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Moving towards multi-layered, mixed-species forests in riparian buffers will enhance their long-term function in boreal landscapes

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A B S T R A C T

Riparian buffers are the primary tool in forest management for protecting the habitat structure and function of streams. They help protect against biogeochemical perturbation, filter sediments and nutrients, prevent erosion, contribute food to aquatic organisms, regulate light and hence water temperature, contribute deadwood, and preserve biodiversity. However, in production forests of Sweden and Finland, many headwater streams have been straightened, ditched, and/or channelized, resulting in altered hydrology and reduced natural disturbance by floods, which in turn affects important riparian functions. Furthermore, in even-aged management systems as practiced in much of Fennoscandia, understory trees have usually been cleared right up to the stream's edge during thinning operations, especially around small, headwater streams. Fire suppression has further favored succession towards shade tolerant species. In the regions within Fennoscandia that have experienced this combination of intensive management and lack of natural disturbance, riparian zones are now dominated by single-storied, native Norway spruce. When the adjacent forest is cut, thin (5 - 15m) conifer-dominated riparian buffers are typically left. These buffers do not provide the protection and subsidies, in terms of leaf litter quality, needed to maintain water quality or support riparian or aquatic biodiversity. Based on a literature review, we found compelling evidence that the ecological benefits of multi-layered, mixed-species riparian forest with a large component of broadleaved species are higher than what is now commonly found in the managed stands of Fennoscandia. To improve the functionality of riparian zones, and hence the protection of streams in managed forest landscapes, we present some basic principles that could be used to enhance the ecological function of these interfaces. These management actions should be prioritized on streams and streamside stands that have been affected by simplification either through forest management or hydrological modification. Key to these principles is the planning and managing of buffer zones as early as possible in the rotation to ensure improved function throughout the rotation cycle and not only at final felling. This is well in line with EU and national legislation which can be interpreted as requiring landscape planning at all forest ages to meet biodiversity and other environmental goals. However, it is still rare that planning for conservation is done other than at the final felling stage. Implementing this new strategy is likely to have long-term positive effects and improve the protection of surface waters from negative forestry effects and a history of fire suppression. By following these suggested management principles, there will be a longer time period with high function and greater future management flexibility in addition to the benefits provided by leaving riparian buffers at the final felling stage.

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1. Introduction

Riparian zones are control points in the landscape, exerting a disproportionately large influence on water quality (Bernhardt et al., 2017; Hjältén et al., 2016; Lidman et al., 2017b) as well as harboring unique (Richardson, 2019) and often diverse plant and animal communities (Nilsson et al., 1989). Riparian zones act as filters for excess nutrients (Ledesma et al., 2018), stabilize streambanks (Polvi et al., 2014), trap sediments (Futter et al., 2016), provide subsidies to streams in the form of leaf litter and invertebrates (Richardson and Danehy, 2007), provide structure and habitat with deadwood (Degerman et al., 2004; Dahlström and Nilsson, 2004), and regulate the thermal and light regimes that influence primary productivity of the stream and riparian zone (Vannote et al., 1980; Oldén et al., 2019a). Because riparian zones lie at the land-water interface, they are both shaped by riverine processes (e.g., flooding – Poff et al., 1997) and sensitive to terrestrial disturbances (e.g., windthrow – Boggs et al., 2016).

In the context of forestry, riparian buffers are typically implemented along streams to protect their important ecosystem functions after final felling (Richardson et al., 2012). Specifically, these buffers are expected to preserve the myriad of functions that riparian zones support and in doing so mitigate unwanted changes to aquatic ecosystems that arise from disturbance in the uplands (Swedish Forest, 2013). Recognition that these buffer zones provide critical services has led to the enactment of policies aiming to increase the application and protection of streamside areas (Richardson et al., 2012; Ring et al., 2017; Hasselquist et al., 2020). At the same time, the optimal spatial arrangement of buffers in managed forest landscapes has been discussed since the 1960s (Castelle et al., 1994; Richardson et al., 2012). This discussion has included the cost-benefit analysis of protection of biodiversity, water quality and quantity (Castelle et al., 1994; Broadmeadow and Nisbet, 2004), as well as the land-owner cost of different designs (Tiwari et al., 2016; Lundström et al., 2018). Depending on the policy around their implementation, riparian buffers in Fennoscandia are most often less than 15m wide, but can range between anywhere from 0-100 m (Gundersen et al., 2010; Ring et al., 2017; Oldén et al., 2019a; Kuglerová et al., 2020). Although fixed width buffers have been the standard and are easy to implement (Richardson et al., 2012), new ideas of HAB (hydrologically adapted buffers) or END (emulating natural disturbance) management within production forestry are emerging (Sibley et al., 2012; Kuglerová et al., 2017). Regardless, a common feature in previous buffer management theory and practice is that implementation is typically conducted in mature forests at final-felling.

What has garnered less attention, both in research and in policymaking, is the long-term planning for and management of riparian buffers based on hydrological, biogeochemical and ecological functioning throughout the rotation period. Since the 1950s, even-aged production forestry has been the standard practice in Fennoscandia (Enander, 2007), and since the 1990s, typically includes saving riparian buffers around surface waters at final felling (Hasselquist et al., 2020). However, other forestry operations, such as pre-commercial or commercial thinning, have been carried out previously with little consideration of where streams are located (Hasselquist et al., 2020). Also, leaving a riparian buffer at final felling assumes that the forest within the riparian zone was functioning well before final felling and can continue to function when the surrounding trees are removed.

Forest management efforts to retain riparian buffers have largely overlooked headwater streams (Hasselquist et al., 2020; Kuglerová et al., 2020) which is why we specifically focus our attention on these small streams (< 3m width, less than 1000 ha catchment area). The majority of these streams in Fennoscandia were likely modified by humans to increase drainage and productive forest land (Hasselquist et al., 2018), but are not identified as waterbodies according to the EU Water Framework Directive (WFD), nor Natura 2000, nor "nationally valuable waters" by the Swedish Agency for Marine and Water Management (SwAM), and are likely not even present on standard maps (Bishop et al., 2008; Ågren et al., 2015). Recent estimates found that in Sweden, less than quarter of the smallest channels, and less than 10% of ditches are on 1:12 500 maps (A. Ågren, personal communication, April 24, 2021). Nonetheless, they have the potential to be of key importance to biodiversity and ecosystem processes and changes in their function likely have cumulative effects to downstream waterbodies (Bishop et al., 2008; Kuglerová et al., 2021). The objectives of this review are to (1) synthesize the current knowledge of the effects of historic forest management on riparian forest structure and function of headwater streams in Fennoscandia, (2) discuss how this legacy of management affects the functioning of riparian buffers when the adjacent stand is felled and (3) describe a science-based riparian forest management strategy that could enhance the functioning of riparian zones over the whole rotation cycle. Our goal is not to present a systematic review of all literature, but to give an overview, and provide a starting point for discussion of our management suggestions. Throughout the review we use the Strategic Management Objectives for good environmental consideration in forestry (SMOs) regarding buffer zones along lakes and waterways, set in a dialogue process with the forest sector in Sweden (Swedish Forest, 2013), as a framework for our discussion. Namely, riparian buffers should act as a (1) filter by preserving important soil biogeochemical processes, such as denitrification and nutrient uptake, (2) stabilize stream banks to prevent erosion and prevent sediment transport from uplands, (3) contribute food, or subsidies, to aquatic organisms through falling leaves and insects, (4) regulate light and hence stream temperature, (5) contribute deadwood, and (6) preserve biodiversity (Swedish Forest, 2013).

2. Legacy effects of forest management in riparian zones of boreal headwater streams and reasons to change

2.1. Changes in hydrology have altered riparian forest composition

Waterways have been historically impacted and modified in ways that influence adjacent riparian zones. For example, in Finland and Sweden, wetlands have been drained for forestry since the early 1900s (Lundberg, 1914). In Sweden, state subsidies were granted during the 1930s to private landowners to drain peatlands and wet forests (Päivänen and Hånell, 2012). In Finland, state subsidies also began in the 1930s, but peaked between 1950 and 1970 (Päivänen and Hånell, 2012). Gundersen et al., (2010) suggested that the millions of km of ditches that exist in Finland and Sweden have similar functions as natural streams since they transport water to rivers and could potentially be considered in the area included in riparian forest estimates. Furthermore, streams as narrow as a couple of meters wide were channelized by removing boulders and wood that would impede timber floating (Nilsson et al., 2005), but streams too small to float timber were also straightened to increase drainage of the surrounding forest (Hånell, 2009). During the timber floating era between the 1800s - 1970s, many riparian forests were cut (Nilsson et al., 2005). Certainly, the creation of streams with riparian zones from what used to be wetlands in addition to the simplification and straightening of headwater streams has changed the hydrology of many riparian zones and limited land-water interactions (Nilsson et al., 2005). The altered hydrology has likely contributed to the lack in variation of tree species composition and structure in riparian zones mainly due to the suppression of long-lasting floods and increased frequency of short floods with lower magnitudes. Thus, management actions to restore the hydrology of these waterways could be as important as restoring the forest composition to help meet environmental goals. Furthermore, future management actions should be prioritized on streams and streamside stands that have been affected by simplification either through forest management or hydrological modification.

2.2. Even-aged forestry

The ecological status of riparian forests and adjacent streams greatly depends on forest management (Kuglerová et al., 2021), which includes a history of fire suppression. Standard forest management practices in Sweden have gone through various changes over time depending on societal needs, contemporary science, and forest policy – all of which have influenced the structure and functioning of riparian forests (Ring et al., 2018a; Hasselquist et al., 2020). Forestry in the Fennoscandian boreal forests is characterized by long rotation times (60-120 years), during which stands are managed to be single-storied and dominated by either of the two native coniferous species Norway spruce (*Picea abies* (L.) Karst.) or Scots pine (*Pinus sylvestris* L.; Fig. 1A, Fig. 2). Contemporary standard practices for management of a forest stand in Fennoscandia begin with tree harvest by clear-felling, followed by mechanical site preparation and planting with commercially profitable tree species – almost exclusively conifers – within three years after felling (Lundqvist et al., 2014). After about 10-15 years or when the trees are 2-4 m tall, pre-commercial thinning is required to remove individuals that are competing with planted trees (Enander, 2007; Lundqvist et al., 2014). These cleared trees have typically been left on site, but this may change in the future with emerging technologies that may allow their use for biomass (Egnell et al., 2011; Sängstuvall, 2018). After 20-70 years, commercial thinning takes place, where trees are removed to reduce competition with those intended for final harvest, but also to provide a potential income for the forest owner mid-rotation. Finally, final felling occurs again after 60-120 years (Lundqvist et al., 2014; Agestam, 2015). At this stage, typically all trees are removed, except those required to be left according to regulations aiming at preserving riparian function and biodiversity (SFS 1993:1096) or certification schemes if the forest owner is certified (Forest Stewardship Council (FSC) 2020; Program for the Endorsement of Forest Certification Schemes (PEFC) 2018).

It was not until the updating of the Swedish Forestry Act in 1993 (SFS 1993:1096), along with the adoption of the FSC (1998) and PEFC (2000) standards, as well as other environmental policies enacted in the 1990s, that riparian buffers were applied in Swedish forestry (Hasselquist et al., 2020). But given these relatively recent policy changes in relationship to the long rotation times of forests, there has likely been previous forest management that promoted commercially important conifer species within the riparian zones (e.g. Dahlström et al., 2005). This outcome may not have been intentional but rather a consequence of riparian zones in headwater streams not being as well defined as for larger streams (Hagan et al., 2006) together with fire suppression that affected landscape-scale processes (Linder et al., 1997; Hellberg et al., 2009). Regardless, we searched for studies that inventoried Fennoscandian riparian forests of streams $<$ 3 m wide and documented that many contemporary riparian forests are dominated by Norway spruce all the way to the water's edge (Appendix A; Fig. 2). While we were only able to find studies from Sweden, it is likely that managers across Fennoscandia will be confronted with the legacy of this simplified riparian tree composition in production stands for a long time to come.

Due to the long history of even-aged forest management on a large proportion of the forest landscape, contemporary riparian zones do not likely function as well as those in old growth unmanaged stands. Historic forest management operations have resulted in changed structure and aquatic habitat by reducing the amount of deadwood entering streams (Dahlström and Nilsson, 2004), decreasing the amount of old and dead trees on land (Linder et al., 1997; Östlund et al., 1997) and changing the

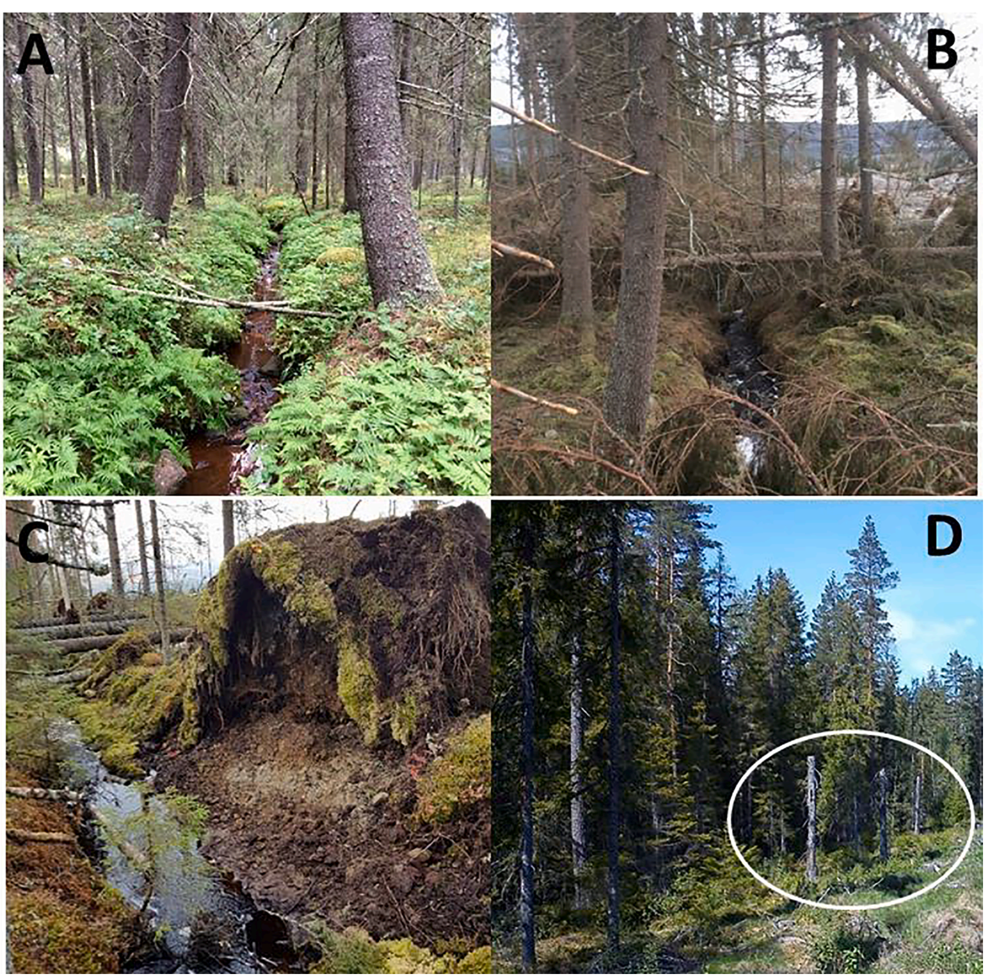

Fig. 1. (A) Typical even-aged Norway spruce forest along a straightened headwater stream in Sweden. (B) The same headwater stream three months after the adjacent forest was cut and a 15 m buffer was left on either side of the stream. These trees are likely to experience windthrow that lifts root wads and releases suspended sediments, but also exposes larger sediment sizes like gravel, cobble, and boulders and widens the stream at that location (as in C). (D) Riparian buffer that included conservation methods such as leaving 'high stumps' (circled), (Photo credits: E.M. Hasselquist (A & B), L. Kuglerová (C), Elisabet Andersson (D)).

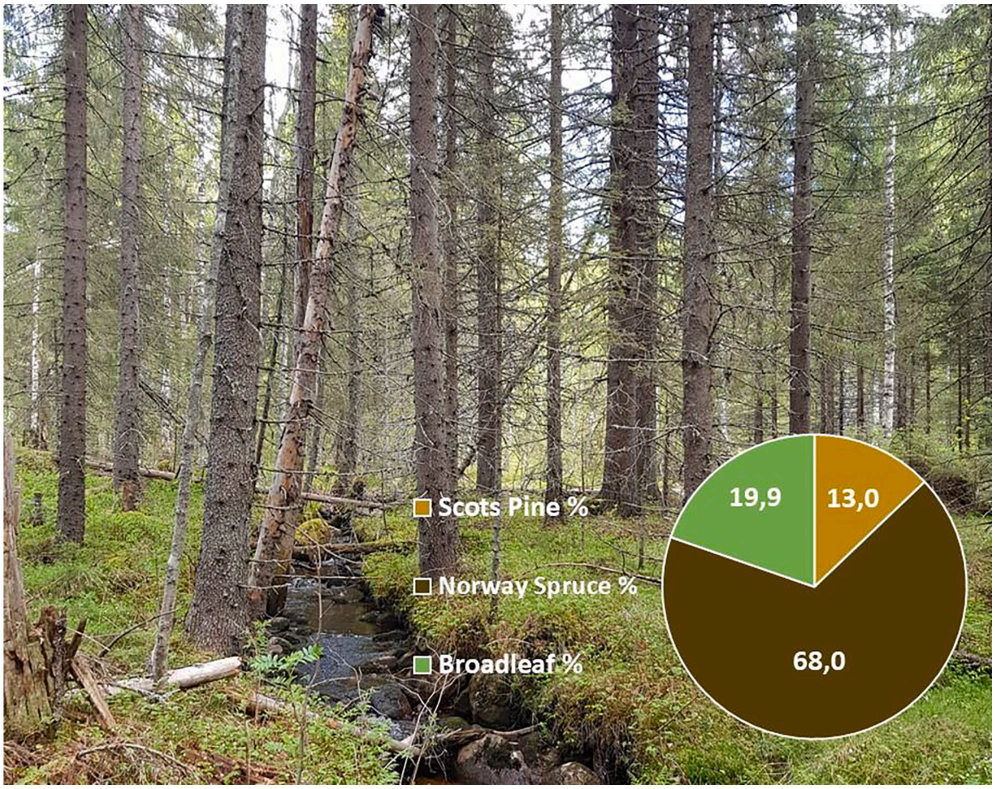

Fig. 2. Small perennial stream in boreal Sweden with riparian zones dominated by spruce. (photo: Lenka Kuglerová). (Inset) Typical species composition (percent) based on stem volume or basal area of riparian forests in Sweden of streams < 3m (derived from literature review that included 171 sites, Appendix A).

succession, age structure, and species composition of the forests (Östlund et al., 1997). A lack of old trees and deadwood poses a threat to many forest species, including plants, animals and fungi (Berg et al., 1994; Siitonen, 2001). What is left behind in riparian buffers when the adjacent stand is felled is a simplified forest structure made up of mainly adult trees with few lower branches because stands have typically developed under dense conditions (Fig. 1A). Thus, although riparian buffers typically left for conservation purposes in production forestry systems might provide some minimal protection, they will not provide sufficient habitat to preserve biodiversity of riparian plants (Oldén et al., 2019a) and terrestrial animals (Hylander et al., 2004). Furthermore, such simplified stand structures dominated by conifers have been associated with reduced aquatic macroinvertebrate community (Jonsson et al., 2017), provide less shade due to the absence of lower branches - influencing summer water temperatures in some systems (Moore et al., 2005), and supply relatively low-quality leaf litter input to the stream (Naiman and Decamps, 1997). Thus, even within a production forest that has not been harvested for more than 50 years, riparian zones under this management are likely functioning differently than they would have if they had developed without human intervention (Liljaniemi et al., 2002; Dahlström and Nilsson, 2004; Dahlström et al., 2005).

2.3. *Typical Fennoscandian boreal forest management has promoted conifers*

In Sweden, there is a long history of promoting commercially important conifers at the expense of broadleaved species (Esseen et al., 1997; Östlund et al., 1997; Enander, 2007). Forest management, including fire suppression, has also changed the natural disturbance regimes, such as wildfires, in Fennoscandia that once was more favorable for broadleaved trees, (Linder et al., 1997; Hellberg et al., 2009). This long-term land-use change from less dense multi-species forests to one more dominated by conifers, typically Norway spruce, may have had an important role in the documented browning of freshwaters (increasing dissolved organic carbon or DOC; Meyer-Jacob et al., 2015; Kritzberg et al., 2020), especially in southern Sweden. Litter from coniferous species, such as spruce and pine, is of lower quality and more recalcitrant substrate for microbial processes compared to litter from broadleaved trees (Duan et al., 2014), and hence more DOC leaches from coniferous than from broadleaved forest soils (Camino-Serrano et al., 2014).

In contrast, a higher proportion of broadleaved tree species in riparian zones has been shown to improve stream conditions by increasing inputs of higher quality leaf litter (Lidman et al., 2017a). Increased litter inputs have been linked to enhanced heterotrophic activity in streams, which plays a fundamental role in the retention of stream nutrients (Hill et al., 2009) and provides energetic support to aquatic food webs (Wallace et al., 1997). The inclusion of diverse broadleaved species into typically conifer-dominated riparian stands may also reduce inorganic nitrogen leaching to streams by providing a higher-quality carbon source for microbes, which promotes immobilization and denitrification, processes that are often limited by low availability and/or quality of C (Duan et al., 2014; Gundersen et al., 2006; Hill and Cardaci, 2004; Hedin et al., 1998). Broadleaved trees are also important for terrestrial and instream biodiversity. Broadleaved forests constitute one of the most species-rich types of forests in Fennoscandia (Berg et al., 1994; Esseen et al., 1997; Jonsell et al., 2007). Particularly old broadleaved trees and forests are important for rare species, such as the nationally threatened white-backed woodpecker and also red-listed beetles (Bell et al., 2015) and lichens (Rudolphi and Gustafsson, 2011). Furthermore, leaf litter from broadleaved species support more abundant and/or diverse macroinvertebrate (Webster and Benfield, 1986; McKie and Malmqvist, 2009; Jonsson et al., 2017) and fish (Inoue et al., 2013) communities when compared to stream reaches surrounded entirely by coniferous trees.

Moving towards multi-layered and species diverse forests surrounding headwater streams will be mostly advantageous both in terms of ecological functioning and biodiversity. Management (e.g., selective logging) that better mimics natural disturbances, such as fire, thus creating canopy gaps or less dense stands has recently been promoted (Sibley et al., 2012), especially for spruce dominated stands (Tolkkinen et al., 2020). Although shading is one of the functions desired from riparian forests (Swedish Forest, 2013), it is likely that primary productivity in northern streams is often light limited (e.g., Rand et al., 1992), and early-successional forests can promote instream algal growth due to higher light and nutrient conditions, with positive consequences for aquatic food webs (e.g., Nislow and Lowe, 2006; Kaylor and Warren, 2017). Small streams with young forest (11-50 years) tend to have higher water pH, larger instream organic matter standing stocks (McKie & Malmqvist, 2009; Lidman et al., 2017a), a greater abundance of aquatic moss, and may have higher macro-invertebrate diversity when compared to streams running through both recently clear-cut stands and old forests (e.g., McKie & Malmqvist, 2009; Jonsson et al., 2017).

Selective logging in riparian areas could help mimic disturbance as well as increase the density of stream macroinvertebrates (Carlson et al., 1990) and improve habitat for lichens (Klein et al., 2020), but for lichens a high tree mortality in these habitats has also been shown to be correlated to time-lagged local extinctions (Johansson et al., 2018). Early-successional forested sites have been shown to have high species diversity, as well as support complex food webs and enhanced rates of ecosystem processes (Swanson et al., 2010). In addition, many red-listed wood-inhabiting beetles are associated with sun-exposed dead wood as a substrate like those found in open broadleaved forests or on the edges of riparian buffers (Bell et al., 2015). Thus, protecting some proportion of the existing stand is good for deadwood and the biodiversity that depends on it, but in many cases, introducing disturbance could promote more variation in the stand structure and light environment of the riparian forest. This would be beneficial for protecting water quality and quantity, ecosystem functioning, and biodiversity.

2.4. *Stand conditioning causes windthrow, and spruce are especially susceptible.*

When the majority of the forest stand is removed during final felling, trees within a conifer-dominated and even-aged riparian buffer have been conditioned to developement in a forest stand and do not have the root system to withstand high winds and are thus more susceptible to windthrow (Figs. 1B & C and 3; Grizzel and Wolff, 1998; Bahuguna et al., 2010; Boggs et al., 2016; Mäenpää et al., 2020). The risk of windthrow depends on buffer width, tree species, exposure, tree height, stem density, time since thinning, and season (Bahuguna et al., 2010; Griess et al., 2012; Mäenpää et al., 2020). Regardless, in a study of more than 100 streams for which final felling was performed 2-8 years prior to inventories in both northern and southern Sweden, nearly 70% of the sites were impacted by windthrow to some extent (Fig. 3; Kuglerová et al., 2020). Similarly, 83% of sites where the adjacent stand was harvested 12 years ago were impacted by windthrow in a Finnish study (Mäenpää et al., 2020).

Norway spruce is considered to be particularly susceptible to windthrow. However, the risk of spruce blowing down due to strong winds decreased by over 50 % when grown in stands with more than 30 % broadleaved trees (Valinger and Fridman, 2011). Thus, mixing spruce with tree species such as birch or pine, which have higher mechanical stability (Peltola et al., 2000), could improve the overall wind stability of stands otherwise dominated by spruce (Dhôte, 2005). Additionally, riparian buffer width can influence windthrow; in Finland, 30 m wide buffers – regardless of if they are selectively logged - had less windthrow near the stream than 15 m buffers (Mäenpää et al., 2020). A further complication in northern latitudes is that climate projections predict milder and wetter winters with less soil freezing (Jungqvist et al., 2014), making trees even more susceptible to windthrow in the future (Felton et al., 2016).

One benefit of windthrow would be the addition of deadwood as habitat and structure in riparian and instream ecosystems. But,

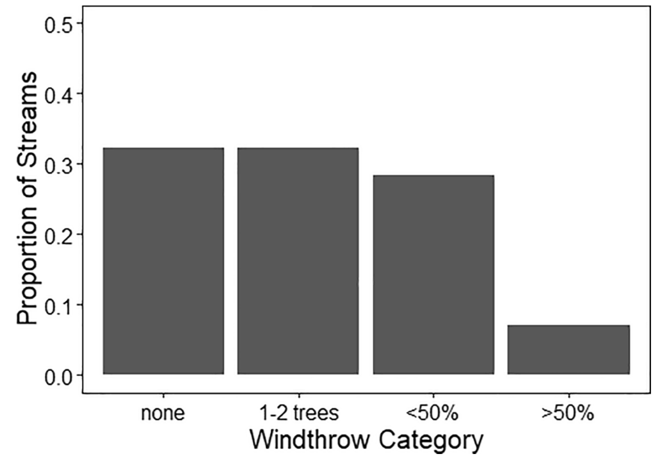

Fig. 3. Proportion of 50 m long stream reaches whose riparian buffers experienced various levels of windthrow along in 111 recent (2-8 year old) clear-cuts in northern and southern Sweden (redrawn from Kuglerová et al., 2020). Windthrow categories were divided by the number of trees blown down: none; 1-2 trees; more than 2, but $<$ 50 %; and $>$50 % trees down.

depending on the size of the stream, windthrown wood seldom makes it into the channel to act as instream habitat because it often hangs suspended, creating bridges that may not breakdown for decades (Bahuguna et al., 2010). However, this delay could benefit some sessile terrestrial species, such as fungi, bryophytes and lichens that depend on dead wood (Kruys et al., 1999; Hylander et al., 2005). Additionally, large spruce that eventually blow down could increase recruitment of boulders and gravel to the stream. Although too much fine suspended sediment can be harmful for water quality (Lavonen et al., 2013) and instream organisms (Österling et al., 2010), many streams in Sweden have been cleaned of boulders and large wood and straightened to increase drainage, and therefore productivity, of forests next to the stream (Hånell, 2009). This simplification of the geomorphology of the stream made flow velocities faster and flashier, often washing out gravel to downstream reaches (Polvi et al., 2014). Ecological restoration of larger rivers has been ongoing in Sweden since the 1980s (Hasselquist et al., 2015), but small streams are rarely the focus of such efforts. When root wads are lifted after blow down, and gravel, cobble, and boulders are exposed, streams could widen at that location (Fig. 1C), which helps to regain geomorphic complexity of substrates as well as meanders, thus, passively restoring streams.

One of the problems with large scale windthrow in riparian zones is that uprooted trees cause a release of sediment (Grizzel and Wolff, 1998; Boggs et al., 2016), and the cavities left behind can provide an environment for methylation of mercury (Ukonmaanaho et al., 2016; Eklöf et al., 2018). The particle size of sediment released is important as fine sediments can bury and clog spawning gravel for salmonid species (Kondolf, 2000), bury or remove algae and bryophytes, and alter the diversity and composition of macroinvertebrate communities (Burdon et al., 2013; Louhi et al., 2017; Turunen et al., 2020). Furthermore, suspended sediments, especially organic particles, are difficult to remove when treating drinking water (Lavonen et al., 2013). Thus, release of fine sediments and creation of conditions that foster mercury methylation close to streams could possibly offset many of the benefits of the buffer – at least in terms of water quality. In addition to causing problems with sediment export, windthrow decreases the ability of riparian buffer to shade. While some level of windthrow could be good for ensuring biodiversity and passively restoring these straightened streams, too much will degrade streams and could cause sedimentation and water quality issues downstream.

3. A new riparian forest management strategy

Based on our literature review, we suggest that increasing tree species diversity in riparian zones, particularly promoting broadleaved species, would increase the long-term function of buffers by providing higher quality food for aquatic organisms (subsidies), supporting greater riparian and instream biodiversity, and providing higher quality carbon to sustain biogeochemical processes in riparian soils. Furthermore, we argue that increasing structural diversity of the riparian zone, such as in a multi-layered forest, with more deadwood would provide for higher biodiversity and a more stable riparian zone with less windthrow, and thus more stable stream banks, and be a better filter for sediments from uplands. A more biologically and structurally diverse forest would provide more shade, but also allow some light in these light limited northern headwater streams. To achieve these functions that are typically desired of riparian buffers, we suggest active planning and management within riparian zones throughout the rotation to restore the functions that are needed to meet stated environmental goals (Swedish Forest, 2013, EU Water Framework Directive, EU Habitats Directive, UN Sustainable Development Goals (SDGs), EU Forest Strategy etc.). To accomplish this, management actions should be prioritized on streams and streamside stands that have been affected by simplification either through hydrological modification or forest management. Thus, we first suggest careful evaluation of the stand structure and composition of riparian zones along headwater streams and promoting broadleaved trees along streams that do not already have desired ecological and biological values. Although many headwater streams have been affected by instream activities that have increased drainage of the surrounding area, forest management, and fire suppression, many are less affected and do not need management to increase their biodiversity values or ecological function. Furthermore, there are factors outside of forest management that will affect the species composition and structure of a forest that cannot be managed, for example soil type, topography (flat vs. ravines with strong north and south facing slopes), presence of certain substrates such as boulders that are important for certain red-listed species (Hylander et al., 2005), and to some extent soil moisture conditions (but restoration of the hydrology and instream complexity may be possible in some cases). If, after an evaluation of the riparian forest has found a simplified stand structure and composition, then we suggest managing the age and size structure of the riparian forest as early as possible in the rotation cycle to achieve the greatest benefit over the long-term.

Some aspects of this management strategy have been included in the Swedish Forestry Act (2013:2, paragraph 7:21) as well as have been included in recommendations developed by the Swedish forest sector (Swedish Forest, 2013, and published in English in Ring et al., 2018b). Although such goals have been stated in policy documents, long-term strategies of how to create these functional riparian buffers that forest managers can directly adopt are lacking. Here, we outline a possible strategy that has however not been tested, and we encourage future studies to empirically examine our proposed approach.

3.1. Start management early

Deciding to start riparian buffer management at the planting stage or while a stand is young provides greater opportunities to guide species composition and structure of the stand (Schütz, 2001). At the planting and pre-commercial thinning stages, managers have many possibilities to promote certain tree species by removing competing species, which is also true in the riparian zone. At these early stages, there are typically many individual trees to choose from that could be promoted because

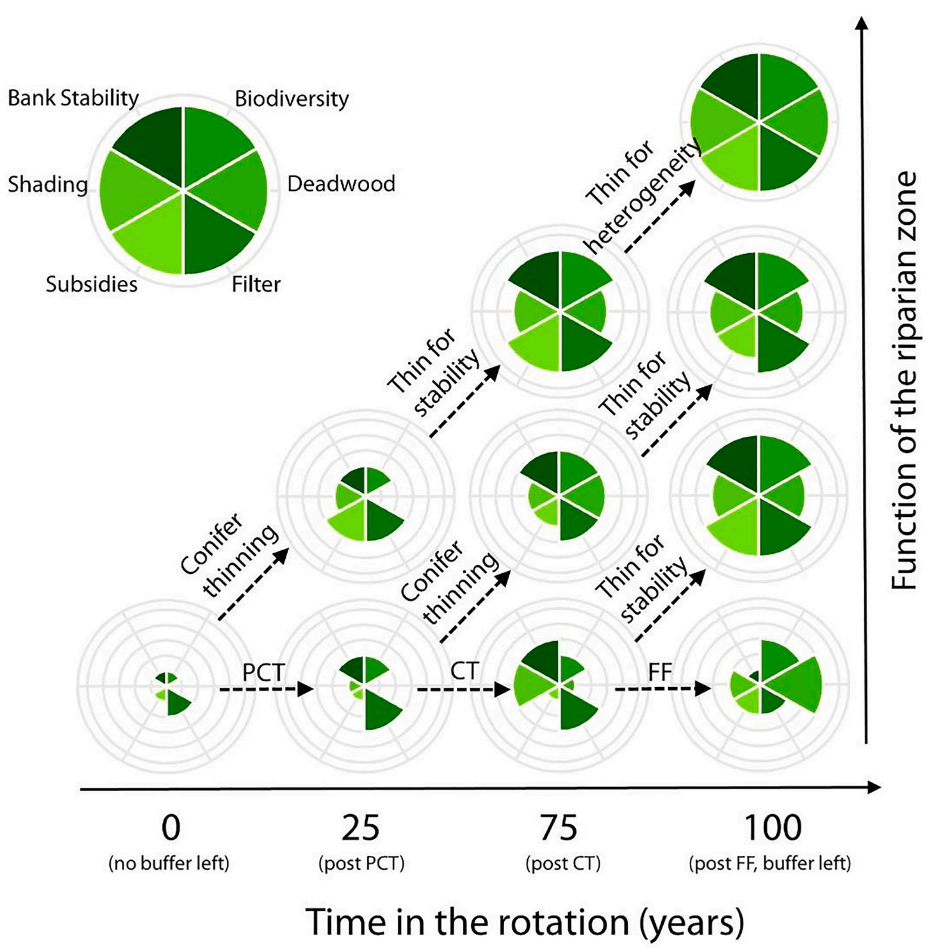

Fig. 4. Conceptual diagram showing how the potential function reached in the future final felling stage can be achieved by early management of the riparian zone. The x-axis represents time in the rotation of a typical even-aged forestry model; the forest stand ages as it moves towards the right and experiences management actions (dotted lines). The circles represent the ecological functioning of a given time point ('state') found in between management actions; depending on the management action taken at each stage in the rotation period, the function of the riparian forest stand will change. Six functions that are typically desired of riparian buffers and listed in the Swedish Strategic Management Objectives (SMOs) are shown within the circles in a polar plot with a scale from 0-5, 5 being the highest function. Namely, riparian buffers should act as a filter by preserving important soil biogeochemical processes, such as denitrification and nutrient uptake; stabilize stream banks to prevent erosion and prevent sediment transport from uplands; contribute food, or subsidies, to aquatic organisms through falling leaves and insects; regulate light conditions – and thus shade and temperature - of streams; contribute deadwood; and preserve biodiversity. Scores are hypotheses based on the literature review and discussions among co-authors. Management actions that are horizontal along the x-axis represent typical management done during even-aged forestry (pre-commercial thinning, PCT; commercial thinning, CT; and final felling, FF), while those done on the diagonal are according our new riparian management strategy (see Fig. 5 for explanations). Please note that management towards a higher functioning riparian buffer can be started at any point in the rotation.

natural regeneration of broadleaved species is common after final felling (Hallsby et al., 2015). Starting management for multi-layered, mixed-species riparian forests as early as possible will increase the possibilities for future management options as well as increase the functioning of the riparian zone over the entire rotation period (Fig. 4). Marking the boundary of, or delineating, the riparian buffer needs to be done much earlier than currently is the case for even-aged management, but otherwise all suggested actions for the riparian zone can be timed with the typical management steps that are part of contemporary production forestry thus not increasing operational cost due to these additional actions.

The suggestion of planning for conservation efforts early in the rotation period is well in line with recommendations from the Swedish forest sector (Swedish Forest, 2013), regulations in the Swedish Forestry Act (paragraph 7:21) and the EU Habitats and Bird Directives (Michanek et al., 2018). The documents can be interpreted as requiring landscape planning at all forest ages, not just at final felling, to meet many environmental and biodiversity goals. However, environmental considerations in young and premature stands are not as developed and examined as environmental considerations in connection with final felling (Weslien and Widenfalk, 2014). Although guidelines for environmental considerations in thinning operations are stipulated by the Swedish Forest Agency (Agestam, 2015), studies that address the extent to which this actually occurs in practice are lacking (but see Kuglerová et al., 2020). Moreover, planning earlier as we suggest can help meet not only biodiversity, but also other policy goals related to the EU Water Framework and Habitats Directives, as well as several Sustainable Development Goals and the EU Forest Strategy. In time, this approach will also help restore a more structurally complex riparian forest that provides the ecological functions to better meet conservation objectives.

The optimal target for the proportion of broadleaved trees and deadwood in riparian zones and streams of such small streams has not been adequately determined. However, Ström et al. (2009) found that riparian sites with an average of 44% broadleaved tree cover *in addition to* higher amounts of broadleaved shrub cover were better than sites with 24% broadleaved tree cover for snail biodiversity. In a study of unmanaged, old-growth riparian zones in NW USA, broadleaved species typically made up about 50% of the basal area in the riparian zone of northern 1st order streams (Pabst and Spies, 1999). Targets for instream deadwood could be based on what is typically found in old growth forests. In central Sweden, headwater (~2m wide) streams running through old growth forests typically had nearly four times the volume of deadwood (93.7 m^3ha^{-1}) compared with managed forests (24.8 m^3ha^{-1}; Dahlström and Nilsson, 2004). A comparison of headwater streams flowing through unmanaged and managed headwater stream sites in Russia and Finland found unmanaged sites had twenty times more instream deadwood than managed forest sites (331.6 vs. 16.8 m^3ha^{-1}; Liljaniemi et al., 2002).

3.2. Implement by complementing the typical even-aged forestry cycle

Forest managers in Fennoscandia typically perform management actions every 20 - 40 years and at each of these time points, the riparian forest could be delineated, evaluated, and managed to improve their long-term function. Here, we present some basic principles of a new riparian forest management strategy that could be implemented to enhance riparian forest buffer function through long-term management towards a goal of an uneven-aged, mixed-species riparian zone (sensu Bigley and Deisenhofer, 2006; Fig. 5). The strategy can be viewed as starting after the final felling/planting stage (early in the rotation) or the management actions described in each stage of the long-term strategy could be implemented at any stage in the forestry cycle to try to achieve

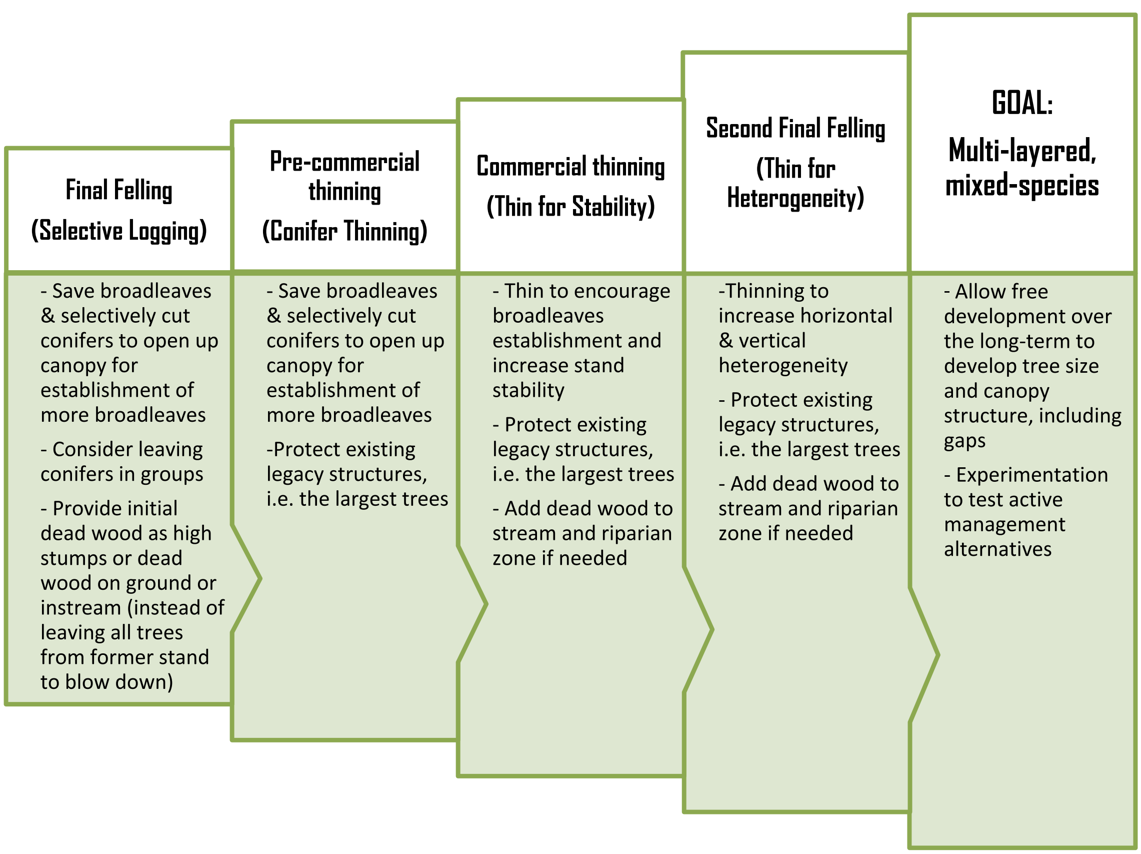

Fig. 5. Summary of basic principles of the riparian forest management strategy to enhance riparian forest buffer function through long-term management towards a goal of a multi-story, mixed-species riparian forest. Typical stand management actions are listed in the headings and in parentheses below are the new riparian forest management actions that coincide with them. The new riparian forest management strategy can start at any point during the cycle.

higher functioning of the riparian zone, albeit it less than if it were implemented earlier (Fig. 4).

3.2.1. Final felling and planting

Irrespective of contemporary forest management actions, stands at the final felling stage are likely, in the next few decades, to be composed primarily of single-storied, spruce up to the water's edge along headwater streams (Fig. 1A & 2; Appendix A). At this first final felling stage, there are the least options for management towards an uneven-aged, mixed-species riparian zone (Fig. 4), thus – if there are no other important biological values on the site - we encourage felling many of these trees to essentially 'start over'. At this stage when the adjacent stand is cut, we suggest conserving all broadleaved trees, which on average are about 20% of the riparian tree cover (Fig. 2, Appendix A), and selectively cutting many of the largest spruces in the riparian buffer. Leaving conifers in groups rather than leaving them scattered throughout the riparian zone would create bigger gaps within the riparian buffer that would likely be needed to open up the canopy to allow for establishment of diverse broadleaved trees and shrubs (Ackzell, 1994; Kuuluvainen, 1994; Mallik et al., 2014). This management would emulate natural disturbances and create variation in light and shade that could also benefit stream biodiversity (Kreutzweiser et al., 2012) and act as a future source of deadwood. It is important to stress that local knowledge and experience is important when planning these kind of measures so that they are feasible given local conditions, such as tree species preferences for different site and soil types. Selective cutting has previously been proposed and modeled by other authors (e.g., Hylander et al., 2004; Oldén et al., 2019b; Sonesson et al., 2020) and the SMOs (Swedish Forest, 2013). Furthermore, leaving some tall spruce would allow for some windthrow that could help to passively restore gravel and boulder recruitment and meanders to the stream (Fig. 1C), but not too much that could cover these larger sediment sizes or transport suspended sediment downstream. To still provide dead wood, but avoid excessive windthrow, a portion of the conifers that are cut could be left as dead trees within the riparian buffer as "high stumps" (trees cut about half-way up their trunk, left for conservation purposes), which is already implemented in some locations along the outside edges of buffers (Fig. 1D). Dead wood could also be placed on the forest floor as substrate for red listed fungi and insects, or directly in the stream to act as structure and habitat for instream organisms. We suggest evaluating the amount of dead wood at each management step and consider if additional dead wood should be created from on-site sources. Additionally, at each management step, there should be a 'machine free zone' where machines do not drive close to the buffer nor should soil preparation occur near the buffer, regardless if trees were left or not. Machine driving and site preparation can reduce tree stability by damaging the roots of trees in the buffer as well as provide sources for sediment that could be transported to the stream (Palviainen et al., 2014).

Within three years after the final felling, stands are typically planted in contemporary Fennoscandian production forestry systems. Seeding of desired species is a widespread practice used in riparian restoration efforts worldwide (González et al., 2015). Thus, to ensure that not just one species of broadleaved tree dominates (i.e., birch) or that invasive species do not establish, sowing seeds of fast-growing, diverse broadleaved species could be beneficial in some cases (Newaz et al., 2019), especially if they are followed-up with thinning of species competing with them – even birch in some cases. It is important to note that not just trees can provide important habitat and subsidies, shrubs can provide nearly 50% of broadleaved litter to streams (Muto et al., 2009). Thus, willows (*Salix* spp.) or other broadleaved trees and shrubs such as alder (*Alnus* spp.), aspen (*Populus* spp.), rowan *(Sorbus* spp.*)*, or cherry (*Prunus* spp.) are common along larger streams of Sweden (Hasselquist et al., 2015) and Canada (Musetta-Lambert et al., 2017) and could be beneficial to increasing diversity of tree species in riparian zones of Fennoscandia. Due to the expense of seeding as well as the follow-up management that would be needed to ensure the establishment of seeded individuals, this can likely not be done at large scales. But, for locations that have a higher potential to be important, e.g., draining directly into Natura 2000 areas, it could be a good investment. Furthermore, if a site is identified as having a high potential for natural regeneration by broadleaved trees (e.g., source populations nearby or good connectivity to upstream reaches and thus capacity for dispersal via hydrochory), riparian zones could also be left without seeding but restoration of plant species richness could take longer than 25 years (Hasselquist et al., 2015). Finally, the density and diversity of woody species should be re-evaluated at each management step to ensure that we are not just switching from a stand dominated by one species (spruce) to another (birch).

3.2.2. Pre-commercial thinning

Riparian zones within stands at the pre-commercial thinning stage (10-25 year old stand) may have existing trees left from the previous stand. This is because the Swedish Forestry Act from 1993 requires forested buffers along lakes and watercourses to the extent needed to protect water quality, species etc. Thus sites harvested after 1993 could be expected to have mature trees left in the riparian zone. Further, both FSC and PEFC standards require protection of riparian forest buffers adjacent to streams and certification started to be applied during the 1990s. Therefore, stands that are at present younger than 20-25 years old are more likely to have a retained forested buffer from the previous stand (Ring et al., 2018a; Hasselquist et al., 2020). Older trees conserved in the riparian buffer (if present) should be protected and the amount of dead wood should be evaluated and created from on-site resources if there is too little. Pre-commercial thinning is typically performed manually using hand-held brush saws to remove any species competing with the commercially planted tree species at the pre-commercial thinning stage. Thus, selective thinning of young conifers could be relatively easy to implement in the delineated buffer zone to promote broadleaved trees and shrubs (Fig. 5); which we have termed "conifer thinning".

3.2.3. Commercial thinning

Riparian zones adjacent to stands at the commercial thinning stage could benefit from a more intense thinning now to try to increase broadleaved cover that would help restore ecosystem functioning and stability when they become a riparian buffer in the future. Most stands at the commercial thinning stage (20-70 years) will have been greatly influenced by a legacy of even-aged, conifer-dominated forestry. We suggest delineating these riparian buffers and managing them by "thinning for stability" - conserving all broadleaved trees and selectively logging conifers. A more intense thinning in buffers than in the adjacent stands can expose the trees within the future buffer to more wind, strengthening the tree root system and making them more stable when the adjacent stand is cut in the future (Lundqvist, 2017; Ring et al., 2018b). Furthermore, "thinning for stability" would also create canopy openings that stimulate natural establishment of broadleaved species (Ackzell, 1994) and create more variation in tree size. This would help to restore ecosystem functioning of the riparian zone as well as develop a more stable stand structure for the future, create openings while the surrounding stand is still in place that will help shade streams and riparian zones. Furthermore, thinning could promote an increase in diameter growth that has been shown to accelerate many of the characteristics of an old growth forest (Busing and Garman, 2002). In the case of a riparian zone having already been successfully regenerated to a multi-layered, mixed-species state, it could be allowed to continue to develop freely to the next stage (Lundström et al., 2018). Similar to the actions proposed at the final felling stage, no machines should enter riparian zones during thinning.

3.2.4. Second final felling

At the end of a full rotation period, we would enter the future final felling stage in our model of the riparian forest restoration strategy (Fig. 4, 5). If this buffer was managed from the first final felling through a full rotation period, then we hypothesize that it will have reached its maximum potential function (Fig. 4, i.e., shade, high quality litter, etc.). However, some management may be needed to ensure those functions continue, especially if the riparian management strategy was implemented for the first time at the commercial thinning stage. In the latter case, we suggest the potential of more thinning to increase horizontal and vertical heterogeneity, while still protecting the oldest legacy trees. Over the long term, we suggest allowing the riparian buffers to be left for free development in all or part of the riparian zone (Lundström et al., 2018). Leaving riparian zones for free development could help to develop tree size canopy structure, and part of the zone could be used for assessment of active management alternatives such as selective logging including gap creation (Fig. 5).

3.3. Risks

Opening up the canopy so that broadleaved species can establish may not be beneficial for all species, and may not even be allowed in some cases. The Finnish Forestry Act is an example of a regulation prohibiting the alteration of the characteristic features of riparian habitats designated as “key habitats,” which are specified as the special growing conditions and microclimate that result from the proximity of water and the tree and shrub layers (Finnish Forestry Act, 2013). Studies of selective logging within riparian buffers created during the final felling stage have shown that indeed, humidity decreases and temperature increases (Oldén et al., 2019b) and this in turn can have a negative effect on some bryophyte species (Oldén et al., 2019a). However, one important assumption when evaluating these impacts is that the riparian habitats were close to natural in the first place (species composition of trees not modified in the past). In the case of Oldén et al.’s work (2019a, b), they studied “key habitats” in Finland (i.e. springs, headwaters and ravines) which only include the most pristine sites. It is unlikely that headwater streams situated in the majority of production stands are environmentally close to those near-pristine sites evaluated by Oldén et al., (2019a,b) due to the past forest management and potentially instream actions. Furthermore, we are suggesting to act earlier in the rotation period to restore these riparian zones, so the effect of selective logging on microclimate would presumably be limited due to the presence of the surrounding intact stand when riparian management is done, for example, at the commercial thinning stage. Thus, when the riparian zone becomes a buffer during the second final felling stage (Fig. 5), the effects should be less, but this is not well studied.

Opening up the canopy so that broadleaved species can establish may also allow for the re-establishment of conifers, which is a common response when small gaps in the canopy occur, also along streams (Leemans, 1991), but thinning at later stages could adjust the species composition. Large gaps, on the other hand, typically encourage the recruitment of birch species (Leemans, 1991) and, in general, more diverse forests (Mallik et al., 2014). Leaving riparian buffers entirely unmanaged from the beginning is, of course, an option, but there is the risk that the riparian areas may not meet the desired cover of broadleaved species, and thus, would not meet policy goals within the time frame required. Thus, continued management during pre-commercial and commercial thinning stages would be important to ensure the trajectory of the riparian forest towards mixed-species stands and strive to be potentially better than nature (O’Hara, 2016).

The loss of some large dead spruce in the landscape due to riparian management could be a concern for biodiversity because deadwood hosts many different species and its reduction could thus negatively affect biodiversity (Kruys et al., 1999; Stenbacka et al., 2010; Hjältén et al., 2012). But, we are advocating for creation of high-stumps and adjusting deadwood amounts in every management stage which could compensate for this. Furthermore, this new riparian forest management strategy is implemented at the stand scale and we need to keep a landscape scale planning perspective. In a forest landscape, felling and other measures are conducted at different times on separate, relatively small forest stands (Michanek et al., 2018). Thus, it is unlikely that all of the large dead spruce would be lost from a given area all at once. Although small headwater streams are numerous in boreal systems (Ågren et al., 2015), there are still many stands that are not crossed by streams. Even so, there are about 2.5 km of streams for every 1 km^2 of land during base flow periods (Ågren et al., 2015) thus long-term management of riparian buffers could account for between 2.5 – 15% of the forest (if assume 5 - 30m fixed-width buffers on both sides of the stream). Selective logging in riparian zones has been shown to decrease the amount of decaying wood in the long-term, and riparian zones are best left unmanaged if we want to increase deadwood (Lundström et al., 2018). Yet, planners still need to consider nature conservation on upland locations as well, so even with early management of riparian buffer zones, we will likely continue to have large spruce in the landscape, but potentially less in riparian zones.

3.4. Interaction of the riparian forest management strategy and riparian buffer width

Our long-term riparian forest management strategy complements ideas about the appropriate spatial arrangement of riparian buffers, especially END (emulating natural disturbance) management (Sibley et al., 2012; Kuglerová et al., 2017), but even HAB (hydrologically adapted buffers) and fixed width buffers (Richardson et al., 2012). In the case of END management, opening up portions of the canopy would mimic the non-stand-replacing fires and windthrow events that have been suggested to better represent the natural disturbance regime of boreal Fennoscandia (Kuuluvainen, 2009). In turn, these canopy gaps would then promote the coexistence of broadleaves and coniferous trees (Kuuluvainen, 1994). We suggested leaving existing trees in groups rather than leaving them scattered throughout the riparian zone to create bigger gaps within the riparian buffer that would likely be needed to open up the canopy to allow for establishment of diverse broadleaved trees and shrubs (Ackzell, 1994; Kuuluvainen, 1994; Mallik et al., 2014). This could complement HAB management (Kuglerová et al., 2014) or management for some red-listed species (Hylander et al., 2005) because these groups of trees could be retained in the groundwater recharge zones or in zones with known or potential values (e.g., large amounts of deadwood or boulders). Previously, it has been noted that sites with a high canopy, as in the case of single-storied spruce dominated sites, should have wider buffers for the microclimate to be maintained (cf. Murica, 1995; Dignan and Bren, 2003). Thus, with management for a multi-storied buffer zone, fixed-width buffers could potentially be narrower at the second final felling stage of our riparian management strategy, at least in some cases. Alternatively, a very narrow riparian zone of five meters could be retained unmanaged with up to 30 m of selectively logged buffer beyond that and with very little additional cost (Sonesson et al., 2020). This wide buffer, but selectively logged design could protect against windthrow nearest the stream (Mäenpää et al., 2020) where it would impact the stream most. Regardless, windthrow will continue to be a problem if fellings are made in such a way that the forest buffer is exposed in the direction of the most likely windstorms, when adjacent final fellings are large, and when final fellings are made on both sides of the stream at the same time (Hylander et al., 2005; Mäenpää et al., 2020).

4. Conclusions

It is well established that riparian areas have key functions in the landscape and harbor unique and often diverse plant and animal communities. With this in mind, it is surprising that the primary function of riparian buffers has previously been thought of mainly as a way to protect water against negative effects of final felling (i.e., clear-cutting), usually in an even-aged forestry context. Due to in stream actions like straightening and ditching, in combination with forest management and fire suppression that promoted commercially profitable conifers all the way to the water's edge, the majority of riparian zones of headwater streams in Fennoscandia are not functioning as well as they could. To improve function throughout the entire rotation period, we suggest delineating the future riparian buffers early in the rotation cycle and managing them for a multi-layered, mixed-species forest. By following this new riparian forest management strategy, we could increase the ecosystem functioning of riparian zones along small streams in managed Fennoscandian boreal forests starting today and throughout the whole rotation period, adding to the benefits provided by riparian buffers at final felling. Future experimental studies should be conducted to verify the impacts of the proposed strategy on the functions of riparian buffers. Early and continuous planning of riparian buffers could aid in the attainment of current environmental policy goals, such as the EU Water Framework Directive and the UN SDGs. Moreover, establishing continuous management of riparian buffers as a practice could help advise and update policies which at present fail to acknowledge its importance.

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.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2021.119254.

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