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Coarse woody debris legacies and their dynamics in retained forest patches

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ABSTRACT

Retaining trees in small patches at final harvest is a common forest conservation measure to maintain structural and biological diversity through the young forest phase. Long-term studies of coarse woody debris (CWD, breast height diameter ≥ 10 cm) changes in retention patches remain uncommon, especially in relation to different types of patches with varying tree species composition, ground moisture, size, shape, and exposure. In the present study we re-inventoried CWD three times (1–3, 5–7 and 18–20 years after harvesting) in 60 small tree retention patches (0.03–0.54 ha) of six commonly created retention patch types, in central boreal Sweden. Most retention patch types, despite being very small (<0.55 ha) and exposed, did not experience severe tree mortality and input of CWD over the two decades. Average total volumes of CWD did not change significantly over time, although volumes of downed CWD generally increased whilst standing CWD decreased. Volumes of different decay classes were dynamic over time, but all retention types supported a variety of decay stages after 18–20 years. The volume of CWD varied significantly between the six retention patch types, with buffer zones to mire having the lowest average volume of 9 m^3 ha^{-1} and buffer zones to rocky outcrop the highest average volume of 32 m^3 ha^{-1}, when summarised over the whole study period. Very few patch-level environmental variables (except type) related to the amount of CWD in retention patches; only the retained living tree volume of patches during creation was clearly positively correlated with higher post-harvest CWD volumes. Patch characteristics such as size and shape index did not relate to the CWD volumes in retention patches, and patch exposure only related to higher CWD volumes within the first 1–3 years after harvest. Retention patches generally supported a variety of living trees, CWD volumes and qualities over time. Several retention patch types; such as free-standing coniferous and deciduous patches, rocky outcrop buffers, wet forest patches and buffers to water, supported average CWD volumes between 19–41 m^3 ha^{-1} after 18–20 years, under remaining canopy cover. Our findings challenge the traditional management principles aimed at minimizing severe windthrow and CWD input (i.e., creating larger patches (>0.5–1 ha), choosing topographically sheltered areas, selecting specific tree species and ground conditions). However, our study was too small in scale to investigate multiple within-patch-type interacting environmental variables. Future larger-scale studies over extended time periods are needed to disentangle such interactions for the dynamics of CWD and associated biodiversity in retention patches.

1. Introduction

Retaining dead and living trees in small patches at final harvest to benefit biodiversity and ecosystem functioning has become a widespread forest conservation practice (Gustafsson et al., 2012; Gustafsson et al., 2020; Lindenmayer et al., 2012). The motivation is that tree retentions support functional and structural biological legacies of pre-harvest forests, such as large and old trees, continuous tree cover, more diverse tree species compositions, and deadwood (Franklin et al., 2002; Gustafsson et al., 2012; Lindenmayer et al., 2012). Since the introduction of retention forestry in the 1990 s (Franklin et al., 1997; Hunter and Bond, 2001; Gustafsson et al., 2012; Lavoie et al., 2012), regenerating young production forests have been shown to become structurally richer (Kruys et al., 2013; Rosenvald and Lõhmus, 2008). Clearcuts with retained trees have also been shown to support higher richness and abundance of forest-dwelling species than traditional clearcuts, acting as refuges or 'lifeboats' for species that are unlikely to survive in the harvested area (Fedrowitz et al. 2014; Johansson et al. 2018). As such, retention patches may act as important short-term refuges and promote the long-term recovery of the developing adjacent forest biodiversity. Despite widespread use, the effectiveness of retention patches at meeting stated objectives remains poorly understood, also in terms of their long-term legacies and dynamics of CWD amounts and qualities.

Coarse woody debris (CWD, downed and standing deadwood with a diameter ≥ 10 cm) is an important component of many forest ecosystem functions (Harmon et al., 1986) and provides habitat for a tremendously high diversity of wood-inhabiting organisms (Stokland et al., 2012). A large proportion of this diversity of bryophytes, fungi, insects and lichens are red-listed in Fennoscandia, because of the low amounts and qualities of CWD in managed forests (Artdatabanken, 2020). If retention patches are to function as refugia or sources of dispersal for CWD-dependent species into adjacent harvest areas, a large proportion of the retained trees need to survive the exposure in the post-harvest

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environment to ensure a gradual long-term input of CWD together with a continuous presence of living trees (Thorpe and Thomas, 2007; Work et al., 2010; Hallinger et al., 2016). As such, designing retention patches to minimize windthrow is desirable to extend standing tree values before they become downed wood (Jönsson et al., 2007; Steventon, 2011). Retention forestry has been shown to influence the size and input dynamics of CWD over several decades (Jönsson et al., 2007; Hallinger et al., 2016; Farnell et al., 2020). Tree mortality rates may be particularly high in recently exposed forest patches and edges (Esseen, 1994), especially when dominated by wind-sensitive trees like Norway spruce *Picea abies.* This is because high wind velocity, increased solar radiation and temperature, and reduced air humidity, induce significant tree mortality rates and modifications of forest composition, structure and function in recently exposed forest patches and edges (Chen et al., 1992). Still, tree mortality may diminish with time since clearcutting (Jönsson et al., 2007) since the depth and magnitude of edge effects may decrease with the re-growth of the adjacent developing forest and trees acclimating to the new environmental conditions (adapting tree crowns, stem growth and root systems; Holgen et al., 2003; Peterson, 2004; Lariviere et al., 2021). Our understanding of the various conditions and factors that contribute to retention-tree mortality is incomplete, particularly in quantitative terms that could inform effective retention practices. This knowledge gap is partly due to a lack of long-term studies. Experimental studies have surveyed the CWD dynamics in the same retention patches (Jönsson et al., 2007) or retention treatments (Farnell et al., 2020) over several decades, but do not encompass the diverse types of retention patches that are commonly retained during harvest (i.e., in relation to tree species, ground moisture and exposure). The long-term dynamics of CWD of different qualities (tree species, standing vs downed, uprooted i.e., windthown, decay class) in relation to different retention types and environmental variables remain relatively unknown. The dynamics of CWD can differ among tree species, since differences in crown properties, growth form, wood properties, and root system influence interspecific mortality and wood decay rates. A large-scale chronosequence study of tree mortality patterns in conifer-dominated retention patches 1–20 years after clearcutting found that only Scots pine *Pinus sylvestris* trees had a higher cumulative tree mortality with increasing time since clearcutting (Hallinger et al., 2016). However, independent of time since clearcutting, tree mortality rates in retention patches are generally higher for Norway spruce than Scots pine and deciduous tree species (Rosenvald et al., 2008; Lavoie et al., 2012; Hallinger et al., 2016). Tree mortality may also be higher in retention patches with moist ground conditions and patches located in more exposed settings (Hallinger et al., 2016), potentially influencing the dynamics of amount and quality of CWD. Furthermore, stochastic mortality agents such as disease and fire can have unpredictable effects on retention-tree mortality (Rosenvald & Lõhmus, 2023), but remain to be further researched in boreal forest ecosystems.

Although handy for snapshot assessments, chronosequence studies may give limited information on the actual succession taking place over time compared to long-term studies (which are rare) that follow changes at the same place over time (Johnson & Miyanishi 2008, Walker et al.2010). In the present study we re-inventoried three times 60 small tree retention patches (0.03–0.54 ha) of six different types commonly retained in boreal Sweden, to evaluate changes in CWD amount and quality occurring over a longer time period of 20 years since creation and harvesting. The retention types surveyed were (i) spruce/pine dominated buffer zone to open mire, (ii) pine-dominated buffer zone to rocky outcrop, (iii) spruce-dominated buffer zone to stream or lake, (iv) free standing tree group dominated by spruce or pine, (v) free standing tree group dominated by deciduous trees, and (vi) moist-wet paludified forest patches, with roughly equal amounts of spruce, pine and deciduous trees. The first objective of the study was *temporal*, to test if any changes in CWD volume of different qualities (tree species, decay class, downed versus standing, and uprooted windthrown), occurred over time (1–3, 5–7, and 18–20 years after their exposure by clearcutting) in the different retention patch types. We hypothesised that the different retention patch types would fulfil their objective of supporting (life-boating) CWD amount and quality, with the majority of the set-aside living trees not dying (e.g., through windthrow), within the first two decades after clearcutting. We supported our hypothesis with the fairly even cumulative tree mortality reported from the 20 year chronosequence study of 583 retention tree groups (mostly conifer dominated) on clearcuts in central Sweden (Hallinger et al., 2016). However, to what extent this would apply to the different retention patch types and detailed repeated inventories *per retention patch* of CWD volumes and densities in our study, remained an open research question. Higher tree mortality on moister grounds (Hautala and Vanha-Majamaa, 2006; Lavoie et al., 2012; Hallinger et al., 2016) could lead to higher CWD volumes in moist-associated retention patch types, although such relationships will also be modulated by local tree characteristics and adaptations. The second objective was *environmental contextual*, to test how CWD volumes in each survey year 2001, 2006 and 2019 correlated with patch-level environmental variables (e.g., retained living tree volumes, thinnings, patch exposure, shape, and size) considering all retention types pooled. Our hypothesis was that CWD volumes per area unit would be higher in smaller patches, associated with lower living tree volumes and more extensive thinnings, and situated in more open and exposed environmental settings. We motivate this with reports of higher tree mortality rates in smaller patches (Jönsson et al., 2007; Steventon, 2011; Hallinger et al., 2016), and in more exposed positions (Jönsson et al., 2007; Steventon, 2011; Hallinger et al., 2016). However, contrasting results of no effect from exposure and retention patch size, have also been reported from grouped retention in Canada (Lavoie et al., 2012), making this a relatively open research question that need more research support. Our expectation of reduced tree mortality rates, and subsequent lower CWD amounts, in patches with higher initial living tree volume or density is based on earlier studies indicating this pattern (Scott and Mitchell, 2005; Steventon, 2011; Hallinger et al., 2016).

2. Materials and methods

2.1. Study region and types of retention patches

The study was carried out in a managed boreal forest region of ca 80 × 70 km in central Sweden (62°30′N, 17°15′E). Tree species Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) dominate in the region, with mixtures of birch (*Betula* spp.) and aspen (*Populus tremula*) as subordinate species. The landscape is composed of managed forests (85 % of land area) fragmented by lakes, open mires (10 % of land area), cultivated land, roads and sparse settlements. Forest fires have been effectively suppressed in the region since the 1900 s (Jönsson et al., 2009); thus, current disturbance agents include windstorms, fungi and/or insect outbreaks (Jönsson et al., 2011).

A total of 60 retention patches distributed over 45 harvested areas (average size ca 10 ha, supplementary material Fig. A.1) were included in the study, ranging in size from 0.03 to 0.54 ha. Retention patches had > 650 stems per ha with diameter at breast height > 8 cm and were classified into six main types. The most abundant type was spruce/pine dominated buffer zone to open or forested mire on mesic-moist (n = 14) or moist (n = 2) ground conditions, characterised by *Vaccinium myrtillus* and *Vaccinium vitis-idaea* in the understory field layer (hereafter 'mire buffeŕ; 16 patches on 10 harvested areas). This patch type is commonly retained in boreal forest regions of Sweden. Pine-dominated buffer zone to rocky outcrop on mesic (n = 8) or dry (n = 3) shallow soils with *V. myrtillus* and *V. vitis-idaea* in the understory field layer ('rocky outcrop buffer'; 11 patches on 7 areas). Spruce-dominated buffer zone to stream or lake on mesic (n = 8), mesic-moist (n = 2) or wet (n = 1) ground conditions with *V. myrtillus*, *V. vitis-idaea*, taller herbaceous plants, grasses and some *Equisetum* in the field layer ('water buffer'; 11 patches on 9 areas). Free-standing tree group on clearcut dominated by spruce or pine on mesic ground conditions with *V. myrtillus* ('free-standing coniferous'; 8 patches on 8 areas). Free-standing tree group on clearcut dominated by deciduous trees (mostly *Populus tremula* and *Alnus incana*) on mesic (n = 6) and mesic-moist (n = 2) ground conditions where half of the stands were characterised by *V. myrtillus* and half with herbaceous plants and grasses in the field layer ('free-standing deciduous'; 8 patches on 5 areas). The final patch type with roughly equal amounts of spruce, pine and deciduous trees, occurred on mesic-moist (n = 3), moist (n = 2) or wet (n = 1) ground conditions with *Equisetum*, *Carex*, *V. myrtillus*, and *V. vitis-idaea* in the field layer ('wet forest'; 6 patches on 6 areas). Retention patches situated on the same harvested area were generally of different type and size, and situated on different parts of the harvested area.

2.2. Coarse woody debris

The first survey of CWD was conducted in year 2001 shortly (1–3 years) after harvest and repeated after five years in 2006 and again after 18 years in 2019. During the two initial surveys CWD was inventoried throughout the whole retention patches. In the third inventory CWD was sub-sampled in 20 m wide transects covering a minimum of 50 % of the patch area (mean 69 % and median 62 %). To avoid subjectivity in transect placement, we used a-priori mapped North-South transects in a field computer where we simply let the first transect cross the approximate geographical centres of each retention patch. A second and sometimes a third transect, depending on patch size and shape, was thereafter randomly established at approximate regular spacing between the centre transect and the edge of the retention patch (with a minimum distance of 40 m to the centre transect). We always surveyed full transect lengths to edges, but did not establish new additional transects if the inventoried transect area exceeded 50 % of the patch area. For four elongated and narrow buffer zones to mire or water we established East-West transects, since 20 m wide transects did not fit in the North-South direction. All CWD units were georeferenced within transects in the 2019 survey.

All standing (snags and high stumps) and fallen (logs or large branches) dead trees with a diameter ≥ 10 cm at breast height (1.3 m from tree base) and height or length ≥ 1.3 m that originated within the patch area (edges were georeferenced and marked by plastic bands in 2001 and 2006) or transects were inventoried. Parts of the stem or branches whose sprouting point could not be estimated were included if more than half of the part that was thicker than 10 cm lies inside the area or transect. A tree was considered dead when missing living needles, leaves or buds. For downed and standing multi-stemmed CWD, all stems that branched below breast height were measured as individual CWD items. For each downed log we recorded the length of the log up to a small-end diameter of 10 cm, as well as the mid-length diameter of the log, tree species, and decay class. We used the four-class decay system of the Swedish National Forest Inventory method; with class 1 being least decayed hard wood (>90 % of the stem volume consists of hard wood, very little affected by decomposing organisms), 2 = slightly decomposed (10–25 % of the stem volume consists of soft wood), 3 = decomposed (26–75 % of the stem volume consists of soft wood), and class 4 = very decomposed wood (76–100 % of the stem volume consists of soft wood). We calculated the volume of logs applying the formula for volume of a cylinder, $V = \pi \times (d/2)^2 \times h$, where V is the log's volume, d is the mid-length diameter of the log and h is its length. The volume measure is a rough estimate, and using the mid-length diameter approximates a truncated cone shape, assuming an equal tapering angle of all tree species. For all logs in year 2006 and 2019 we also recorded approximately how the tree died, summarised in this study as uprooted windthrown trees. We also noted butt- and stem-breakages, but for these types mortality cause (i.e., wind) was more difficult to determine. For high stumps with a diameter at breast height ≥ 10 cm and height ≤ 6 m, we measured tree species, diameter at mid height, and full height. We calculated the volume as a cylinder, in the same way as for logs. For snags with a diameter at breast height ≥ 10 cm and a height > 6 m we recorded tree species, diameter at breast height, and height (i.e., estimated from local height functions to a top diameter of 10 cm from subsampled living trees in 2001 and measured for all trees in 2006 and 2019). We calculated the volume of snags (with a truncated top at estimated 10 cm diameter) using functions by Brandel (1990) for spruce, pine and birch (we used the birch formula for all deciduous tree species) adapted to the regional latitude and trees taller than 6 m.

We calculated CWD volume estimates per hectare for each retention patch and survey year, for deciduous trees, Norway spruce, Scots pine, summarised for all tree species, standing high stumps and snags, downed logs, four log decay classes, and for uprooted windthrown trees in year 2006 and 2019.

2.3. Environmental variables

In addition to the study year, we used six explanatory environmental variables in our analyses representing the retention conditions at the onset in 2001 (i) patch size, (ii) shape index of forest patch (ratio between patch perimeter and perimeter of a perfect circle of the same area, where a higher value means a more irregularly shaped patch; Bastin and Thomas, 1999), (iii) living tree volume per hectare after thinning, (iv) thinned volume per hectare, (v) area of open land within 100 m of the retention patch, and (vi) the general exposure/shelter of the patch. Retention patch sizes, shape index, and areas of open land within 100 m (e.g., visually interpreted from aerial images to be relatively recent clearcut areas approximately < 20 years since harvest, agricultural fields, roads) were calculated using geospatial analyses and aerial imagery from 2001 (Perhans et al., 2009). The living tree volume in 2001 was calculated based on field measurements of all trees with a diameter at breast height > 8 cm (Perhans et al., 2011). All stumps in patches were measured (cross-calipered for diameters) and used to estimate thinned volumes in connection with the final felling. Stump diameters were used to estimate breast height diameters following Ager et al. (1964), and local height functions from subsampled living trees in 2001 and volume functions by Brandel (1990) were used to estimate tree volumes. The 2001 exposure of patches to wind was estimated on a binomial scale: retention patches were classified as *exposed* if they were situated on a hill or on flat land and far (>50 m) from adjacent closed forest or *sheltered* if they were situated in a depression or on flat land within short distance (<50 m) from the nearest closed forest (following Hallinger et al., 2016). Table 1 provides a summary of the environmental variables across different retention patch types. We also added the average diameter at breast height of standing dead CWD in 2001 in Table 1.

2.4. Statistical analyses

2.4.1. CWD volumes and qualities over time in different retention types

Statistical analyses were performed in R version 4.03 (R Development Core Team, 2021). We modelled the effect of retention type and time (years post-harvest) on the volume for various tree species, decay classes, downed and standing, and uprooted CWD, using linear mixed effects models with the "lmerTest" package v. 3.1, providing p values for type II Anova and summary tables (Kuznetsova et al., 2017) using the Kenward–Roger degrees-of-freedom method. The fixed effects were retention type (mire buffer, with lowest average CWD volume, as reference), survey year (year 2001 as reference), and the retention type × year interaction. Retention patch identity was included as a random factor (i.e., random intercept per patch), to account for repeated surveys over time in patches and possible variation associated with site-based spatial correlations. Volumes and densities for all CWD fractions were ln-transformed (plus 0.1 times the lowest volume to avoid zero values) in order to meet the model assumptions. We checked the model diagnostics with the *Performance* and *DHARMa* packages in R (Hartig, 2021; Lüdecke et al., 2021). In order to obtain good model fit, we analysed volumes of merged "hard CWD" (decay class 1 and 2) and "soft

Table 1
Summary table of mean and standard deviations in parentheses of all environmental variables and percentage of CWD volumes of the living tree volume retained in 2001, for each retention patch type studied. Also included is the mean diameter and standard deviations at breast height (dbh, cm) of standing CWD in 2001. F. coniferous = free-standing coniferous and F. decidious = free-standing deciduous.

Retention patch type	Patch size (ha)	Shape index	Living tree volume (m^3 ha^{-1})	Thinned volume (m^3 ha^{-1})	Open area (ha)	Exposed (% of patches)	CWD/Living tree volume*	Dbh, standing CWD
Free-standing coniferous	0.12 (0.08)	1.30 (0.12)	117.31 (45.93)	18.94 (13.57)	2.48 (0.67)	100	21.27 (33.36)	17.4 (8.7)
Free-standing deciduous	0.06 (0.02)	1.29 (0.14)	194.29 (137.85)	52.95 (33.45)	1.95 (0.92)	75	13.64 (12.73)	13.6 (5.5)
Mire buffer	0.15 (0.09)	2.56 (0.66)	112.64 (38.89)	22.32 (22.24)	1.57 (0.79)	25	8.69 (8.10)	15.1 (5.3)
Rocky outcrop buffer	0.15 (0.11)	1.50 (0.36)	172.47 (73.64)	6.86 (8.47)	1.93 (0.97)	91	22.20 (19.01)	16.3 (5.5)
Water buffer	0.20 (0.13)	2.10 (0.69)	138.27 (52.03)	34.88 (20.17)	1.43 (0.47)	73	15.57 (14.43)	15.2 (4.9)
Wet forest	0.07 (0.04)	1.26 (0.13)	138.22 (17.70)	42.46 (44.23)	2.20 (0.54)	50	22.04 (16.96)	15.3 (6.2)

* Percentage based on CWD year 2001, 2006 and 2019, and living tree volumes retained and measured at onset in year 2001.

CWD” (class 3–4) and dropped the type × year interaction term in these two models. Nonetheless, we plot the decay-class distribution for all four decay classes and provide average values (supplementary Table A.1).

2.4.2. CWD volumes and patch-level environmental variables

To test for patch-level environmental variables effects on CWD volumes in post-harvest patches in 2001, 2006 and 2019, respectively, we used three linear models with patch size, shape index, living tree volume per hectare, thinned volume per hectare, area of open land within 100 m of the retention patch, and the general exposure/shelter of the patch as fixed effects. We analysed all retention types pooled (n = 60), due to relatively few patches of each retention type. None of the continuous explanatory variables correlated (Pearson’s r < 0.6) so we kept all the variables in the models (Dormann et al., 2013). The CWD volumes were ln-transformed (plus 0.1 times the lowest volume). We scaled all continuous explanatory variables by subtracting the mean and dividing by the standard deviation in order to obtain comparable standardized coefficients. We checked the model diagnostics with the Performance and DHARMa packages in R (Hartig, 2021; Lüdecke et al., 2021) and plotted regression outputs (standardized coefficients) with the dot-whisker package (Solt et al., 2022).

3. Results

3.1. Amount of total CWD through time

The total average volume of CWD per ha did not icrease over time in retention patches, independent of retention patch type (Fig. 1, Table 2). CWD volumes differed between retention types (Table 2, see supplementary material for a summary table of volumes Table A.1 and full model output Table A.2) and was on average higher in rocky outcrop buffers (41.4 m^3 ha^{-1} in 2019, significant Table A.2) and lowest in mire buffers (8.3 m^3 ha^{-1} in 2019). One water buffer retention patch had exceptionally high CWD volumes.

3.2. Amount of CWD of different tree species through time

The amount of CWD of different tree species did not increase over time in retention patch types (supplementary file Appendix A.3 and Fig. A.3, Table 2). The only exception was Norway spruce CWD volumes which were significantly higher by 2019 in free-standing coniferous patches (p = 0.037, Table A.2). Wet forest (p = 0.045) and water buffer (near significant p = 0.098) retention patches had the greatest amount

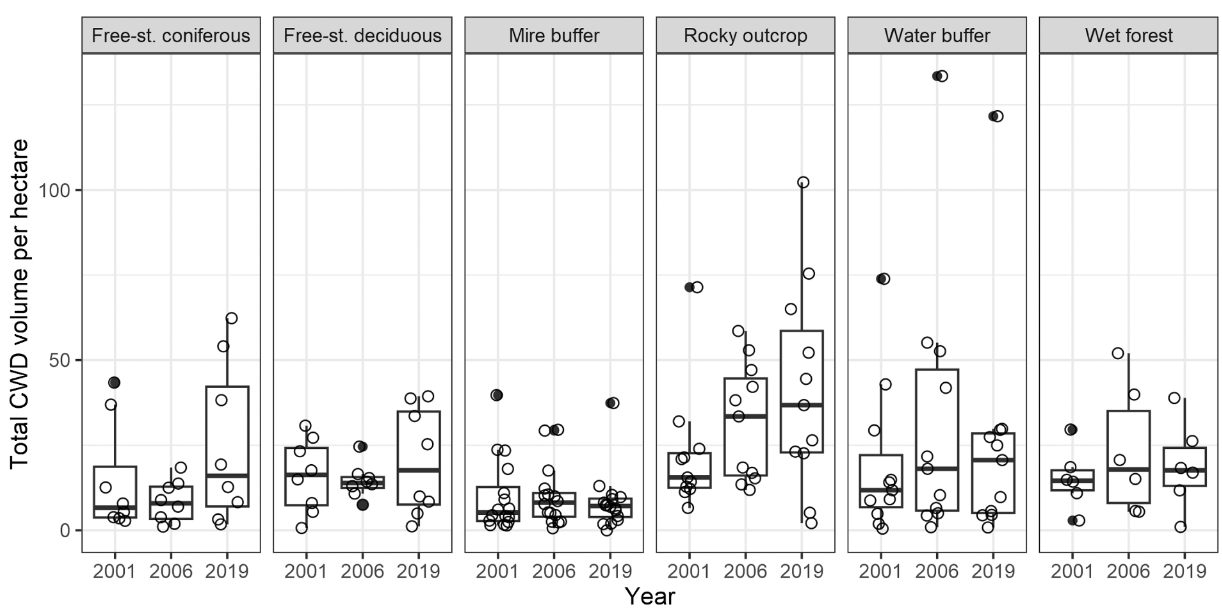

Fig. 1. The CWD volumes per hectare across survey years for the six different types of retention patches. In the box plots, the boundaries of the box represent the lower and upper quartiles, the black line within the box marks the median, whiskers show the range (largest respective smallest value within 1.5 times the inter-quartile range), and black dots are outliers. Raw data as jittered open points.

Table 2
Type II Analysis of Variance Table with Kenward-Roger method of linear mixed effects models (F stat, numerator (ndf) and denominator (ddf), degrees of freedom, and P value), for CWD volumes (m^3ha^{-1}) of different tree characteristics and total CWD density (CWD units ha^{-1}). The model's total explanatory power was substantial (most conditional $R^2 > 0.60$) and the part related to the fixed effects alone (type and year, marginal R^2) ranged between 0.15 and 0.30. For regression outputs for individual retention types and years see supplementary Tables A.2. Significant variables are marked in bold. N = 180.

Response variable	Years post-harvest	Factor	F [ndf, ddf]	*P*	Marginal R^2	Conditional R^2
All tree species	1–3, 5–7, 18–20	Retention type	3.3 [5,54]	**0.011**	0.19	0.66
		Year	1.7 [2,108]	0.182		
		Retention type × Year	1.0 [10,108]	0.444		
Norway spruce	1–3, 5–7, 18–20	Retention type	3.2 [5,54]	**0.013**	0.18	0.65
		Year	2.4 [2,108]	0.100		
		Retention type × Year	0.9 [10,108]	0.500		
Scots pine	1–3, 5–7, 18–20	Retention type	4.1 [5,54]	**0.003**	0.22	0.67
		Year	0.0 [2,108]	0.981		
		Retention type × Year	1.6 [10,108]	0.130		
Deciduous	1–3, 5–7, 18–20	Retention type	3.4 [5,54]	**0.010**	0.18	0.61
		Year	2.0 [2,108]	0.138		
		Retention type × Year	0.7 [10,108]	0.712		
Decay early	1–3, 5–7, 18–20	Retention type	15.1 [5,54]	**0.002**	0.21	0.46
		Year	9.8 [2,108]	**0.000**		
Decay late	1–3, 5–7, 18–20	Retention type	5.0 [5,54]	**0.018**	0.20	0.67
		Year	9.8 [2,108]	**0.000**		
Standing	1–3, 5–7, 18–20	Retention type	1.8 [5,54]	0.124	0.19	0.46
		Year	16.2 [2,108]	**0.000**		
		Retention type × Year	0.8 [10,108]	0.618		
Downed	1–3, 5–7, 18–20	Retention type	3.5 [5,54]	**0.009**	0.24	0.69
		Year	17.3 [2,108]	**0.000**		
		Retention type × Year	0.6 [10,108]	0.182		
Uprooted	5–7, 18–20	Retention type	3.8 [5,54]	**0.005**	0.22	0.69
		Year	2.4 [1,53]	0.129		
		Retention type × Year	1.4 [5,54]	0.237		
CWD density Number /ha	1–3, 5–7, 18–20	Retention type	3.2 [5,54]	**0.013**	0.20	0.68
		Year	5.5 [2,108]	**0.005**		
		Retention type × Year	1.3 [10,108]	0.240		

of deciduous CWD, whilst rocky outcrop buffers had the greatest amounts of Norway spruce (p = 0.021) and Scots pine (p = 0.026) CWD. All retention patch types maintained both deciduous and coniferous CWD volumes over time.

3.3. Amount of standing and downed CWD through time

The volume downed CWD generally increased in retention patches over time, and especially in rocky outcrop buffers (Fig. 2, Table 2, and Table A.2). In contrast, the volume of standing CWD decreased in retention patches by year 2019 (p = 0.047).

3.4. Amount of CWD decay classes through time

The average volume of hard and soft CWD depended on both retention type and year (Fig. 3, Table 2, and Table A.2). Particularly volumes of fresh hard CWD was higher in most retention types compared with mire buffers, and were generally higher in 2019 compared to 2001 (p = 0.000). Volumes of more decayed soft CWD were higher in rocky outcrops (p = 0.000) and water buffers (p = 0.011), and were generally

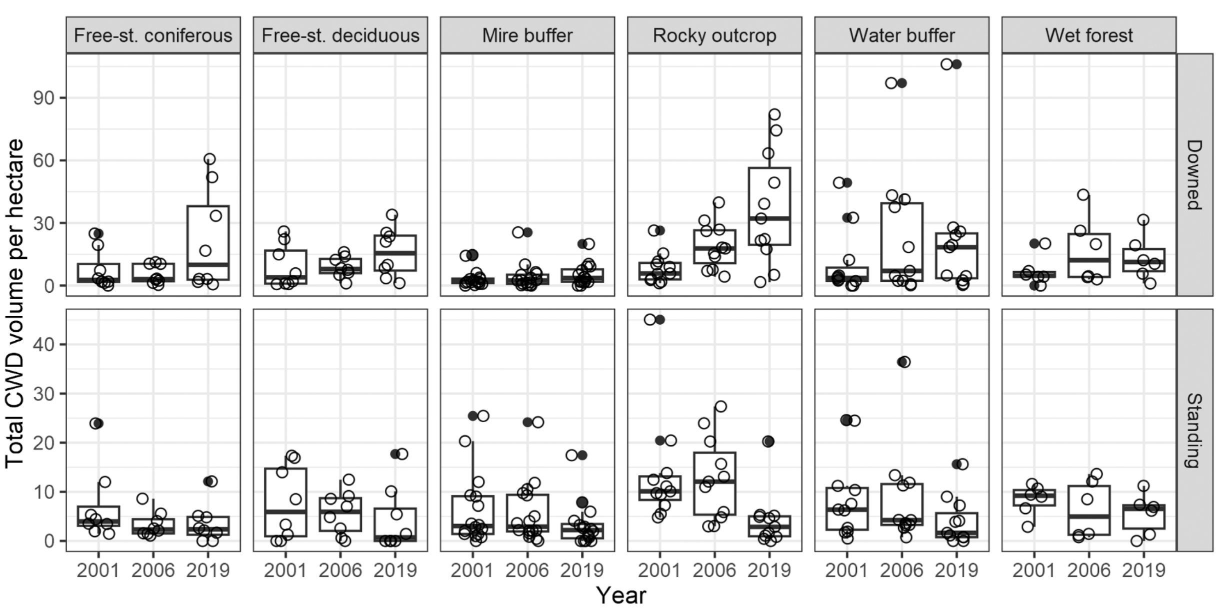

Fig. 2. The CWD volume per hectare of downed and standing CWD, across post-harvest survey years for the six different types of retention patches. Volumes as boxplots with the medians, quartiles, range and outliers. Raw data as jittered open points. Note differences in y-axis scaling.

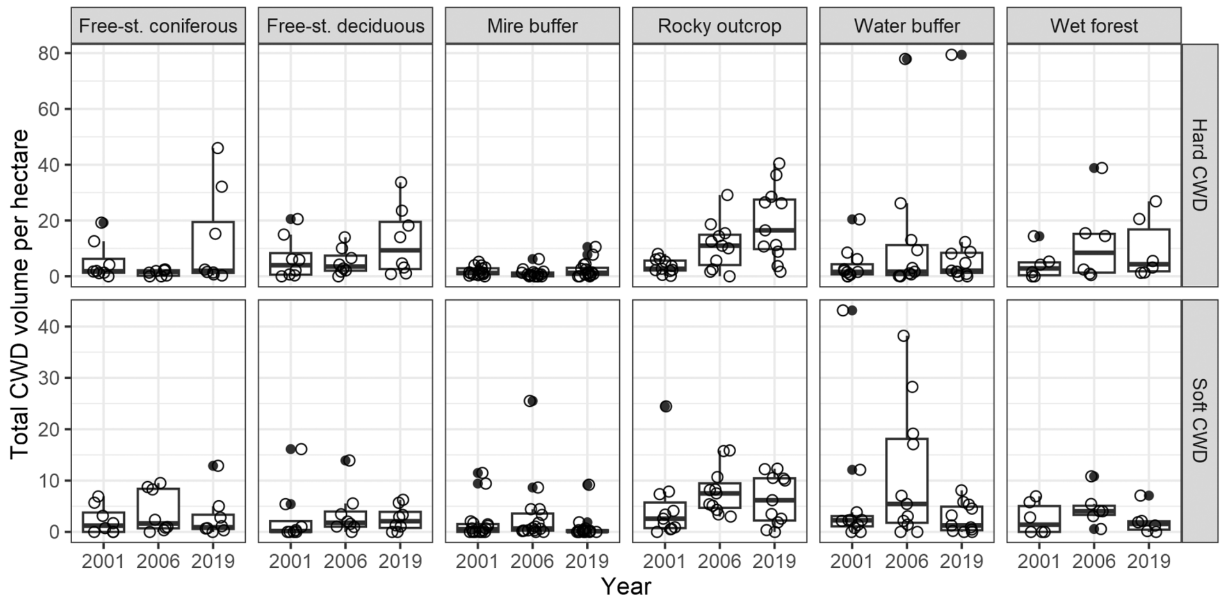

Fig. 3. The volume per hectare of hard (decay class 1–2) and soft (decay class 3–4) CWD, across post-harvest survey years for the six different types of retention patches. Volumes as boxplots with the medians, quartiles, range and outliers. Raw data as jittered open points. Note differences in y-axis scaling.

higher in 2006 ($p = 0.000$) but lower again in 2019. The temporal trends varied between retention patch types (Fig. 3), but we were not able to fit models to analyse such interactions. All retention types generally had some amount of CWD in all four decay classes after 18–20 years (Fig. 4). From the total volume of CWD, however, the proportion of fresh decay class 1 wood was generally lower in 2006 and the proportion of very decomposed decay class 4 wood decreased over time (Fig. 4).

3.5. Amount of uprooted (windthrown) CWD in 2006 and 2019

The volume of uprooted CWD did not differ between 5 and 7 years and 18–20 years after harvest for retention patch types (Fig. 5, Table 2). Only free-standing coniferous stands on average had near significantly higher volumes of uprooted trees in 2019 compared to 2006 ($p = 0.052$, Table A.2). CWD volumes of uprooted trees differed between retention types and was on average highest in rocky outcrops ($p = 0.001$, 24.3 m^3 ha^{-1} in 2019), water buffers ($p = 0.005$), wet forests ($p = 0.033$), compared with the lowest volumes in mire buffers (1.5 m^3 ha^{-1} in 2019).

3.6. Densities of CWD through time

The number of CWD units per ha differed among retention patch types (higher in rocky outcrops; $p = 0.029$) and increased with years' post-harvest in wet forests in 2006 ($p = 0.032$) and water buffers in 2019 ($p = 0.330$) (Fig. 6, Table 2, and Table A.1). However, whilst the number of CWD units increased in wet forests and water buffers, we note that this did not lead to a significant increase in average CWD volumes (Fig. 1 and Table A.2). This may be because a greater proportion among small trees than large trees died in the long term in these retention types. In wet forests, the average volume of individual CWD was 0.11 m^3 in 2001, 0.08 m^3 in 2006, and 0.09 m^3 in 2019. In water buffers, the average volume of individual CWD was 0.13 m^3 in 2001 and 2006, but 0.09 m^3 in 2019. The highest average CWD densities were measured in water buffers in 2019 (242 ha^{-1}, Table A.1) and lowest in free-standing coniferous and mire buffers in 2006 (96 ha^{-1}).

3.7. Amount of CWD and patch-level environmental variables

Generally, there were weak relationships with patch-level

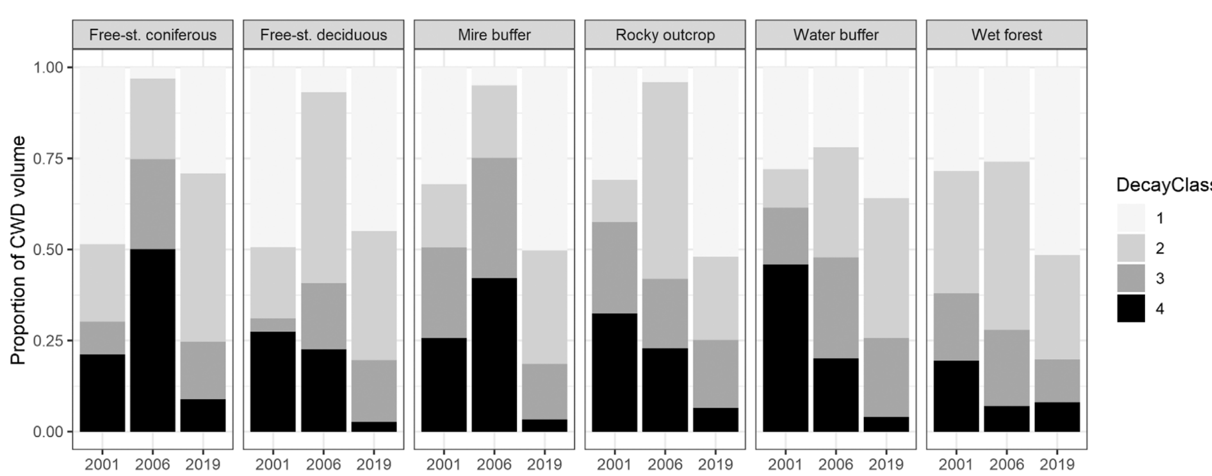

Fig. 4. The proportion of the CWD volume per hectare of decay class 1–4, across post-harvest survey years for the six different types of retention patches.

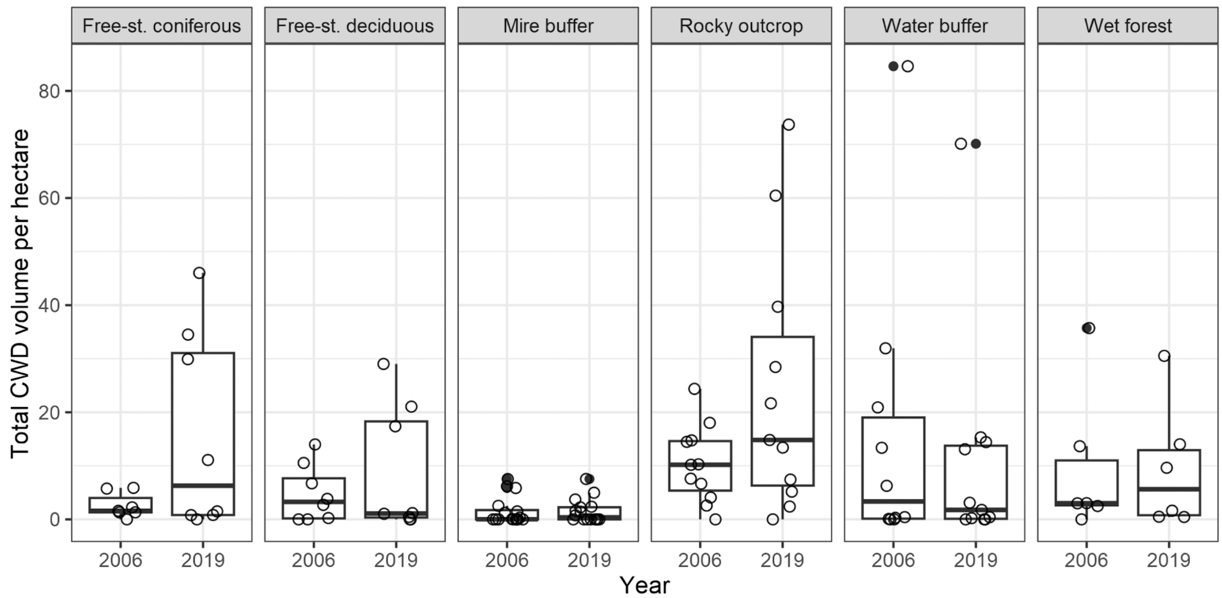

Fig. 5. The CWD volume per hectare of uprooted CWD after 5–7 years in 2006 and 18–20 years in 2019, for the six different retention patch types. Volumes as boxplots with the medians, quartiles, range and outliers.

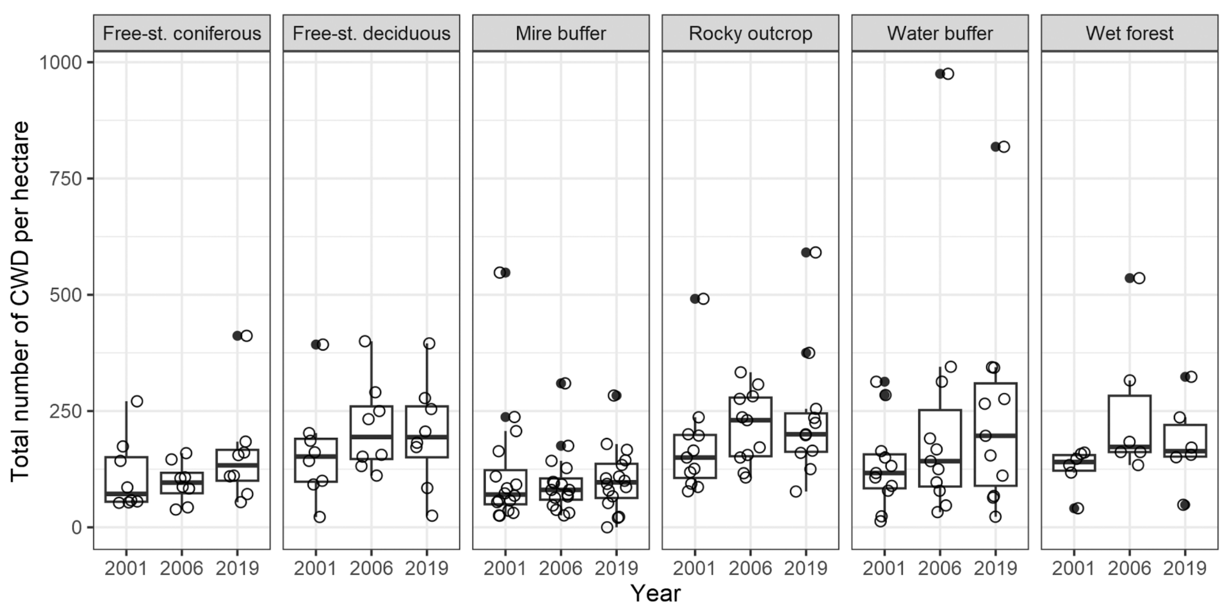

Fig. 6. The number of CWD units per hectare over time, for the six different retention patch types. Volumes as boxplots with the medians, quartiles, range and outliers. Raw data as jittered open points.

environmental variables and the amount of CWD in retention patches in different years (Fig. 7, supplementary material Table A.3, adjusted R^2 values < 0.2). The only clearly significant variable was the living tree volume of the retention groups in 2001, having a positive relationship with the short- and long-term CWD volume of retention patches. Retention patches in exposed locations had higher CWD volumes within the first 1–3 years after harvest in 2001, but not in the longer term.

In 2001, the CWD volumes comprised on average 13 % of the volumes of retained living trees of retention patches, considering all retention types. We did not have access to data on living tree volumes of retention patches in 2006 and 2019, but the CWD volumes in both years comprised on average 16 % of the retained living tree volumes in 2001 (see data for individual retention types in Table 1). Hence, the retention patches generally maintained substantial living tree cover over almost two decades, and<7 % of all retention patches had CWD volumes > 50 % of the original living tree volumes.

4. Discussion

In agreement with our temporal hypothesis, we found that retention patches effectively achieved and retained substantial CWD volumes over two decades, without severe or stand-replacing windthrow or die-off of the set-aside living trees in patches. After 20 years, only a very small percentage of patches had total CWD volumes > 50 % of the retained living tree volumes and volumes of uprooted windthrown CWD was moderate (on average 49 % of volumes). Coarse woody debris volumes varied with the retention patch type (mean 8–41 m^3 ha^{-1} in 2019) and volume of living trees retained in patches. The total and uprooted volumes were highest in rocky outcrop buffers (mean 41 respective 24 m^3 ha^{-1} in 2019) and free-standing coniferous patches (total mean volumes

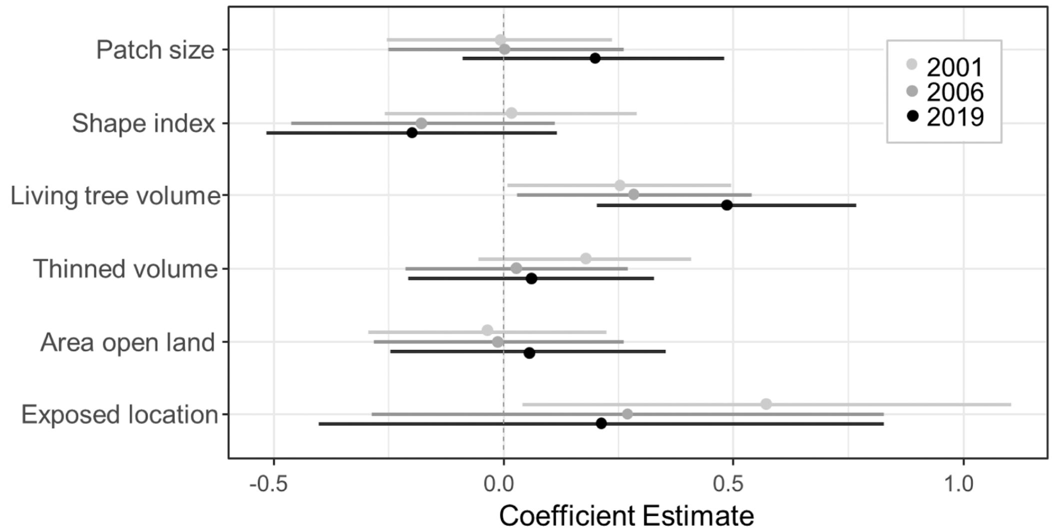

Fig. 7. Standardized coefficient estimates as dots and 95 % confidence intervals as whiskers for models of total CWD volumes in year 2001, 2006 and 2019, respectively. Insignificant parameter estimates are those with confidence intervals overlapping zero.

25 m^3 ha^{-1} in 2019 and uprooted mean volumes increasing from 2 to 16 m^3 ha^{-1} between 2006 and 2019). For these two patch types, the mean *total* CWD volume increased by 11 respective 19 m^3 ha^{-1} over 20 years. Retention patches were diverse in CWD characteristics and thus effective at retaining structural elements not otherwise present in the harvested areas. In disagreement with our broader environmental context hypotheses, however, environmental variables such as patch shape, size, exposure and area of open land in the surrounding did not relate substantially to CWD volumes in retention patches. The CWD volumes were only significantly higher in exposed patches 1–3 years after harvest, but not over the longer term. We discuss the individual results and their implications for forest management and conservation in more detail below.

4.1. Coarse woody debris amounts

We did not detect severe temporal changes in total CWD volumes, but the results of CWD amount for different retention patch types form a first small-scale study that can inform retention forestry planning and future research. The average CWD volume across all retention patch types was 22 m^3 ha^{-1} in 2019, which is higher than the average CWD volumes of the forest land in the region. Swedish National Forest Inventory estimates from the county of our study, Västernorrland, from 2016 to 2020 show that the forestland on average hosts CWD volumes of 14 m^3 ha^{-1} and slightly higher average volumes of 16 m^3 ha^{-1} in formally protected forests (SLU, 2021). However, on productive forest land in Västernorrland County the oldest forest management class "mature forest" on average hosted 27 m^3 ha^{-1} in year 2019 (SLU online source https://www.taxwebb.slu.se, accessed on 220914). Retention patches supported CWD amounts in parity with one earlier study of Norway spruce retention patches in Sweden (25 m^3 ha^{-1}; Djupström et al., 2008). Although the CWD volume in retention patches varied substantially between different retention patch types, all types except mire buffers, had average CWD volumes > 19 m^3 ha^{-1} in 2019. The results that mire buffers had lower levels of CWD is not surprising, given that these low-productivity forested mires are known to support lower amount and diversity of CWD (Hämäläinen, et al., 2018; Jönsson and Snäll, 2020; Kyaschenko et al., 2022). However, it should be noted that our study did not consider fine woody debris, which may have higher densities and volumes in mire buffers compared to other patch types. Although we used the same size criteria and decay class system for CWD as the Swedish NFI, there may still be biases in our comparisons due to differences in methods and volume calculations. Given that our data was collected from a limited number of patches and small sampling areas, volume calculations and scaling to hectare could potentially bias the data and comparisons with NFI data. Thus, comparisons should be viewed cautiously as approximate differences in CWD amounts. We also observed high among-patch variability in CWD volumes in several patch types, partly due to a few wind-affected stands with very high CWD amounts (e.g., one water buffer). Our conditional and marginal R^2 values indicated that a significant portion of the variation could be explained by the site-specific random effect, in addition to patch type and time since harvest. Therefore, there are likely other influential environmental variables within patch types, such as patch size, exposition, and moisture, which our small dataset was unable to investigate. Larger-scale studies in the future will be needed to identify such variables. In terms of the time component and CWD variability, subsampling in transects in 2019 may have influenced our results, particularly if a smaller proportion of "edge habitat" was surveyed in 2019 compared to previous survey years. However, we estimated that this bias in edge influence was relatively small, given the small size of patches and extensive (>60%) sampling in multiple transects. All substrates were georeferenced in 2019, and future studies could potentially examine such edge influences in relation to aspect and wind direction in retention patches.

4.2. Coarse woody debris qualities

Our results showed that retention patches supported a diversity of CWD qualities relating to tree species, decay class, position (i.e. standing and downed CWD), and tree mortality agent (i.e. windthrow). Thus they were effective at retaining a range of structural elements, which have been shown to be lacking in clearcut regenerating forest areas (Hautala et al., 2004). We did not analyze the number of deadwood types per se, but Djupström et al. (2008) found that the rarefied number of dead wood types in Norway spruce retention patches was comparable to old managed forests, although significantly lower than in reserves and key habitats. Naturally, it is easier to retain a mixture of tree species, sizes and conditions in larger areas (Franklin et al., 1997), but our study shows that even small and exposed retention patches were able to maintain volumes of a variety of CWD qualities long-term.

The CWD volume of different tree species varied between them and among retention patch types, but mostly did not change significantly over time. The average volume of Norway spruce CWD, however, increased over time in free-standing coniferous forests. Norway spruce has previously been reported as the tree species with the highest tree mortality in boreal forest fragments (e.g., Jönsson et al., 2007; Hallinger et al., 2016), where it is prone to uprooting due to its shallow root system (Hautala and Vanha-Majamaa, 2006). We did not detect severe tree mortality and windthrow of spruce in parity with Jönsson et al. (2007), and instead our results were more in line with studies showing slightly elevated tree mortality of spruce (e.g., Hallinger et al., 2016) and subsequent slightly elevated CWD input. The total average volumes of CWD of Scots pine and deciduous trees did not change over time, in agreement with Hallinger et al. (2016) showing that these tree species are more resistant than Norway spruce to elevated exposure- and wind-induced tree mortality within the first decades after clearcutting and retention.

The volume of CWD of different decay classes related to both retention patch type and time since harvest. We found an increase in hard CWD with time since harvest, whilst soft CWD initially increased in 2006 but decreased back to 2001 levels again in 2019. In terms of soft CWD volumes, including the relatively low and decreasing proportion of very decayed class 4 CWD in 2019 (on average 9 % of the CWD volume), such moist and decayed CWD will peak later with continued decomposition of hard CWD and increasing shelter (i.e. reduced edge effects) from the regenerating surrounding stand. The decreasing proportion of very decayed wood highlight that qualitative changes in CWD occur in retention patches over time, and further research is needed to understand the importance of such changes for the life-boating of saproxylic species. Falling snags will comprise an important input of soft CWD over time (e.g., Jönsson et al., 2007; Lõhmus et al., 2013).

The volume of downed CWD increased over time, especially in rocky outcrop buffers, whereas the volume of standing CWD decreased over time and generally did not differ between retention patch types. These opposing trends meant that the total average volume of CWD in retention patches did not change significantly over time. Earlier studies have not examined changes in volume of accumulated CWD in retention patches over time, but have shown that large and tall trees (especially spruce) are more prone to become uprooted or windthrown (i.e., downed deadwood) (Jönsson et al., 2007; Hallinger et al., 2016). The elevated death and uprooting of large trees in retention patches, although much less severe in our study and Hallinger et al. (2016) than Jönsson et al. (2007), generally agree with the accumulation of downed CWD over time in our study (i.e., deadwood input of downed deadwood surpassing decomposition rates). Our results that the volume of standing CWD decreases over time is likely related to the falling of snags over time (e.g., Lõhmus et al., 2013).

4.3. Uprooted windthrown coarse woody debris

Volumes of uprooted windthrown CWD was higher in certain retention patch types, but was only shown to increase in free-standing coniferous types between 2006 and 2019. Higher levels of tree mortality often occur in the first few years after clearcut harvest when trees are not yet adapted to the abrupt change in environmental conditions (Beese et al., 2003; Scott and Mitchell, 2005; Jönsson et al., 2007). Exposed patches had higher average total volumes of CWD in 2001, which suggest elevated wind-induced tree mortality may have been more influential shortly after harvest. However, we could not investigate this since we did not register uprooted wind-induced mortality in 2001. Local windstorms have historically created landscape-level synchronous pulses in CWD input in boreal forest fragments in the region (Jönsson et al., 2011). The increasing amounts of uprooted CWD in free-standing coniferous forests between 2006 and 2019 could be explained by two severe windstorms that occurred in the region during the winter 2011 (storm Dagmar) and 2013 (storm Ivar). At the same time, these strong winter storms could have been expected to cause even more extreme uprooting in small and exposed patches. Jönsson et al. (2007) showed that a local wind storm generated a total CWD volume input of 132 m^3 ha^{-1} during an 18-year period in small Norway spruce patches.

4.4. Coarse woody debris and patch-level environmental variables

The volume of retained living trees in patches at final felling was the only environmental variable positively related to CWD amounts over time. Similar to our study, Moussaoui et al. (2016b) showed that boreal black spruce forest patches with higher initial stand volume (>60 m^3 ha^{-1}) generated more deadwood volume over time. Our results collectively contradict our postulated hypothesis that reduced tree mortality rates in patches with higher initial living tree volume or density (sensu Scott and Mitchell, 2005; Steventon, 2011; Hallinger et al., 2016) would result in lower CWD amounts. The volume of thinned trees within patches did not significantly influence CWD amounts in patches, but there was a tendency for a more positive effect on CWD amounts 1–3 years after harvest, compared to later years. Thinning activities and associated harvester trails could lead to increased disturbance of roots and soils in patches, causing elevated tree mortality (Hautala et al., 2004; Thorpe et al., 2008). Rocky outcrops had the lowest average volume of thinned trees during final felling, and although not significantly related to total CWD volumes, this indicate that rocky outcrops may be less affected by forest management than more productive and accessible (i.e., with fewer boulders) patch types. Thus, the higher CWD densities and volumes in rocky outcrops observed in this study could in part be a result of less intensive management and higher tree age. This agrees with studies from Canada, showing that older post-harvest retention patches (i.e., with older and larger trees) of boreal black spruce more closely maintain the range of structural complexity found in natural stands than younger patches (Moussaoui et al., 2016a, 2016b).

Larger and more circular patches (assumed to have the least severe edge-effects) could possibly reduce tree mortality rates (e.g., Laurance et al., 1998) and subsequent CWD amounts. Similar to Moussaoui (2016b), we did not find a significant relationship of patch area or shape with CWD volume. In terms of tree mortality rates, both neutral (Hautala and Vanha-Majamaa, 2006; Lavoie et al., 2012) and positive (Jönsson, et al. 2007; Steventon, 2011; Hallinger et al., 2016) effects of patch size have been found. Hallinger et al. (2016) also did not find patch shape to correlate with cumulative tree mortality, and speculated that patches < 1 ha essentially do not have an interior unexposed core (Steventon, 2011) independent of the shape.

Positioning retention patches in exposed or open habitats did not influence long-term CWD volumes in our study, but exposed patches had higher CWD volumes 1–3 years after harvest. Earlier studies are contradictory regarding the effect of exposition with Jönsson et al. (2007), Rosenvald and Lõhmus (2008), and Hallinger et al. (2016) identifying it as one of the most important factors while Scott and Mitchell (2005) and Rosenvald et al. (2008) found it to be insignificant.

4.5. Conclusions for conservation and management

Our study found that the majority of trees in small retention patches, regardless of patch type, did not experience severe windthrow or mortality in the first few decades following creation and clearcutting. Although our study had limitations in terms of scale and analysis of within-patch-type variability (e.g., in relation to patch size, shape and exposition), we demonstrated the value of various retention patch types for maintaining fair amounts of diverse CWD over time. Our results challenge the concerns of forest managers regarding the vulnerability of small retention patches to extreme windthrow, suggesting that factors such as patch size (Jönsson et al. 2007; Steventon 2011; Scots pine: Hallinger et al., 2016), location (Scott and Mitchell, 2005; Hallinger et al., 2016), tree species (Rosenvald et al., 2008; Lavoie et al., 2012; Hallinger et al., 2016), and moisture (Hautala and Vanha-Majamaa, 2006; Hallinger et al., 2016) may not always be critical in mitigating tree mortality and windthrow. Rather, our findings support the lower cumulative tree mortality rates observed in a large-scale study of boreal forest retention patches in central Sweden (Hallinger et al., 2016). However, studies over even longer time scales are needed to understand the impacts of stochastic mortality agents such as storms, disease and fire on CWD dynamics in retention patches.

We highlight the importance of avoiding very low tree densities in retention patches to ensure long-lasting CWD legacies. While some retention patch types may temporarily bridge gaps in CWD availability, edge effects such as desiccating winds and strong solar radiation can diminish the habitat value for dependent biodiversity and ecosystem services. Edge effects may lessen with increasing patch size and time since harvest for certain organisms (Ruete et al., 2016), or persist long-term for others (Johansson et al. 2018; Jönsson et al., 2022). Thus, when conserving microclimatically sensitive forest organisms dependent on CWD in retention patches, it is important to consider patch size, overall structural heterogeneity, and exposition (Jönsson et al., 2022; Koelemeijer et al., 2022).

The average volume of CWD in all retention patch types was significantly lower than the 80–120 $m^3 ha^{-1}$ range found in old-growth natural forests (Siitonen, 2001) and at the lower end of the threshold range of 20–30 $m^3 ha^{-1}$ proposed for biodiversity conservation in boreal coniferous forests (e.g., Müller and Bütler, 2010; Hekkala et al., 2023). Further studies are necessary to assess the efficacy of different retention patch types in sustaining CWD and associated saproxylic biodiversity. While retention patches can support conservation-interesting epiphytic and epixylic species over time, the decline of some species may still occur due to patch type, size, exposure, or intrinsic species traits (Rudolphi et al., 2014; Jönsson et al., 2022). The within-patch-type variability in CWD observed in this study underscores the need for precautionary management recommendations due to the varying abilities of retention patches to provide suitable saproxylic habitat. Additionally, the small size and relative isolation of these patches may increase the risk of extinction for saproxylic species due to stochastic events.

CRediT authorship contribution statement

Mari Jönsson: Conceptualization, Methodology, Investigation, Formal analysis, Funding acquisition, Data curation, Writing – original draft, Visualization. **Jan-Olov Weslien:** Conceptualization, Methodology, Writing – review & editing. **Lena Gustafsson:** Conceptualization, Methodology, Data curation, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

I have included the data in the supplementary material, but can also share in an open database

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121063.

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