC 2023) are combining to cause the increased loss of global biodiversity (Ceballos et al. 2017; IPBES 2019). A major cause of the biodiversity crisis is the loss, degradation, and homogenization of natural forest habitats (Haddad et al. 2015; Maxwell et al. 2016; Van Der Plas et al. 2016). The preservation and sustainable management of the world's remaining natural and semi-natural forests is critical to halting this loss, due to the biodiversity and ecosystem services these systems provide (Brockerhoff et al. 2017). Of central concern will be how to simultaneously conserve forest biodiversity while sustaining the long-term provision of forest-derived materials for building, energy, and other forest ecosystem services.

This task is complicated by the fact that much of the world's forests are managed for wood production, as well as other economic, environmental, or cultural values, and only 18% of the world's forests are formally protected for biodiversity conservation (FAO 2020), though only a subset of this percentage is protected adequately (Jones et al., 2018; Wolf et al. 2021). Furthermore, an increasing proportion of the world's forest cover consists of intensively managed production forests (Payn et al. 2015), and in many regions, there are now limited opportunities to rely on large, diverse, and high-value protected areas for biodiversity conservation (Branquart et al. 2008). Conserving biodiversity under such circumstances typically requires combining a limited number of large, protected areas and intermediate-scale reserves with the use of retention forestry (e.g. leaving buffer zones, clusters of larger trees) in the majority of the forest landscape that consists of production-orientated forests (Felton et al. 2020).

Retention forestry is a common means of integrating biodiversity conservation with timber production stands (Gustafsson et al. 2020). First emerging in the 1980s, the widespread adoption of retention forestry was facilitated by the global embrace of forest certification. In Sweden, 67 % of all productive forest outside formally protected areas are certified, of which 11.2 million ha or 75% are double certified by FSC and PEFC, whereas 0.9 million ha (6 %) are solely FSC certified, and 2.8 million ha (19 %) are solely PEFC certified (Swedish Forest Agency (SFA) 2023). The current national FSC standard requires that at least 5 % of productive forests on the certified estate be set aside for nature conservation, and an additional 5 % should be managed with the primary long-term goal of developing nature and social values. Furthermore, FSC requires that at least 10 trees per ha be left during clear felling and emphasizes the importance of maintaining border zones to water bodies with a prioritized focus on promoting broadleaves (FSC 2024).

Voluntary forest certification has substantially contributed to the integration of retention practices into even-aged forestry (Simonsson et al. 2015; Gustafsson et al. 2020). As the name indicates, the emphasis in retention forestry can be as much on what is left behind at harvest as on what is taken out (Gustafsson et al. 2013). Choosing what to leave behind generally involves identifying important structures, such as individual trees and tree patches, and creating additional deadwood by cutting high stumps, which help restore natural growth and decay processes in production forest landscapes (Lindenmayer et al. 2012). In Sweden, national statistics for all forest owners, regardless of certification status, report that, on average, 9 % of the stand area is retained, of which one-third is allocated to border zones, plus approximately four trees/ha retained within the area of final felling (SFA 2024). During 1993-2022 Swedish forestry has created approximately 525,500 ha of retention patches, which corresponds to 2.2 % of productive forestland (i.e. capable of producing ≥ 1 m^3 of wood/ha/yr) (Statistics Sweden 2023).

Key documents governing the management of Swedish Forests include the Forestry Act (SFA 2020a), certification standards (FSC 2024; PEFC 2024), and the target goals for environmental consideration (Andersson et al. 2013). All of these documents emphasize the importance of retaining border zones adjacent to specific landscape elements (e.g. streams) or non-forest ecosystems and land uses (e.g. mires, agriculture). In particular, the Swedish national FSC standard (FSC 2024) contains multiple specific provisions on border zones such as: (i) The forestry sector's targets for border zones along lakes, watercourses and wetlands are implemented in applying, following-up, adapting and documenting forestry measures. Ecologically functional border zones along watercourses and open water surfaces are preserved or recreated if necessary. The design and width of the edge zone are planned and adapted based on the natural value and sensitivity of the water environment and the forest nature values of the border zone. (ii) Areas of environmental consideration, such as border zones, groups of trees, or single storm-resistant thicker trees, are left during clear fellings to avoid larger bare areas. (iii) Pre-commercial thinnings in border zones are carried out only with the aim of benefiting natural values. (iv) Deciduous border zones are recreated where possible. (v) Damage from driving does not occur in border zones. (vi) Non-native tree species are actively removed in consideration areas and edge zones when carrying out silvicultural measures. (vii) Border zones along watercourses and marshes are left as sources of spreading lichens on lands within the reindeer husbandry area.

Here, we use the term "border zone" to specifically refer to forested transition zones between different ecosystems (e.g. streams, waterbodies, riparian forests) and/or land uses (borders between agriculture and forestland) that are purposely retained at final felling for conservation purposes. Other studies have used different terminology to describe these zones, such as riparian buffers (adjacent to streams and rivers) (Kuglerová et al. 2014); buffer zones (Perhans et al. 2011; Lundström et al. 2018); buffer strips (Hylander et al. 2002; Oldén et al. 2019a; Oldén et al. 2019b) or forest strips (Hågvar et al. 2004), whereas the SFA uses the term "protection zones" ("skyddszoner" in Swedish) (SFA 2020b). In general, border zones are areas exempt from conventional forestry (e.g., as are retention trees and patches during final felling), although in some cases, nature conservation management is recommended to maintain or increase their existing conservation values. The forest sector's target goals (Andersson et al. 2013), which were produced in a dialogue process between the forest sector and the SFA, provide the most detailed guidance for the management of border zones. These guidelines include instructions for managing forests that border water bodies, wetlands, mires, and agricultural land (Andersson et al. 2013, p. 59-72). However, in line with the current governance model in Sweden (Appelstrand 2012; Beland Lindahl et al. 2017), no detailed legally binding requirements exist which specify what actions are required to be taken in forest border zones. For example, no legal limits dictate border zone width at final felling, even when adjacent to water bodies. Partially as a result, Swedish policies regarding border zone retention in those areas adjacent to streams, for example, have been found to be relatively lax in comparative studies of global (McDermott et al. 2010, p. 314-319) and North European (Ring et al. 2017) environmental policies. Recent assessments have found that approximately 30% of harvested area perimeters adjacent to water bodies and streams lack border zones (SFA 2024). This is despite the aforementioned guidelines (Andersson et al. 2013) and the stipulations of FSC standards (sections 6.6.5, 6.7.1 and 6.7.2; FSC 2024).

Scientific support for the biodiversity benefits of forested border zones, including studies investigating border zone retention after final felling, comes from various studies and contexts. For example, forest borders in agricultural lands can fulfill a wide range of ecological functions, including direct habitat provision, movement corridors, and refugia for species sensitive to modern agriculture (e.g., fertilizers, pesticides) (Fry and Sarlöv-Herlin 1997). Furthermore, the added structural complexity can increase the aesthetical qualities of the landscape (Fry and Sarlöv-Herlin 1997). When established adjacent to lakes and mires, post-logging border zones can increase the diversity of breeding birds (Hågvar et al. 2004). If retained along streams, border zones can improve water quality and protect biodiverse forests from logging-related edge-effects (Gundersen et al. 2010; Kuglerová et al. 2014), act as lifeboats for vascular plant and bryophyte species dependent on cool and humid riparian microclimates (Oldén et al. 2019a, Oldén et al. 2019b), as well as benefiting the diversity of bryophytes (e.g., refer to Hylander et al. 2002; Hylander et al., 2004; Dynesius and Hylander 2007; Hylander and Weibull 2012) and land snails (Hylander et al. 2004). More generally, riparian forests, which only cover a small fraction of the total forestland, are often species-rich, and their inherent association with water courses increases their potential to increase landscape connectivity when retained as border zones (Naiman et al. 1993; Naiman and Decamps 1997; Gundersen et al. 2010). Border zones can, therefore, act as effective building blocks for ecological landscape planning (Fries et al. 1998a; Fries et al. 1998b). Finally, border zone retention has the potential to allow for higher wood production in the remaining areas of the stand compared to more scattered retention strategies. A retention tree from the previous generation reduces the growth in the new stand within 5-10 m of its trunk (Elfving and Jakobsson 2006). Concentrating the retention efforts on a given retention level, as in border zones, the area affected by such competition from the retained trees can be reduced, though with potentially adverse consequences for species dispersal across open, clearcuts (Gustafsson 2012).

Both within and outside border zones, tree species composition and its projected development through time are key to understanding the likely effects of different management methods on habitat provision and, thus, biodiversity conservation (Felton et al. 2016). Forest management practices in Sweden are currently dominated by the rotational clear felling of even-aged stands of the two native conifers, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). Together, these two species comprise approximately 80% of Sweden's standing volume of productive forestland at the national level and 75% in southern Sweden (SLU 2023, p. 65). These circumstances are not consistent with historical patterns of vegetation cover, nor disturbance regimes (Berglund and Kuuluvainen 2021), as mixed or broadleaf forests were once common within this and many other regions of Northern Europe (Lindbladh et al. 2014). Increasing the share of broadleaves is therefore of high conservation concern (Felton et al. 2016), as is reflected in certification requirements which demand both minimum levels of broadleaf admixture in production forest stands (> 10%), as well as the use of broadleaved dominated stands (> 5%) (FSC 2024; Brukas et al. 2013). Nature conservation management in voluntary set-asides is also oriented towards the promotion of broadleaved tree species via the active removal of Norway spruce (Grönlund et al. 2020). Notably, some forest categories and circumstances may already support higher proportions of broadleaved species than alternatives. For example, Swedish riparian forests are often rich in broadleaves (Dahlström and Nilsson 2006; Ring et al. 2018), as are borders between forests and agricultural land, which is the most common forest edge type in southern Sweden (Essen et al. 2016, Appendix 5 and 6).

Prioritizing the retention of border zones at final felling may thus be an effective and efficient way to exempt broadleaved rich zones from conventional conifer-oriented forestry, and the share of broadleaves may increase further with subsequent nature conservation management. Such practices can potentially create retention areas rich in broadleaves and increase the share of broadleaves in the wider forest landscape. Our aim in this study was to investigate a prioritized retention of border zone areas as an alternative to a non-prioritized retention allocation to harvesting areas in general, as a potential means of improving tree species composition in the production forest lands of southern Sweden. We also evaluated the economic implications of so doing and provided policy-relevant information about potential obstacles to practical implementation. To do so, we used long-term projections of two alternative retention scenarios over a 100-year period, using both data from the Heureka decision-support system (Lämås et al. 2023) and a forest owner simulation model developed for the EU Horizon project ALTERFOR. Our simulations used the forests and owner structure data of Kronoberg County, situated in southern Sweden. Having Kronoberg County as the case area allowed us to design the allocation of border zones in collaboration with key actors in the ALTERFOR project, including the County Administrative Board, which is in charge of promoting green infrastructure in the region. With its high share of small-scale private owners and prevalence of rotational conifer forestry, the region is representative of prevalent forest conditions in Southern Sweden.

MATERIAL AND METHODS

Forest data including border zone data

Kronoberg County has 665,000 ha of productive forestland (SLU 2023, p. 59). To limit the amount of data processing and still be able to reflect the conditions of the county, 10% of all forest owning properties in Kronoberg County were sampled. After removing small properties and isolated forest patches of less than 0.5 ha, 56,583 ha productive forest remained, distributed across 920 properties and 43,965 stands. The average property size in the selected subset was 50 ha for small scale forest owners, which is comparable to the Swedish average of 48 ha (Haugen et al. 2016), if the removal of small holdings is considered. The average for institutional owners, such as the church, Sveaskog, and municipalities, was 580 ha. The small average stand size (slightly >1 ha) was partly due to the large share of small-scale owners (80% of the forest area) and the varied nature of the landscape.

We used pixel data from the SFA with a 12.5 x 12.5 m grid (SFA 2018, Nilsson et al. 2017). Tree species data that provides the volume of pine, spruce, and broadleaf trees was imported from the 'SLU Forest Map' (SLU 2020). Tree species data was predicted using a combination of Sentinel 2 spectral data and Lidar data, as well as by using field data collected between 2012 and 2016 by the Swedish National Forest Inventory (NFI). Other details on data preparation can be found in Lodin et al. (2020). We restricted our allocation of border zones to areas designated for use as production forests, and all border zones were allocated a width of 12.5 m, corresponding to the pixel size. The accuracy of the tree species classification was evaluated using three different comparisons.

The first comparison was based on a set of NFI data from 2017 and 2018 for Kronoberg and its neighboring five counties. The user's accuracy, i.e. the frequency by which the classification provided on the map accurately reflects what is present on the ground, was above 75% for Scots pine, Norway spruce, and broadleaf forest, i.e. forest where each species group holds at least 70% of the volume. In contrast, the mixed forest class only had an accuracy of 40%, meaning that pixels denoting mixed forest tended to include species groups that were Scots pine, spruce, or broadleaf forest. This indicates that broadleaf forest could be underestimated.

Another comparison concerned tree species proportions, specifically for forest borders in Kronoberg County, using data from the SLU Forest Map and NFI for the same location (Table 1). The NFI data consists of plots that are divided between productive forests and other land uses or non-productive forests where the productive forest belongs to a stand of at least 0.25 ha. The SLU Forest Map tends to overestimate the proportion of pine in forest borders and underestimate broadleaf volumes.

Table 1. Proportion of pine, spruce and broadleaf volumes in Kronoberg County as provided by data from SLU Forest Map (SFM) and NFI in forest borders adjacent to different land use classes represented by at least 10 NFI plots.

	Pine		Spruce		Broadleaf		
Adjacent land use	SFM	NFI	SFM	NFI	SFM	NFI	No. Plots
Arable land	20.2	5.0	39.1	42.9	40.5	52.0	10
Peatland	47.9	45.9	32.2	23.1	20.0	30.9	45
Road	39.3	27.4	35.5	37.1	25.2	35.6	38
Water	46.7	24.8	24.5	32.3	28.8	43.0	10

The third comparison involved a limited set of border zone types. Among stakeholders, the County Administrative Board (CAB) was directly involved in helping us select border zone types. The CAB is an influential regional governmental actor involved in decisions regarding nature conservation, especially for formal set-asides but also for those decisions affecting production forests. The use of border zones was one of several alternatives conservation pathways we discussed with the CAB for increasing the share of broadleaves in the forest landscape (see Lodin, 2018, p. 5-6). The distribution of the total border zone area of the study data for the forest border types selected by the CAB was: 22% adjacent to agricultural land (cultivated land, meadows, and pastures), 3% developed land (mainly urban, industrial, otherwise built up areas, and infrastructure), 27% other open lands (open land, with or without vegetation, which is not agricultural land, wetland, or developed land), 16% lakes and big streams, and 32% adjacent to small streams and ditches. The listed border zone types were the ones maintained in this study.

The corresponding NFI data was sourced from all NFI plots located in southern Sweden (approximately all land south of the northern tips of the lakes Vänern and Vättern and corresponding to almost 5 million ha productive forest) to limit the effect of sampling size for the NFI divided plot data. The divided plots are those where the forest is crossed by any of the border zones mentioned above. The comparison is presented in Table 2.

Table 2. Data on border zones, all forest on Kronoberg sampled properties and NFI data for southern Sweden.

	Size[(a)]	Species distribution (%)			Mean age	Volume	Net growth
		Pinus Sylvestris	*Picea abies*	Broadleaf	(y)	(m^3 ha^{-1})	(m^3 ha^{-1} y^{-1})
			Study data				
Border zones	3,586	25	45	30	69	175	6.32
All forest	58,251	39	43	18	51	139	6.23
			NFI plot data				
Divided	7,886	23	36	41		211[(b)]	
non-divided	120,370	30	48	22		173	

[(a)] Area in ha for the study data and no. of calipered trees for NFI data.
[(b)] The ha^{-1} volume refers to the productive forest on the divided plot.

Border zones and divided NFI plots had relatively higher volumes of broadleaf trees than the rest of the productive forestland. The mean net annual growth of border zones approximates the rest of the forest area, indicating that age and stocking density differences more likely stem from management differences than site conditions. Comparing the total volumes and the proportions of the study data with the NFI data there is an indication of broadleaves to be underestimated in the study data.

Retention scenarios

Our projections relied on climate change mitigation and retention scenarios developed and implemented by Lodin et al. (2020). Projections were made for a 100-year time period, divided into 20 five-year-planning periods. Forest stand development was projected with the Heureka forest decision-support system, interface Planwise (Heureka 2019; Lämås et al. 2023), which encompasses a complete set of growth and yield models based on single tree data. The projected management practices were derived through a forest owner decision simulator, which determined the management of each property. The management actions of forest owners were guided by timber prices and total harvest volume per 5-year period for Kronoberg County. For this study we used the mitigation scenario “GLOBAL BIOENERGY” from Lodin et al. (2020), which encompasses a specified trajectory of future warming, wood product demand, and timber prices.

Retention at final felling was set to 8% of the final felling area. This corresponds to the average retention patches for southern Sweden from 2016/2017 to 2018/2019 (SFA 2024, Table 1a).

Two retention scenarios were projected (Table 3). The retention scenarios involved the same level of retention but differed in regard to how the retention was allocated. In scenario AveCOND, 8 % of the area of each production stand was retained and subject to undisturbed growth. Retention reflected the average conditions of the stand. In contrast, for the BORDER scenario, retention was prioritized for allocation to borders, and a width of 12.5 m was assigned. The allocation of patches to 8% of the production forest area was done at the landscape level without any maximum constraints on the amount retained at the property level. To do so, all borders in the production forest of all forest owners were first assigned undisturbed growth. This constituted 6% of the production forest area. Second, the remaining 2% was allocated to properties with less than 8% border zone retention. This was done in the same way as the AveCOND scenario. To compare the economic outcomes, we calculate net present values for the two scenarios, using a discount rate of 3% as accustomed in Swedish forest capital analyses (Brukas et al. 2001) and evaluating timber assortments with Heureka system default values.

Table 3. Description of the retention scenarios projected in this study.

Retention scenario	**Description**
Retention patches reflect average stand conditions (AveCond)	Retention areas were assigned to 8 % of the total production forest stand area, with forest conditions reflecting the stand average. These patches were assigned as having no management from the first period in the projections.
Retention patches involve prioritizing border zones (BORDER)	Retention areas were assigned to 8% of the total production forest stand area, as per AveCond. Retention was composed of (A) All border zones adjacent to water, agriculture land, other open lands and developed land in production stands (6% of the production forest area) and (B) Representative stand-level patches as described under AveCOND (2 % of the production forest area). The border zones and the representative patches were assigned no management from the first period in the projections.

RESULTS

We found that moving retention from harvesting sites (AveCond) to borders (BORDER) resulted in an increase in broadleaf volume in the landscape over time (Figure 1). The transition takes time since it only takes place at the final harvest. The increase in broadleaf volume follows a general trend of increased stocking over the first 50 years. The total volume of broadleaves per hectare increases from a starting value of 26 m^3 to 47 m^3 in the AveCOND and 50 m^3 in the BORDER scenario over 50 years, to 43 and 47 m^3 after 100 years, respectively. The initial volume share of broadleaf is 18% and increases to 21% after 50 years for both scenarios. The proportion is reduced to 18% and 16% after 100 years for BORDER and AveCOND, respectively.

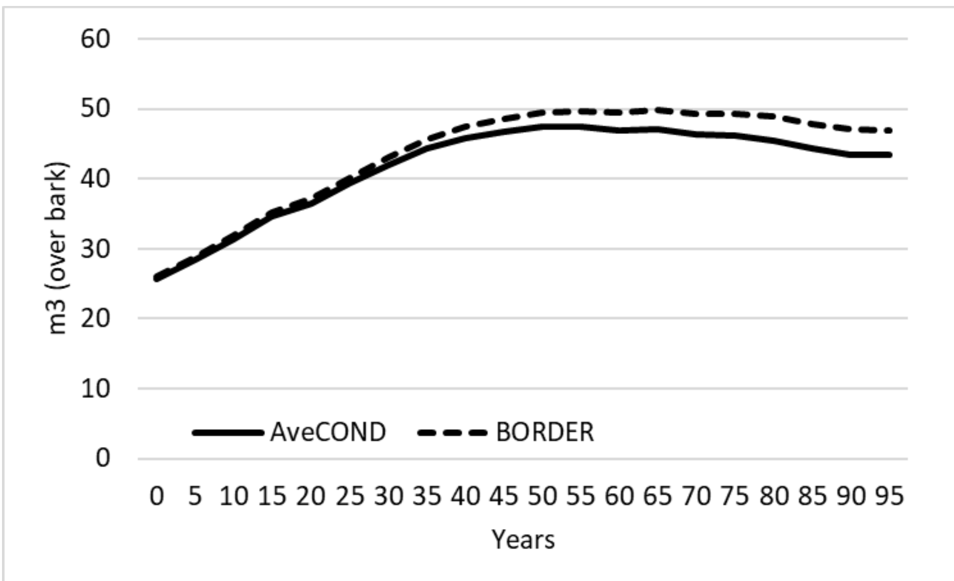

Figure 1. Broadleaf volume per hectare for AveCOND and BORDER scenarios.

The development of broadleaf volume of the areas that are allocated as retention in the two scenarios follows the same relative trend (Figure 2). However, the absolute development is different, with retention in edges favoring more broadleaf trees.

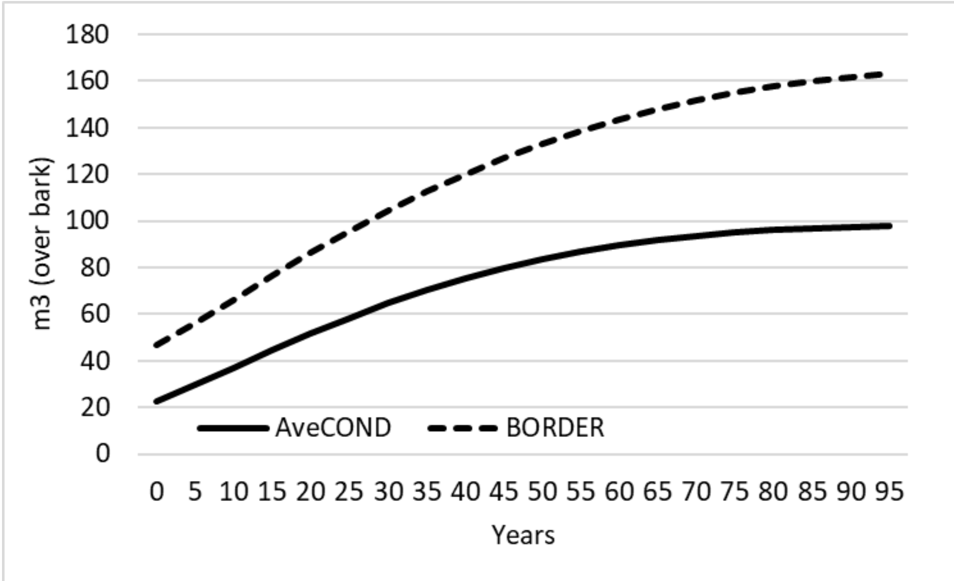

Figure 2. Broadleaf volume per hectare in retention patches.

The economic outcome favors edge retention. The net present value over the 100 years is slightly higher (0.5%) with BORDER compared to AveCOND for the landscape.

DISCUSSION

Border zone prioritization effects

The border zones evaluated in this study supported a higher proportion of broadleaf trees than the average composition of all productive forestland and all production forest stands. This result highlights the potential to target these areas for retention actively. The fundamental driver of this outcome is that border zones were primarily composed of categories of forest adjacent to streams and agricultural land, which, as previous research has found (Essen et al. 2016; Ring et al. 2018), are relatively rich in broadleaves. As our results suggest, retaining border zones at final felling in these forest categories increased the share of broadleaves in the retention patches. However, as retention patches were, on average, only left on a small fraction of each production stand at the time of harvest, the projected increase in broadleaves at the landscape level was relatively small (Figure 1).

The modelled economic outcomes indicate a positive net present value of the border zone strategy. This result stemmed solely from the advantage of harvesting more conifers, which are assumed to be more valuable than broadleaves when more of the timber harvest is allocated to the non-border zone. According to our data, conifers had a higher prevalence on the harvesting site than at the site's border. Thus, whether the gain is realized in practice depends highly on what is retained at the harvesting site. It is likely that retention patches are selected among trees with defects, groups of trees on wet ground, trees not accessible by machinery, etc. Since a buffer zone gives less freedom of tree selection, the small yet positive economic outcome of the border alternative may be an exaggeration. An indication that the study assumption is valid, though, is the SFA (2024, Figur 9) investigation, reporting that 78% of all tree volume left at harvesting sites are coniferous, i.e., close to the national average for living trees.

Border zone implementation

In our study, we were able to model the allocation of border zones across the entire landscape. The real-world use of larger planning areas can facilitate a more targeted and optimized selection of important conservation areas, leading to the more efficient utilization of conservation resources (Strange et al. 2006). In our study, a landscape retention budget without maximum constraints at the property level enabled the retention of all border zones adjacent to open land and water areas. This also meant that those properties with large amounts of border areas faced a larger toll on their land compared to those with less borders (Figure 3).

Retention decisions are generally made at the stand level by forest managers when planning for final felling (Wikberg et al. 2009). In Sweden owners have strong property rights (Nichiforel et al. 2018) and are entitled to compensation if the planned restrictions on forestry activities, such as those involved in the creation of retention patches, "*considerably obstruct ongoing land use*" (SFA 2020a, 30§ on p. 58). To facilitate the increased landscape-scale allocation of retention features to border zones, while accepting that properties can vary greatly in the extent of forest land with borders, may require mechanisms involving financial compensation. For example, property owners with large amounts of border zones could be compensated to ensure adequate protection of these areas is achieved without inflicting disproportional financial costs on their owners. However, government allocations for nature conservation are primarily channelled to establishing or maintaining new and existing formally protected forest areas. Thus, authorities may be reluctant to allocate substantial resources to compensate for additional conservation restrictions that take place over extensive areas. Another pathway for increasing the landscape scale allocation of retention to border zones would be to establish a system for the collection and redistribution of financial resources among forest owners (e.g., the tax-fund system suggested by Michanek et al., (2018) and Zabel et al. (2018)). In this case, owners with a high share of border zones could be compensated for the obstruction of their land use by owners with fewer border zones, thus potentially enabling better conservation outcomes at landscape scales. However, no system is currently in place for such a redistribution of finances, and installing and running a compensation system could involve considerable transaction costs.

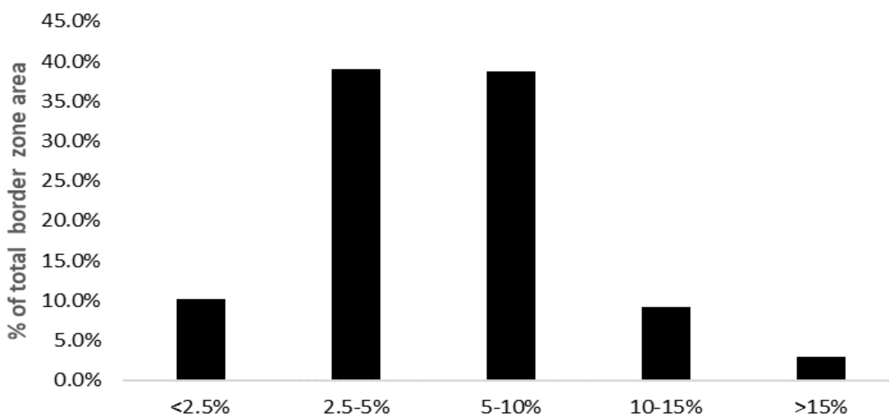

Figure 3. The distribution of the border zone area over the production forest area (i.e. excluding set-asides) of the properties, showing how the extent of border zone differs between properties.

Looking at the larger picture, our projections' prioritized retention of border zones invariably reduces opportunities to retain other categories of forest patches or individual trees. Different types of retention patches (e.g., border zones, tree groups, swamp forests, and rock outcrops) host distinct communities of forest-dependent species. Moreover, target goals for environmental consideration highlight many examples where higher levels of retention can be motivated by the need to achieve conservation targets or additional (e.g., cultural) concerns (Andersson et al. 2013). These aspects indicate that the more forest area allocated for retention, the better the outcomes can be for conservation; a conclusion that mirrors the findings of a recent review of retention forestry benefits (Gustafsson et al. 2020). This highlights that, while there are clear environmental benefits of concentrating retention to border zones, the increased use of retention inside and outside of border zones is desirable in general as a means of helping Sweden fulfil its national environmental objectives for living forests. It is also worth noting that the proportion of broadleaf trees in otherwise conifer-dominated stands can also be increased by using broadleaf trees to create mixed-species production forests (Felton et al. 2010), with recent evidence suggesting synergistic benefits to forest biodiversity and a range of ecosystem services from their establishment (Felton et al. 2024). Notably, most of these broadleaf trees will nevertheless be harvested at a fraction of their potential lifespan, with only a few trees per hectare retained even if broadleaf trees are prioritized for retention (FSC 2024).

With respect to the projected biodiversity benefits of prioritizing the retention of border zones, the resultant conservation value to forest-dependent and broadleaf-associated species (Lindbladh et al. 2014; Felton et al. 2016) is likely to be highly context and taxa-specific. For example, in addition to the impact that fragmentation and edge effects can have on the value of small forest remnants to forest biodiversity (Haddad et al. 2015), the species richness of border habitats can vary depending on the extent of environmental contrast that occurs across such zones (Willmer et al. 2022), as can the community composition of indicator taxa vary in response to changes over time in border zone conditions (Hylander and Weibull 2012; Johansson et al. 2018; Ruete et al., 2016). Furthermore, it is worth noting that one of the motivations for using retention trees is to improve spatial connectivity and temporal continuity (Gustafsson et al. 2012; Lindenmayer et al. 2012), which in some circumstances may motivate the placement of at least some retained trees within the harvested area, rather than confining their use to its edges (Lindenmayer and Franklin 2002). So, whereas the prioritized retention of border zones is likely to benefit broadleaf-associated species, beyond this, the net conservation value of such actions is difficult to predict and requires further study.

Caveats

The increase of broadleaf volume from border zone retention may be larger than shown here. There are indications that the increase of broadleaves in border zones compared to the harvesting sites, in general, could be underestimated due to likely limitations in accurately detecting the presence of broadleaf trees in the border zones of the study data. The comparisons with NFI data for borders adjacent to different land uses (Table 1 and Table 2) and in total volumes (Table 2), as well as the tendency to mistake broadleaf-dominated stands for the mixed forest, support this contention.

We emphasize that the data our models are built on may exaggerate the potential for real-world gains in broadleaves that result from prioritizing border zones for retention. This is because some conservation actions are already being directed towards border zones and thus already influencing starting values. In this regard, almost 25% of retention areas in southern Sweden are allocated to border zones (SFA 2024). The placement of a subset of retention areas into border zones may be the result of third-party certification standards (FSC 2024; PEFC 2024), and the forest sector's target goals for environmental consideration (Andersson et al. 2013), all of which recommend that border zones are prioritized when selecting areas for retention. Nevertheless, the border zones of private forest owner properties only represent 1.7% of the productive forest area, whereas the study area data indicates a potential of 6% (3.5 out of 58 thousand ha; refer to Table 2). Furthermore, almost 40% of border zones adjacent to water on small-scale forest owner properties have no retention areas after final harvest (SFA 2024). An increased prioritization of border zones for retention could help increase habitat benefits from these conservation actions.

CONCLUSIONS

Our study provided three key findings directly relevant to the allocation and prioritization of retention patches for achieving biodiversity goals in Sweden. First, prioritizing border zones appears to be an effective means of capturing higher proportions of broadleaf trees when selecting areas for retention. This result has direct implications for the selection of retention patches for Swedish forestry. Second, our results indicate that the prioritization of border zones may come with economic benefits. Third, our results highlight issues concerning implementation at landscape scales since border zones are distributed differently among forest properties. This final aspect will become increasingly important for conservation outcomes if larger areas are allocated to retention in the future.

CONFLICTS OF INTEREST

The authors confirm there are no conflicts of interest.

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