Ecological Processes

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Research on retention forestry in Northern Europe

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Abstract

Retention approaches in forest management are today common in several North European countries, integrated into the clearcutting practice as a way to promote biodiversity and maintain ecosystem functions. Individual green trees and retention patches (tree groups) are retained at final harvest, and deadwood is left at site or created. Here, we review research on retention in Sweden, Finland, Norway, the Baltic States, and NW Russia, with special focus on biodiversity. Following the first publication in 1994, about 180 peer-reviewed articles have been published. We present results from a systematic search of the retention literature, separated into the following topics: buffer zones, retention patches, high stumps, other types of deadwood, European aspen *Populus tremula*, and cost-efficiency. Russian literature is synthesized separately since studies from this region have so far almost exclusively been published in the Russian language. Furthermore, we describe six ongoing large-scale, replicated experiments with varying retention levels, five in Finland and one in Sweden, and summarize their main results. Among main conclusions for practice from the literature and experiments are that retention patches as large as 0.5 ha and 10-m-wide buffers to watercourses are not enough to maintain pre-harvest species composition but survival of forest species is still larger than on conventional clearcuts. Deadwood on clearcuts may present important habitats to saproxylic species, including rare and red-listed ones and a prioritization of tree species per stand is recommended. We identify several important future research directions including switch of focus towards the landscape as well as the species population level. Surveys in parts of European Russia where retention has been unintentionally implemented already for a century would indicate possible future trajectories of biodiversity and their drivers in other regions of Northern Europe. A stronger link to ecological theory would help in study designs and in the formulation of predicted outcomes.

Keywords: Biodiversity, Buffer strips, Conservation, Deadwood, Experiments, Forestry, High stumps, Retention patches, Variable retention

Background

Retention forestry (variable retention, variable retention forestry, retention silvicultural system, retention system, see Beese et al. 2019) is a relatively new forestry management concept in which measures to promote biodiversity are integrated into harvest operations (Gustafsson et al. 2012). It has expanded globally during the last decades and is today practiced on several continents (Lindenmayer et al. 2019; Palik and D'Amato 2019; Martínez Pastur et al. 2019; Shorohova et al. 2019), most commonly at clearcutting operations but the approach is equally justified at selective harvest (Gustafsson et al. 2019). Main actions are to leave individual living trees and tree groups (retention patches) and often also to maintain or create deadwood at site, with provisioning of biodiversity as a key important objective (Martínez Pastur et al. 2009; Lindenmayer et al. 2012). Other objectives include structural enrichment of the post-harvest stand, secured continuity of structures and processes, maintenance of connectivity at the landscape scale, minimization of off-site impacts, and improved esthetic perception (Gustafsson et al. 2012).

Retention approaches were introduced in Northern Europe already in the 1980s (Simonsson et al. 2015), but large-scale application did not start until the late 1990s, when national certification standards (FSC, PEFC) were launched, and

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certification schemes were widely implemented by a large share of forest owners (Gustafsson et al. 2010). Research on ecological effects of retention is extensive worldwide (Lindenmayer et al. 2012), and several large-scale experiments have been established in different parts of the globe (Gustafsson et al. 2012). Meta-analyses demonstrate benefits to several species groups (Rosenvald and Lõhmus 2008; Mori and Kitagawa 2014; Fedrowitz et al. 2014). A summary of research in Finland, Norway, and Sweden was published about a decade ago and listed about 50 biodiversity-oriented articles, with a dominance of studies on beetles and deadwood (Gustafsson et al. 2010). Due to increasing amount of research and newly established experiments in Northern Europe, this overview needs to be expanded and updated, including a systematic approach to literature retrieval. Furthermore, a summary of research published in the Russian language, so far largely unavailable to most researchers, is urgent.

Level of retention varies greatly between countries and regions; Gustafsson et al. (2012) report a range from a few percent of the logged area up to almost 50%, in a global comparison. Data on current state suitable for comparisons between North European countries are lacking, but an average of 11% of the area of harvested stands plus about 10 trees with special habitat value were recently reported from Sweden (Skogsstyrelsen 2019; Sveriges Officiella Statistik 2019). In Finland up to about 2% of the total volume of the growing stock is retained in final felling operations (Kuuluvainen et al. 2019). An indication of large differences between countries is a compilation of prescriptions on buffer zone widths along lakes and watercourses on forestland in the Nordic-Baltic region (Ring et al. 2017), revealing a very large between-country variation. Here we present an overview of research on retention approaches in Northern Europe (Norway, Sweden, Finland, the Baltics states, and NW Russia) with special emphasis on aspects of biodiversity. The aim of our study is to (1) compile and synthesize research on retention forestry from the region, (2) identify important future research directions, and (3) draw conclusions for practice. We divide the research synthesis (aim 1) into three separate parts. First, we analyze systematically retrieved literature on retention forestry from Sweden, Finland, Norway, and the Baltic states, published in peer-reviewed scientific journals. A compilation is also made of so far largely unknown literature from European Russia, published in the Russian language. Finally, we describe and present results from large-scale, replicated retention experiments conducted in Finland and Sweden.

Literature on retention in Northern Europe excluding Russia

Systematic search

We made a search in Web of Science Core Collection, Biosis Citation Index, and CAB Abstracts at the library of Swedish University of Agricultural Sciences on August 9, 2019, using systematic literature retrieval methodology (Collaboration for Environmental Evidence 2018). We used the following search string: (retention OR retain*) AND (forest*) AND (Sweden OR Finland OR Norway OR Estonia OR Latvia OR Lithuania OR Fennoscandia OR Nordic OR Scandinavia OR Baltic). We applied the following criteria for filtering of articles: (1) peer-reviewed scientific natural science article published in English, (2) focusing on forest, retention, biodiversity, terrestrial environments, and (3) study conducted in Sweden, Finland, Norway, Estonia, Latvia, or Lithuania. A total of 1760 articles were found, reduced to 271 after reading title, 162 after reading abstract, and 120 after reading the whole text. A total of 59 articles were added from other sources, and thus the final compilation embraced a total of 179 articles. Articles were classified into their main research direction, and knowledge was synthesized for topics covered by several studies (border zones, retention patches, high stumps, other types of deadwood, *Populus tremula*, cost-efficiency) (see Additional file 1: Appendix A).

Characterization of studies

Most of the about 180 studies were performed in Sweden (51%), followed by Finland (31%), Estonia (10%), Norway (5%), and Latvia (2%) while only one originated from Lithuania. Only 5 articles were published before 2001, while 57% were published during the period 2001–2010, and 40% after that. Beetles were the most common study organisms (39% of studies), followed by lichens and bryophytes (both 16%). Deadwood was in focus for most studies (34%) compared with about 25% for retention patches and solitary/dispersed trees, respectively (Fig. 1, see also Additional file 1: Appendix A).

Border zones along watercourses

About 15 studies have evaluated biodiversity effects of leaving border zones edging to watercourses, with research conducted in Sweden, Norway, and Finland. One review has been published, focusing on water quality and biodiversity (Kuglerová et al. 2014).

Several studies have been conducted in the same study area in boreal mid-Sweden with retained (10 m on each side) or logged border zones to streams, and with forest in nature reserves as control. A general finding from this study area is that buffer strips maintain species richness and abundance of several organism groups, including red-listed species, better than open, logged areas, but worse than unlogged forest. After 10–11 years, 60% of the pre-harvest bryophyte species were found in retained border zones but only 20% in clearcut borders (Hylander and Weibull 2012). Number of species and individuals of land snails showed a similar trend (Hylander et al. 2004).

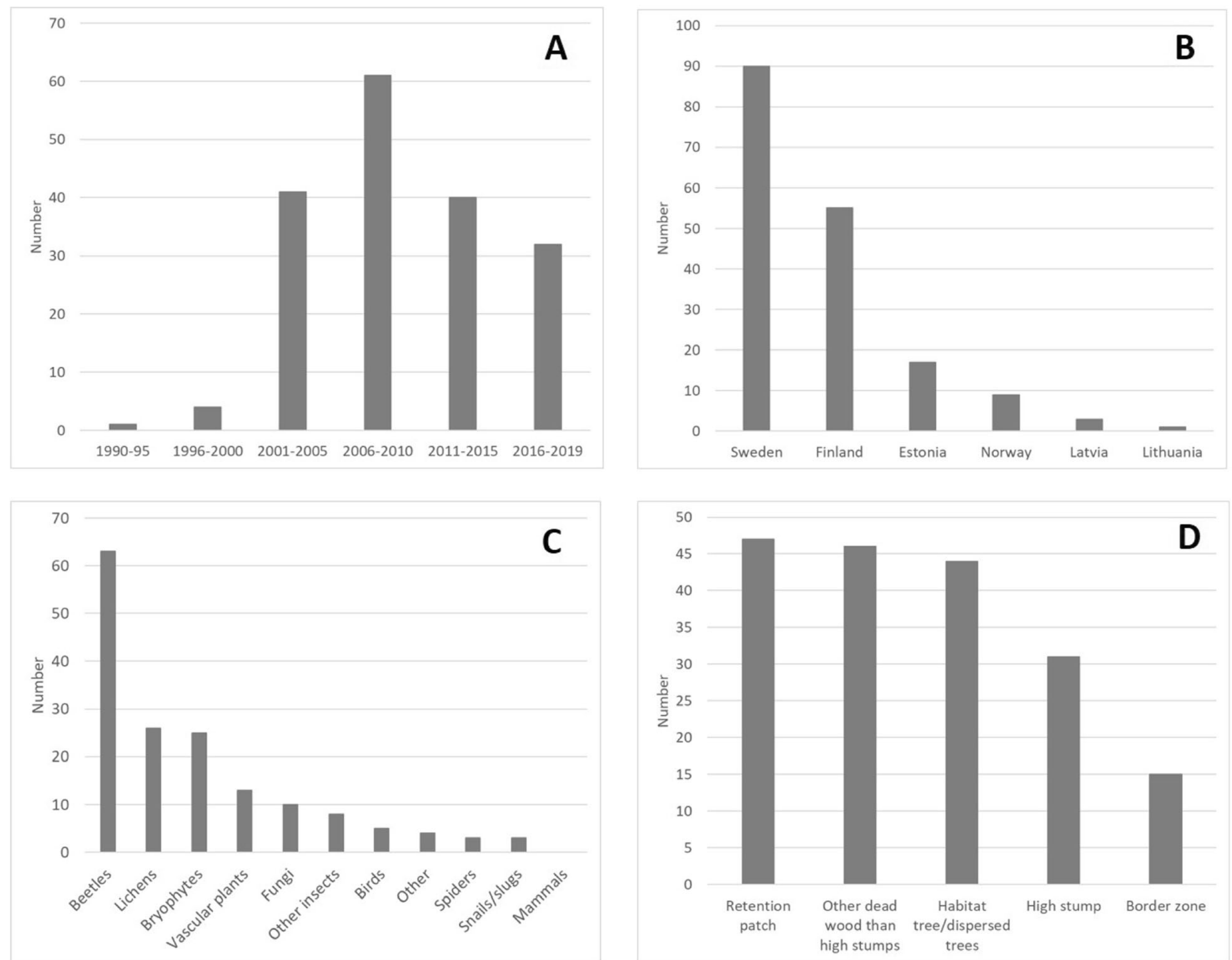

Fig. 1 Classification of articles from the systematic literature search on biodiversity and retention forestry in Sweden, Finland, Norway, and the Baltic states, conducted in Web of Science August 2019, using pre-defined search strings. A = year published, B = country, C = organism group, D = type of retention

In a follow-up on lichens, local extinction was time-lagged; a significant decrease in richness of red-listed/indicator and calicioid species in the retained buffer strips was found 17 years after logging but not after 3 years (Johansson et al. 2018). A chronosequence study from the same region in Sweden showed that recovery of bryophytes after logging of border zones might take a long time. Streamside borders logged 30–50 years ago had an impoverished bryophyte flora compared to borders in older forests (Dynesius and Hylander 2007).

In a Finnish study on moths, buffer strips were considerably wider, 30–70 m, and were compared with logged borders and reference forests. Number of species and individuals did not differ between buffers and control forests but were significantly lower in clearcut borders (Mönkkönen and Mutanen 2003). In another Finnish study, buffer strips of at least 30 m on both sides of streams were needed to maintain species composition of vascular plants but for mosses 15 m sufficed (Oldén et al. 2019). For birds in Norway (Hågvar et al. 2004), the number of species increased with buffer width, up to 30 m from the watercourse. Strips 11–20 m wide had the highest density of species and individuals per hectare.

Retention patches

About 30 scientific articles have been published on retention patches in Northern Europe with > 90% conducted in Sweden and Finland, and with insects, lichens, and bryophytes being the most commonly studied organism groups. The first study on retention in Northern Europe was published in 1994 (Esseen 1994), reporting tree-uprooting in Norway spruce *Picea abies* L. H. Karst-dominated retention patches of different sizes. In a follow-up study 18 years, later main conclusions were that patches as large as 1 ha are affected by wind disturbance and that most trees fall within the first 5 years while later on mortality is only a few percent per year (Jönsson et al. 2007). Early, high tree mortality was also found in an Estonian study monitoring > 3000 dispersed retention trees over a period of 6 years (Rosenvald et al. 2008). Norway spruce has the highest mortality while Scots pine *Pinus sylvestris* L. and birch *Betula* spp. are less sensitive (Hallinger et al. 2016), and the risk of wind-felling is larger on paludified than on mineral soil (Hautala and Vanha-Majamaa 2006).

Only a few studies have focused on biodiversity responses to the size of retention patches, up to 0.6 ha in size. In a Finnish study, spider communities changed less after logging in large than in small patches at paludified sites (Matveinen-Huju et al. 2009), and two lichen species, *Calicium parvum* Tibell and *Micarea globulosella* (Nyl.) Coppins, decreased more in small than large patches when re-inventoried after 6 years in Central Sweden (Perhans et al. 2009). Time-series with repeated species recordings in retention patches are overall uncommon. In Perhans et al. (2009), the number of records of species of conservation concern decreased 30% for bryophytes while only 1% for lichens. In another Swedish study, exact locations of red-listed bryophytes and lichens were determined before harvest, re-located 3–7 years post logging, and were compared with unlogged control forest (Rudolphi et al. 2014). About half of bryophyte occurrences on logs remained in retention patches as well as in control forests, while only 10% were rediscovered on open clearcuts. About half of the lichen occurrences on living trees in patches remained compared with 75% in controls. Rudolphi et al. (2014) is the only study so far to assess the impact of location of patches. These authors found that the survival of desiccation-sensitive species may increase if patches are located in shady positions; local extinction was lower in north-facing than in south-facing patches, and in patches located close to mature forest.

High stumps

Every year, at least one million high stumps (stumps cut at a height of 3-5 m) in final felling and thinning are set in Sweden, aiming to support deadwood-associated species. This measure started in Sweden in the late 1990s and is nowadays also applied in other parts of the Nordic region. Here, 26 studies on this type of deadwood are summarized, of which 24 were conducted in Sweden. Many of these reports are on spruce stumps sampled within a few summers after cutting (Schroeder et al. 1999; Abrahamsson and Lindbladh 2006; Hedgren 2007; Lindbladh and Abrahamsson 2008; Abrahamsson et al. 2008; Fossestøl and Sverdrup-Thygeson 2009). Most studies are on a small spatial scale (tree), but some general patterns can be identified. First, high stumps differ in species composition from ordinary harvesting stumps (Abrahamsson and Lindbladh 2006; Hedgren 2007; Hjältén et al. 2010) and logs (Jonsell and Weslien 2003; Gibb et al. 2006; Hjältén et al. 2007, 2010; Fossestøl and Sverdrup-Thygeson 2009). Second, species composition of insects and fungi differs considerably between tree species (Jonsell et al. 2004; Lindhe et al. 2004, 2005; Lindhe and Lindelöw 2004; Lindbladh et al. 2007). Third, diameter has little effect on early succession spruce communities (Jonsell and Weslien 2003; Lindbladh et al. 2007; Abrahamsson et al. 2008) whereas diameter seems to affect communities of species associated with deciduous tree and late successions (Jonsell et al. 2004; Lindhe et al. 2004; Lindhe and Lindelöw 2004; Weslien et al. 2011). Fourth, and important from a conservation point of view, many red-listed species occupy aspen high stumps (Jonsell et al. 2004; Lindhe et al. 2005). At the landscape scale, two studies explore how high stumps benefit recruitment of beetles (Schroeder et al. 2006; Djupström et al. 2012), and three explore how landscape structure affect the beetle fauna of high stumps of spruce and birch (Lindbladh et al. 2007; Abrahamsson et al. 2009; Jonsell et al. 2019). The vast majority of studies deal with beetles, two are on solitary bees and wasps nesting in cavities of dead trees (Westerfelt et al. 2015, 2018), two focus on parasitoids of early successional beetles (Hilszczański et al. 2005; Hedgren 2007), and one is on polypore fungi (Lindhe et al. 2004). In contrast to much other deadwood that is retained during cutting, the time of tree death is always known for high stumps. High stumps also remain standing during a long time and can be followed for decades of decay. Thus, high stumps have initiated novel studies on ecological succession which have added to the understanding of how communities assemble in deadwood (Weslien et al. 2011; Jacobsen et al. 2015; Jonsell et al. 2019). The studies are summarized in Table 1 with respect to stump age and investigated spatial scale.

Other types of deadwood

How important is deadwood retention at final harvest for supplying habitats for saproxylic species? The answer can partly be found among the about 30 papers included in this section. Although the volumes of dead trees in clearcuts have increased during the last decades (Kruys et al. 2013), they still constitute a small part of the total volumes in closed forests in the surrounding landscape (Schroeder et al. 2006; Ekbom et al. 2006). Consequently, short-term responses of recruitment among saproxylic species should be found among those species that avoid shaded habitats in the closed forest and instead prefer sun-exposed deadwood on clearcuts, mostly insects.

European aspen *Populus tremula* L. (see below) hosts the highest proportion of sun-promoted beetle species followed by common oak *Quercus robur* L. and birches *Betula pendula* Roth, *B. pubescens* Ehrh. (Lindhe and

Table 1 Studies on high stumps by age (years after cutting) and spatial scale. The same set of stumps may recur in several papers but with different age, and several spatial scales can be addressed in the same paper

Years after cutting	Tree	Stand	Landscape
≤ 2	Schroeder et al. 1999; Hilszczański et al. 2005; Lindhe et al. 2005; Gibb et al. 2006; Johansson et al. 2006; Abrahamsson and Lindbladh 2006; Hjältén et al. 2007; Hedgren 2007; Fossestøl and Sverdrup-Thygeson 2009	Hilszczański et al. 2005; Johansson et al. 2006; Hjältén et al. 2007; Lindbladh and Abrahamsson 2008	
3–6	Jonsell and Weslien 2003; Jonsell et al. 2004, 2005; Lindhe et al. 2004, 2005; Lindhe and Lindelöw 2004; Abrahamsson et al. 2008; Westerfelt et al. 2015	Lindbladh et al. 2007; Lindbladh and Abrahamsson 2008; Westerfelt et al. 2018	Schroeder et al. 2006; Lindbladh et al. 2007
7–10	Lindhe et al. 2004, 2005; Lindhe and Lindelöw 2004; Westerfelt et al. 2015	Westerfelt et al. 2018	Schroeder et al. 2006; Abrahamsson et al. 2009; Jonsell et al. 2019
≥ 11	Weslien et al. 2011; Jacobsen et al. 2015; Westerfelt et al. 2015	Westerfelt et al. 2018	Djupström et al. 2012

Lindelöw 2004; Lindhe et al. 2005). Aspens retained in clearcuts are important habitats for sun-loving insect species (Martikainen 2001; Sverdrup-Thygeson and Ims 2002; Sahlin and Ranius 2009; Sverdrup-Thygeson and Birkemoe 2009; Ranius et al. 2011). Birch stems in clearcuts harbor different species than those of similar diameter and decay stage inside forests (Kaila et al. 1997). Even small diameter retained birch stems can be valuable in this respect (Rubene et al. 2014). Clearing around ancient oaks in spruce plantations attracts beetle species that breed in dead branches of these oaks (Widerberg Koch et al., 2012). Spruce is shade tolerant which applies also for many saproxylic insects colonizing spruce stems (Lindhe and Lindelöw 2004; Lindhe et al. 2005; Gibb et al. 2006; Johansson et al. 2006; Hjältén et al. 2007; Fossestøl and Sverdrup-Thygeson 2009; Djupström et al. 2012).

Solitary bees and wasps nest almost exclusively in sun-exposed habitats and thus retained standing dead trees are important nesting sites for some species (Westerfelt et al. 2015, 2018). For saproxylic fungi, the degree of sun-exposure seems to be of minor importance compared to decay stage and diameter (Lindhe et al. 2004; Junninen et al. 2007).

Modeling of long-term effects of green tree and deadwood retention shows that retention levels of today affect deadwood amounts and qualities in future forest landscapes (Ranius & Kindvall 2004, Roberge et al. 2015). Some studies also show detrimental effects of forestry operations on deadwood amounts, particularly soil scarification (Hautala et al. 2004) and fuel wood extraction (Rudolphi and Gustafsson 2005).

One important question is whether one should retain deadwood in many small or a few large patches. Several studies indicate that species occupancy often increases with increasing substrate density (Komonen et al. 2000; Ranius 2002; Sahlin and Schroeder 2010; Rubene et al. 2014; Ranius et al. 2017). This would call for large habitat patches meaning retention of many stems of the same tree species per clearcut.

European aspen *Populus tremula*

European aspen is a keystone species with particular importance for biodiversity in northern Fennoscandia (Kouki et al. 2004). It is the most studied individual retention tree species with a total of about 25 articles. Several studies show that dead aspens in open, sun-exposed conditions are important for many species both for survival of pre-harvest species and for colonization. Fallen retention aspens have a more diverse flora of saproxylic fungi compared to other tree species (Runnel et al. 2013). Compared to mature forest, dead aspens on clearcuts host more polypore species (Junninen et al. 2007), and as about equally many beetle species (Martikainen 2001; Sverdrup-Thygeson and Ims 2002). Many beetle species on man-made high stumps of aspen thrive in sunny or semi-open conditions (Lindhe et al. 2005), and such stumps provide as important habitat as natural snags (Jonsell et al. 2004). Epiphytic lichens adapted to closed canopy conditions may survive on solitary live aspens, and with time, more light-tolerant species will colonize (Lõhmus and Lõhmus 2010; Lundström et al. 2013). The red-listed lichen *Lobaria pulmonaria* (L.) Hoffm. can survive and grow on retained green aspens, particularly on their northern side (Gustafsson et al. 2013). Epiphytic bryophytes are more sensitive than epiphytic lichens (Lundström et al. 2013; Oldén et al. 2014), but *Orthotrichum gymnostomum* Bruch ex Brid. is an example of a rare moss species that thrives on solitary retention aspens (Rudolphi et al. 2014). Volume of aspen and number of epiphytic lichens usually correlate positively (Hedenås and Ericson 2000; Lundström et al. 2013). However, many small aspen trees can host as many species as a few large trees, counted per bark area (Schei et al. 2013).

Cost efficiency

The relationship between lost wood production and biodiversity has been studied in about 10 articles. A Swedish project found that leaving dead trees and producing high stumps was a cost-efficient way of creating habitats for red-listed insects and cryptogams (Ranius et al. 2005; Jonsson et al. 2006, Jonsson et al., 2010). Extended rotation time was, however, as efficient as artificial creation of deadwood. Leaving birch and aspen was more cost-efficient than leaving spruce and pine in southern Sweden, while conifers were more cost-efficient in the north. The cost-benefit ratio may be lower if retention patches are selected based on combined information on species content and timber volume (Perhans et al. 2011). Maintaining woodland key habitats (important sites for biodiversity) may, however, be the most cost-efficient conservation measure, based on the number of rare species, but retention patches are also cost-efficient due to their usually low timber volumes (Wikberg et al. 2009). By selecting small and crooked aspens with black bark as retention trees, many lichens can be preserved with low cost (Perhans et al. 2014). Retention of solitary pine trees in clearcuts reduces the growth of surrounding trees by a few percent, but losses can be compensated for by increased growth of the retained pines (Jakobsson and Elfving 2004; Elfving and Jakobsson 2006). A Finnish simulation study including different conservation scenarios and using habitat for deadwood-associated species as a proxy for biodiversity, concluded that compared to larger set-aside areas, small retention patches (0.01 ha) are an ineffective way to spend conservation funding (Mönkkönen et al. 2011).

Research in European Russia

Russian literature was not included in the systematic search since such studies have rarely been published in peer-reviewed, English-language scientific journals. Thus, we give a short overview of publications on retention trees and patches that have been published in the Russian language. In NW Russia (reaching from Finland and the Baltic states to the Ural mountains), forest patches, individual trees, and deadwood have been commonly retained at harvesting areas from the 1930s to the 1960s, mainly due to incomplete clear felling (Shorohova et al. 2019). During the last 20 years, the role of such unintentional retention has been documented in some monitoring reports and observational case studies. In the Republic of Karelia, many rare and threatened tree-associated birds, small mammals, wood-inhabiting fungi, lichens, and bryophytes occupy uncut forest patches surrounded by vast clearcuts or young forests (Kravchenko 1999; Gromtsev et al. 2010; Ivanter and Kurhinen 2016). Forest buffers on wet sites along rivers and around springs are of special importance for biodiversity and ecological integrity (Kravchenko 1999; Markovsky and Iljina 2014). Patches of undergrowth, seed tree patches and uncut patches of trees with non-merchantable wood may act as refugia for late-successional forest lichens, vascular plants, and bryophytes after felling (Kravchenko et al. 2004; Kryshen 2006; Fadeeva and Kravchenko 2018).

Studies on contemporary, intentional retention are scarce. Inventories in the Pskov model forest (southwesternmost part of the region) demonstrate an association of many rare and threatened species of wood-inhabiting fungi (Kotkova 2010), lichens (Glushkovskaya 2010) and bryophytes (Kushnevskaya 2010) to retention elements and tree groups. In a study covering seven consecutive years following harvest, the total number of species and number of threatened species of invertebrates, vascular plants, bryophytes, polypores, and lichens were higher in areas where deadwood and special biotopes (such as paludified patches and creeks) had been retained than on open clearcuts (Romanyuk et al. 2009). Compilations made by species experts also show that many red-listed and indicator species are associated with certain structural elements and biotopes (Andersson et al. 2009; Markovsky and Iljina 2014).

Retention experiments in Finland and Sweden

Ecological responses to retention approaches have been studied experimentally in Finland since 1995, following the establishment of the “Biodiversity in regeneration of managed forests” (MONTA) experiment in southern Finnish spruce forests (Table 2 and Figs. 2 and 3). In Sweden, the only retention experiment so far, Effaråsen, was established in 2012.

Following the MONTA experiment (W and E Finland; Fig. 2), four other experiments have been established in Finland. The small retention-tree groups in MONTA (0.01–0.09 ha, 20–30 trees per group) were not able to maintain the pre-treatment forest species and communities of, e.g., understory vegetation (especially mosses and liverworts) and ground beetles (Jalonen and Vanha-Majamaa 2001; Koivula 2002a). Following this observation, RETREE was designed in 1997 to determine whether larger, up to 0.6 ha in size, retention-tree groups can maintain the pre-treatment (forest and moist habitat) species better than the small ones (Hautala et al. 2011). In 2000, the FIRE experiment was established in Eastern Finnish pine-dominated forests to study variable retention with and without prescribed burning. In 2001, the EVO experiment was established in southern Finnish spruce forests with a somewhat different study design and aims, the focus being on restoration measures (downed deadwood and burning). Here, an additional aspect was the comparison between upland and paludified biotopes within each stand, allowing an assessment of interactions between management operations and moisture. The most recent Finnish experiment is the “Forest management inspired by natural disturbance dynamics” DISTDYN (W and E Finland; Fig. 2), established in

Table 2 Experiments on retention forestry in Finland and Sweden. The Finnish experiments are located in the middle boreal biome and the Swedish experiment in the north boreal biome (Ahti et al. 1968). The Finnish experiments are ordered according to establishment year. For location of experiments, see Fig. 2, and for photos from a selection of experiments, see Fig. 3. *Year* establishment year, *Age* stand age at establishment (year), *NS* Norway spruce *Picea abies*, *SP* Scots pine *Pinus sylvestris*. Blocks, size = number of blocks or stands, and their size ranges. *LUKE* Natural Resources Institute Finland, *Metsähallitus* Finnish forest and park services, *Metsäteho* Metsäteho Ltd., a research and development company by Finnish forest industry organizations, *UEF* University of Eastern Finland, *UH* University of Helsinki, *Skogforsk* Forestry Research Institute of Sweden. For explanation of Finnish experiment names, see the section "Abbreviations" in the text

Experiments	Characteristics						
	Year	Age, tree species	Blocks, size	Treatments	Response variables	Responsible	Information
MONTA (East and West) (Finland)	1995	90, NS	48, 1–2 ha	Clear felling, retention felling (up to 0.02 ha patches), gap felling, selection felling	Wood-inhabiting fungi, vascular plants, lichens, mosses, liverworts, beetles, spiders, ants, land snails, timber volume, sapling establishment, coarse woody debris	LUKE, Metsäteho, UH	Jalonen and Vanha-Majamaa 2001
RETREE (Finland)	1997	90, NS	11, 1–3 ha	Retention of 0.1–0.6 ha patches in clear-felled stands	Vascular plants, lichens, mosses, liverworts, beetles, spiders, land snails, timber volume, sapling establishment, coarse woody debris	LUKE, UH	Matveinen-Huju et al. 2006
FIRE (Finland)	2000	150, SP	24, 3–5 ha	Retention of different intensity (0, 10, or 50 m^3/ha), burning	Polypore and other fungi, beetles, flat bugs, pollinators, small mammals, ungulates, lichens, tree monitoring, tree regeneration, dendrochronology	UEF	Hyvärinen et al. 2005
EVO (Finland)	2001	90, NS	24, 1–3 ha	Down wood retention (5, 30, or 60 m^3/ha), standing tree retention (50 m^3/ha), burning	Wood-inhabiting fungi, vascular plants, lichens, mosses, liverworts, beetles, timber volume, sapling establishment, coarse woody debris	LUKE, UH	Vanha-Majamaa et al. 2007
DISTDYN (East and West) (Finland)	2009	90, NS/ SP	12, 200–300 ha	Selection felling, gap felling, clear felling, deadwood addition. 5–20% retention volume	Wood-inhabiting fungi, vascular plants (some lichens and mosses), beetles, timber volume, sapling establishment	LUKE, Metsähallitus, UEF, UH	Koivula et al. 2014
Effaråsen (Sweden)	2012	120, SP	24, 5–14 ha	Retention gradient (3–100% volume) and burning	Wood-inhabiting fungi, mycorrhiza fungi, epixylic lichens, beetles, timber volume, logging performance and opportunity costs, carbon stock, albedo	Skogforsk	Djupström and Weslien 2019

2009, expanding the scope from stand-level comparisons to landscape-level assessments (Koivula et al. 2014).

Publications from the Finnish experiments so far cover 10–20 post-harvest years. Their main findings can be summarized as follows: (1) selection felling removing 33% of stand volume (dispersed retention), supports most of the common forest species, including ground beetles, spiders, soil fauna, and understory vegetation (Koivula 2002b; Matveinen-Huju and Koivula 2008; Siira-Pietikainen and Haimi 2009; Vanha-Majamaa et al. 2017), (2) retention felling with 7% retained volume in tree groups (aggregated retention) of about 0.05 ha mitigate some faunal and floral alterations (Jalonen and Vanha-Majamaa 2001; Koivula 2002a; Siira-Pietikainen and Haimi 2009; Koivula et al. 2019); however, even considerably larger retention patches (0.6 ha) do not maintain species composition of mosses, liverworts, or lichens (Hautala et al. 2011; Hämäläinen et al. 2016) and species composition of more common species is also altered (Matveinen-Huju et al. 2006, 2009), (3) gap felling with up to 50% of the stand clearcut as three 30 × 40 m gaps mitigate effects of clear-felling via their retained parts, but also their cleared parts are less altered than 1–2-ha clearcuts (Koivula and Niemelä 2003; Matveinen-Huju and Koivula 2008), (4) as partly reflected above, a common finding in retention experiments is that the higher the retention, the better it mitigates the effects of clearfelling (Hyvärinen et al. 2005; Martikainen et al. 2006; Toivanen and Kotiaho 2010; Toivanen et al. 2014; Johnson et al. 2014; Rodríguez and Kouki, 2015; Heikkala et al. 2016; Vanha-Majamaa et al. 2017; Jokela et al. 2019; Suominen et al. 2019), (5) restoration efforts, such as addition of deadwood and/or prescribed burning, support rare and red-listed species (Hyvärinen et al. 2006; Toivanen and Kotiaho 2007; Suominen et al. 2015, 2019; Heikkala et al. 2017), but some species groups containing many red-listed species are negatively affected, such as lichens (Hämäläinen et al. 2014; Hämäläinen 2016), and (6) closed-forest species benefit from moist patches and high micro-habitat variation at harvested sites (Koivula 2002a; Toivanen et al. 2014; Koivula and Vanha-Majamaa 2020, in press).

For the Swedish Effaråsen experiment, baseline data and modelling studies have been published. Logging

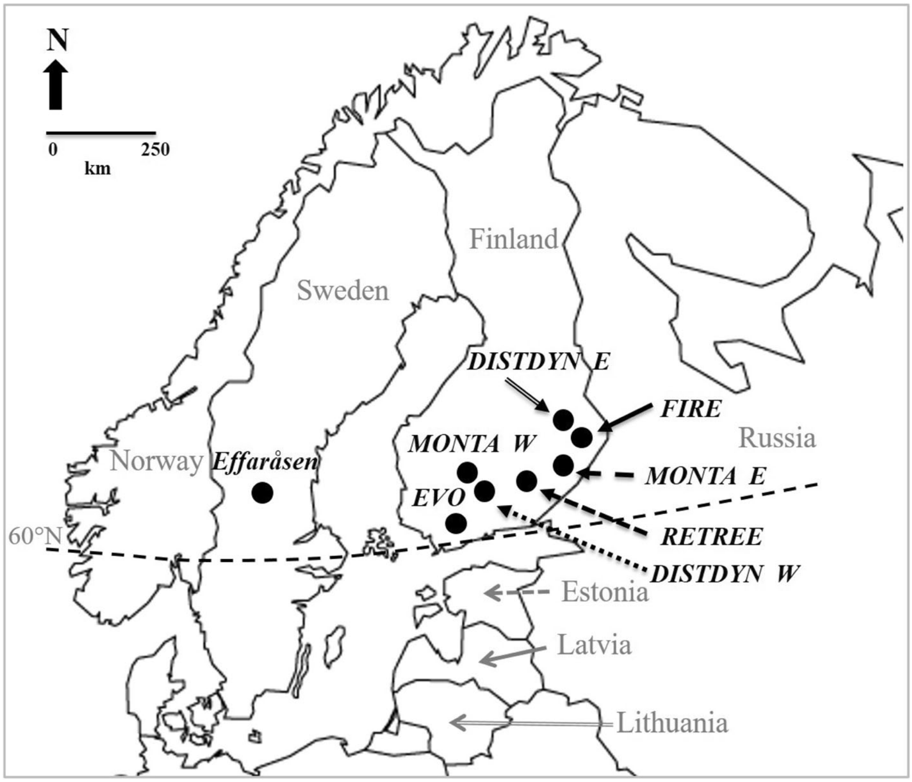

Fig 2 Location of the retention experiments in Finland and Sweden, Northern Europe. For further information, see Table 2. Country names are given in gray, experiment names in black. Line types for countries: Lithuania double, Latvia solid, Estonia dashed. Line types for experiments: DISTDYN W dashed (short), RETREE dashed (longer), MONTA E dashed (longest), FIRE solid, DISTDYN E double.

time (minutes per m^3 wood), opportunity costs, and deadwood diversity increased with an increasing retention level (Santaniello et al. 2016). Baseline data show that old hard pine wood is a valuable habitat for epixylic lichens (Santaniello et al. 2017a). Modelling approaches include wood production, deadwood accumulation, and climate-related issues on carbon stocks and albedo (Santaniello et al. 2017b; Cherubini et al. 2018).

Reflections on retention forestry research in Northern Europe

Our analysis of peer-reviewed publications, overview of grey literature from NW Russia, and compilation of findings from experiments in Finland and Sweden demonstrate that substantial research efforts have been made in Northern Europe to better understand the relationship between biodiversity and the retention forestry system. Our findings are valid also for other boreal and temperate forest regions, since the retention forestry system has notable similarities in application in different biomes (Gustafsson et al. 2012). The number of articles (almost 200) was highest in the period 2006–2010 (about 60 studies) but the interest continues, and the last 3 years more than 20 papers have been published. Already almost a decade ago, Lindenmayer et al. (2012) reported about 500 studies on retention approaches and biodiversity globally, with publications from Northern Europe comprising about 20%. Diverse aspects have been studied in the Nordic and Baltic countries but the focus on deadwood is particularly prominent; almost 35% of all studies have assessed this component. High stumps have been the target of more than 25 studies, which might be surprising but there is a special interest in this type of deadwood since high stumps are associated with certification. In Sweden for instance, both FSC and PEFC require a creation of at least three high stumps per ha at each harvest occasion. Another characteristic of studies from Northern Europe is the large emphasis on invertebrates, bryophytes, lichens, and fungi (focus in 90% of studies), and less so on the better-known taxonomic groups of vascular plants and vertebrates. Remarkably, no study has been done on mammals. Most studies have been performed in Sweden and Finland (80% of all publications), and also all large-scale, replicated experiments have been established in these countries, with a striking concentration to Finland (5 out of 6 experiments). The Russian literature corroborates the peer-reviewed publications and demonstrates the importance of (intentionally or unintentionally) retained patches and buffer zones as refugia for organisms. A similar focus on lesser known

Fig. 3 Examples of retention experiments in Finland and Sweden. **a** Gap felling with 5% group retention inside a gap, spruce forest, third post-harvest summer. DISTDYN project in Finland. Photo: Matti Koivula. **b** In the Swedish experiment, Effaråsen, Scots pine stands have been harvested with retention levels varying from 3 to 100%. At each level the retention included equal proportions of intact green trees, girdled trees, high-cut trees, and felled trees. In the picture, a level of 30% retention is shown. Photo Line Djupström. **c** Retention tree group inside a clear-felled area. In the RETREE project, varying sized retention tree groups, 0.1-0.6 ha were left in a harvested area. Photo: Erkki Oksanen/LUKE. **d**. Naturally regenerated gap in the MONTA experiment 14 years after harvesting. Photo: Erkki Oksanen/LUKE. For more information on the experiments, see Table 2, and for their location, see Fig. 2.

organisms (bryophytes, lichens, fungi) is also evident in studies from this part of Northern Europe. The overview on large-scale, replicated retention experiments given here supplements earlier descriptions of experiments performed around the globe (Gustafsson et al. 2012). Results from the experiments are clear; substantial amounts of retention are needed to counteract negative effects of logging on species associated with old forest, agreeing with meta-analyses on retention forestry and biodiversity (e.g., Fedrowitz et al. 2014). In selection felling as well as gap felling, > 50% of stand volume needs to be retained in order to maintain common forest species, and retention patches need to be more than half a ha in size, and probably larger, to preserve old-forest species communities. Important mechanisms for the long-term survival of old-forest species include moist microclimate and availability of various microhabitats. Insights into restoration efforts have also been gained from the experiments; many saproxylic species benefit from addition of deadwood and prescribed burning, actions compatible with retention forestry.

Future research

Continued research on retention approaches is urgent in Northern Europe, to evaluate current practices but also to provide an improved knowledge base necessary for future development of forest management. Some research directions associated with biodiversity stand out as especially important. First, there is a need for upscaling to the landscape level, since many species depend on large-scale patterns and processes and to date almost all surveys and experiments have been done at the stand level. Second, there is a lack of population-oriented studies, since current literature is largely dominated by assessments of species richness and composition, measures that are difficult to evaluate. As management modifications should support species that need conservation efforts, i.e., rare and threatened species, their responses are particularly relevant. Third, the European part of Russia offers a unique opportunity to evaluate long-term effects of retention. In this region large areas have been logged since 1910 with mainly unintentionally retained single trees and groups of trees (Shorohova et al. 2019). Surveys of species as well as forest and landscape structures would indicate the future composition of biodiversity and its drivers in landscapes in which retention has been more recently introduced, like in other parts of Northern Europe. Fourth, although most studies to date have attempted to answer applied questions, we recommend stronger links to ecological theory. Such would aid in study designs and in the formulation of predictions of outcomes, and strengthen the interpretation of results. Fifth, maintenance of current experiments is essential, and implementation of cross-country monitoring programs would greatly aid in the evaluation of benefits to biodiversity of current management models. Finally, our review only includes natural science literature but more social science studies and studies in humanities are also needed in order to reach a more complete understanding of the complex retention forestry system.

Conclusions for practice

The large amount of research from Northern Europe enables some broad conclusions for practical forest management. First, the importance to biodiversity associated with old forests and elements herein increases with retention level, i.e., the more that is retained, the better for forest plants, animals and fungi. Although a general finding from the Finnish experiments is that some taxa are negatively affected even in retention patches as large as 0.6 ha, studies also show that some old-growth-forest species, including many of special conservation concern, may survive in smaller retention patches and on dispersed trees. Thus, as much trees as possible should be retained and size of patches should be maximized but even leaving small amounts is better than traditional clearcutting with removal of all trees. Second, buffer strips need to be few tens of meters on each side of a stream to maintain pre-logging richness and composition of various taxa. Compared to logged buffers, several species including certain red-listed ones nevertheless may survive in narrower strips, i.e., the conclusion is the same as for retention patches: leaving a little is better than leaving nothing at all. Third, retention and creation of sun-exposed deadwood in the form of logs, snags, and high stumps on clearcuts should be encouraged since they form important habitats for saproxylic taxa such as certain beetles and fungi, including some rare and red-listed species. Fourth, assuming a given volume to be retained, the research indicates that concentration of deadwood of one tree species per site is more efficient than leaving deadwood of a diversity of tree species. Fifth, a conclusion put forward in many publications, with which we agree, is that retention forestry is not a panacea for biodiversity but instead one way to mitigate negative effects of clearcutting. For some forest species, large forest reserves are necessary for their long-term survival.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s13717-019-0208-2.

Additional file 1: Supplementary material. 3 Appendix A literature on retention (Excel file with 4 worksheets).

Abbreviations

DISTDYN (W and E): A large-scale and long-term research and development project "Forest management inspired by natural disturbance dynamics"; EVO: Experimental research project established in Evo to study the biodiversity effects of variable retention, burning and deadwood manipulation; FIRE: An experimental project "Boreal forest fire experiment," established in eastern Finland to study the biodiversity effects of variable retention and burning; MONTA (W and E): Experimental research project "Biodiversity in the regeneration of managed forest"; RETREE: Experimental research project to study the effects of variable retention tree group size on biodiversity

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Authors' contributions

LG was the lead author in writing, made the systematic search and classification of literature, edited the manuscript, and prepared the figures. MH wrote the sections on aspen and cost-efficiency. ES wrote the section on the Russian literature. IVM and MK wrote the section on the Finnish experiments. JW wrote the sections on highs stumps and deadwood, and the text on the Swedish experiment Effaråsen. All authors read and approved the final manuscript.

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