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# Costs and benefits of seven alternatives for riparian forest buffer management

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**ABSTRACT**
Stand development in riparian forest buffers was simulated for three forest landscapes in Sweden, using data taken from a sample plot inventory along 38 streams. The objectives were: to quantify the effects on wood production and the economy of management alternatives for buffers; and to evaluate the development of important stand structures for buffer functionality. Buffer widths from 0 to 30 m were analyzed with unmanaged or selective logging as alternatives. Leaving unmanaged buffers resulted in the cost being generally proportional to the area of productive forest land covered by buffers in the landscape. The cost for the widest buffer alternative, 30 m, when left unmanaged, was between 4 and 10% of the total net present value of the entire forest landscape. Allowing selective logging to promote broadleaved trees in the buffer reduced the costs to 1–3% of the net present value. Selective logging increased the volume share of broadleaved trees in the buffer, thus enhancing some of its ecological functions. Unmanaged buffers increased the amount of dead wood more than the alternatives with selective logging. Decisions about buffer zone management must consider the trade-off between economic and environmental benefits, as well as the trade-offs between contrasting environmental goals.

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**KEYWORDS**
Boreal; water; forestry; economy; wood production; protection

## Introduction

A broad development in forestry over the past three decades has been the move towards integrating ecological and environmental considerations and values other than simply timber production and economics as part of forest management regimes. In Sweden today on average 11% of the total area of a logging site is left unlogged to benefit these values according to the Swedish Forest Agency (SFA 2019). This figure includes tree patches, forest edges and riparian forest buffers. Increased awareness on the importance of headwater streams (Bishop et al. 2008) and new possibilities to map them (Kuglerová et al. 2014b; Ågren et al. 2015) has currently put the focus on how to manage riparian forests.

Forests and surface waters are closely interconnected. Riparian forests, here defined as forests bordering lakes and watercourses, play a key connecting role between the two. The riparian system, with its special vegetation composition, can be viewed as a transition zone between terrestrial and aquatic ecosystems (Clinton et al. 2010; Kuglerová et al. 2014a; Nilsson and Svedmark 2002). Riparian forests provide energy and nutrients via litterfall and large amounts of wood to adjacent aquatic ecosystems (Dahlström and Nilsson 2006; Wallace et al. 1997). The species composition of terrestrial litter inputs is important for stream food webs (Wallace et al. 1997). Researchers have found that deciduous litter is processed or decomposed faster than needle litter (Collen et al. 2004; Lidman et al. 2017b). Thus, to facilitate energy turnover in boreal headwaters, Lidman et al. (2017b) propose that forest management for conifer production should aim at increasing the proportion of native deciduous trees along streams.

Large wood, or coarse woody debris, is often defined as pieces of wood with a diameter ≥10 cm and a length of 1 m or more (Wohl et al. 2010, 2017). The presence of large wood in rivers create various physical and ecological effects and is important for river process and morphology (Wohl et al. 2017). Large wood instream increases hydraulic resistance and obstructions to flow, thereby affecting local erosion of the channel bed and banks, increasing the retention of mineral and organic particles and ultimately habitat diversity, as summarized by (Wohl et al. 2017). In a study from Sweden, amounts and characteristics of coarse woody debris were compared between streams and adjacent riparian forests in old-growth and managed forest sites and the instream coarse woody debris volumes were found to relate to, but exceed, the coarse woody debris volumes found in the adjacent forest (Dahlström and Nilsson 2006). In ten near-natural streams in Sweden, more wood pieces and a higher wood volume were found compared with ten streams within managed forest landscapes (Dahlström and Nilsson 2004), suggesting that traditional forestry practices may lower the input of large wood to surface water, cf. Burton et al. (2016).

Forestry operations carried out near surface water can, for example, increase the influx of sediments, nutrients and

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mercury as well asaffect water temperature and litter inputs to adjacent waters (Croke and Hairsine 2006; Eklöf et al. 2016; Kreutzweiser et al. 2008; Moore et al. 2005). Negative impact may occur if the special characteristics of the riparian zone (such as its vegetation composition, hydrological connectivity and importance for stream water quality) are not acknowledged (Kuglerová et al. 2014b; Ledesma et al. 2018; Lidman et al. 2017a). To protect surface waters and maintain important functions of the riparian forest, strips or zones of forest (hereafter referred to as forest buffers) are required along surface waters at logging operations in many parts of the world (McDermott et al. 2009). Forest buffers with a fixed width have commonly been used (McDermott et al. 2009; Richardson et al. 2012; Ring et al. 2017). Lately, however, variable forest buffer widths have been proposed, based on the location of riparian groundwater discharge areas (Kuglerová et al. 2014b). Intentional riparian forest disturbance has been discussed as a mean to sustain aquatic habitat complexity and ecosystem integrity by emulating natural disturbance (Kreutzweiser et al. 2012; Mallik et al. 2014). Sweeney and Newbold (2014) concluded that ≥30 m wide forest buffers are needed to protect the physical, chemical and biological integrity of small streams, i.e. streams with catchment areas between about 0.05 and 100 km$^2$. However, there are still large gaps in our knowledge on the minimum forest buffer width required to protect and maintain vital processes for surface waters. One main reason for this absence of information is the great variability in geomorphology, hydrology, forest types and surface water bodies both across and within different regions; this presents significant challenges for research.

Other important aims for leaving riparian forest buffers are the conservation of terrestrial habitats, conditions and species. Hylander et al. (2005) studied presence and cover of bryophytes after clearcutting with and without 10 m forest buffers on each side of the stream. Bryophytes declined less in the buffer strips than on the clearcuts, where they strongly declined. However, the species in most need of protection (i.e. the red-listed species) were among the ones with strongest declines in the 10 m strips. Studies on microclimate in forest buffers from north America suggests that the light availability in the buffer is affected within at least 5 m from the logged area, and this may reduce the functional width of the buffer (Zenner et al. 2012) and that a 30 m wide forest buffer adequately protects the riparian microclimate gradient (Rykken et al. 2007). Leaving sellable timber in the buffer zone obviously reduces the harvested volumes and consequently the revenue from logging operations. Tiwari et al. (2016) compared fixed width buffer zones with hydrologically adapted zones, delineated using a cartographic depth-to-water (DTW) index (Murphy et al. 2008), in a catchment in northern Sweden. They found that the costs of setting aside forest buffers were slightly lower, calculated as net present value (NPV) per area of buffer zone, for the hydrologically adapted width as compared to the fixed width buffers. For the same catchment Lundström et al. (2018) calculated the cost for a fixed width unmanaged buffer of 15 m. This management alternative reduced the NPV of the forests in the area by 5.0%, which was similar to the area proportion covered by the buffer zones. In the same study, unmanaged buffers were also compared with buffers that were recurrently thinned. The thinned buffers reduced the NPV rather less, i.e. by 1.2%, than the unmanaged ones.

To manage buffer zones with partial logging presents an option to reduce costs by leaving wider forest buffers and may represent viable trade-off options between timber production and environmental protection. Several studies suggest that limited logging can take place in buffer zones without significant risks for other values (Elliott and Vose 2016; Kreutzweiser et al. 2009, 2010), while other studies suggests that selective logging in the forest buffer disturbs the cool and humid riparian microclimate (Oldén et al. 2019a; Zenner et al. 2012). Indeed, selective logging to promote broadleaved trees in mixed species buffer zones may actually improve ecological values as suggested by Lidman et al. (2017b). Leaf litter inputs to headwater streams have been shown to correlate well with the basal area of broadleaved trees in the buffer zone (Muto et al. 2009). Selective logging of conifer trees in mixed stands has the potential to increase the broadleaved basal area over time.

There is still a need for better understanding of the trade-offs between timber production, economic, ecological and water quality values which underpin and support decisions about riparian forest buffer delineation and management. In this study, different management options for riparian buffers were analyzed, using a detailed dataset from field inventories of trees and site conditions along watercourses in three landscapes in Sweden (Ring et al. 2018). The objectives were to: (i) estimate the effects on wood harvest potential and the economy of different alternatives for management of the riparian forest buffers, and (ii) evaluate the development of important stand structures for forest buffer functionality for the same management alternatives, by simulation of forest development in three forest landscapes in Sweden.

## Material and methods

### *Data collection*

Forest development, wood production and economy were simulated for three sites (landscapes) dominated by forest land (Table 1) located along a south–north gradient in Sweden. Seven management alternatives (Table 2) for the buffer zone (0–30 m from the stream) were evaluated. Stand registers provided by the landowners and a field inventory of sample plots in the buffer zone were used as input to the simulations.

In the field inventory a total of 139 transects along 38 stream reaches (<10 m wide) were established. Stream reaches were delimited by the borders between stands on the forest management map, so that each stream reach was bordering only one stand, or two stands in the case when the stream constituted the border between stands. Only stream reaches showing no or little anthropogenic impact on the stream channel were included in the study. Ditches were visually identified in hill-shade view of the national

**Table 1.** Description of the studied landscapes and the inventory.

| | Southern site | Central site | Northern site* |
|---|---|---|---|
| Latitude (degrees, minutes) | $57^{0}$ 44′ | $59^{0}$ 41′ | $64^{0}$ 14′ |
| Altitude (m) | 225 | 110 | 250 |
| County | Jönköping | Örebro | Västerbotten |
| Vegetation zone** | Boreonemoral | South boreal | Middle boreal |
| Area forest land (ha) | 1880 | 20041 | 6638 |
| Area within 30 m from watercourses (ha) | 78 | 1324 | 392 |
| Area within 30 m from watercourses (%) | 4.15 | 6.61 | 5.91 |
| No. of inventoried stream reaches | 15 | 12 | 11 |
| No. of inventoried transects | 52 | 45 | 42 |
| No. of inventoried plots | 149 | 134 | 122 |
| Total area of inventoried plots (ha) | 2.91 | 2.67 | 2.40 |

*The northern site is the Krycklan catchment (Laudon et al. 2013), a scientific field study area in northern Sweden.

**Classification following "Naturgeografisk indelning av Norden", Nordic Council of Ministers 1984.

digital elevation model, based on LIDAR-data with 2 m resolution, and excluded from the study. The remaining stream reaches were stratified into three classes, based on the age of the adjacent forest according to the stand registers. The age classes were 0–25, 26–75 and >75 years, the classes chosen being based on assumptions about historic forest management (Lundmark et al. 2013; Simonsson et al. 2015). For each age class within site, two to five stream reaches were randomly selected with a probability proportional to the length of the stream reach (Thompson 1992), adding up to 11–15 stream reaches per site.

Along each selected stream reach, two to four transects (perpendicular to the stream) were established at a fixed distance (at least 20 m) depending on the length of the reach (Figure 1). In most cases, the stream reach constituted the border between two stands, but when a stand was intersected by a stream the side on which to locate the transects was randomly selected. Starting from the stream edge, each transect was divided into three zones: 0–5, 5–15 and 15–30 m in order to capture the anticipated gradient in forest composition and ground conditions near the streams. The 15–30 m zone is most likely to have stand features similar to the adjacent stand, since areas more than 15 m from watercourses historically have been managed as ordinary production forest. Along each transect three rectangular plots were established, based on the three zones and a plot width that varied between stands depending on stand age. The width was 4 m for age class 0–25 years, 7 m for 26–75 years and 10 m for >75 years. A detailed description of the vegetation and site conditions in the sample is available in Ring et al. (2018)

**Table 2.** Management alternatives for the zones analyzed in the study, i.e. 0–5 m, 5–15 m and 15–30 m from the stream edge.

| Alternative | Zone **0–5** m | Zone **5–15** m | Zone **15–30** m |
|---|---|---|---|
| CCC | **C**learcut | **C**learcut | **C**learcut |
| UCC | **U**nmanaged | **C**learcut | **C**learcut |
| UUC | **U**nmanaged | **U**nmanaged | **C**learcut |
| UUU | **U**nmanaged | **U**nmanaged | **U**nmanaged |
| USC | **U**nmanaged | **S**election | **C**learcut |
| USS | **U**nmanaged | **S**election | **S**election |
| UUS | **U**nmanaged | **U**nmanaged | **S**election |

Note: The three management options for each zone are unmanaged, clearcut, followed by regeneration with conifer seedlings and further management as per the adjacent stand, and selective logging ("Selection"), with repeated thinnings to promote broadleaved trees.

On each plot all stems with a breast height diameter ≥4 cm were calipered at breast height, and tree species was recorded as well as site conditions. For smaller trees, height was recorded. Standing and downed dead wood (the latter assumed to have been germinated on the plot) with a diameter larger than 10 cm was also calipered. Established sampling techniques based on, and used in, the Swedish National Forest Inventory (Fridman et al. 2014) were used to register site factors (soil texture class, soil moisture class, field layer class, site index), trees (tree species and diameter for all trees with a breast height diameter > 4 cm) and dead wood (standing and downed with diameter > 10 cm). Stem volume was calculated using the Heureka software (Wikström et al. 2011) and summed up to volumes and stem numbers per hectare.

During the field inventory, additional variables describing site factors, landforms and structures and species indicating high conservation values were recorded. The results were analyzed statistically and have been reported in Ring et al. (2018).

## *Scenario analysis*

The scenario analysis was performed using the Heureka system, a decision-support system for analysis and management planning of forest landscapes (Wikström et al. 2011). Heureka can be used to simulate a set of different management alternatives for each forest stand within frames set by the user. The optimal alternative for each stand is then selected based on the objectives and constraints set by the user, using the built-in optimization tool. Stand development in Heureka is mainly driven by models for tree growth (Fahlvik et al. 2014) and mortality (Fridman and Ståhl 2001), but it also handles ingrowth of young trees, dead wood decomposition, soil carbon, output of sawlogs, pulpwood and energy assortments as well as costs of forestry operations and revenues from logging.

Seven different management alternatives for the buffer zone were defined, with different combinations of unmanaged, clearcut or selective logging (with repeated thinnings to promote broadleaved trees) in the three zones (Table 2). The selective logging was performed as repeated thinnings with 20 years intervals and removing 30% of the standing volume each time. The thinning quotient vas set to 1,1 and the algorithm was set to remove conifers

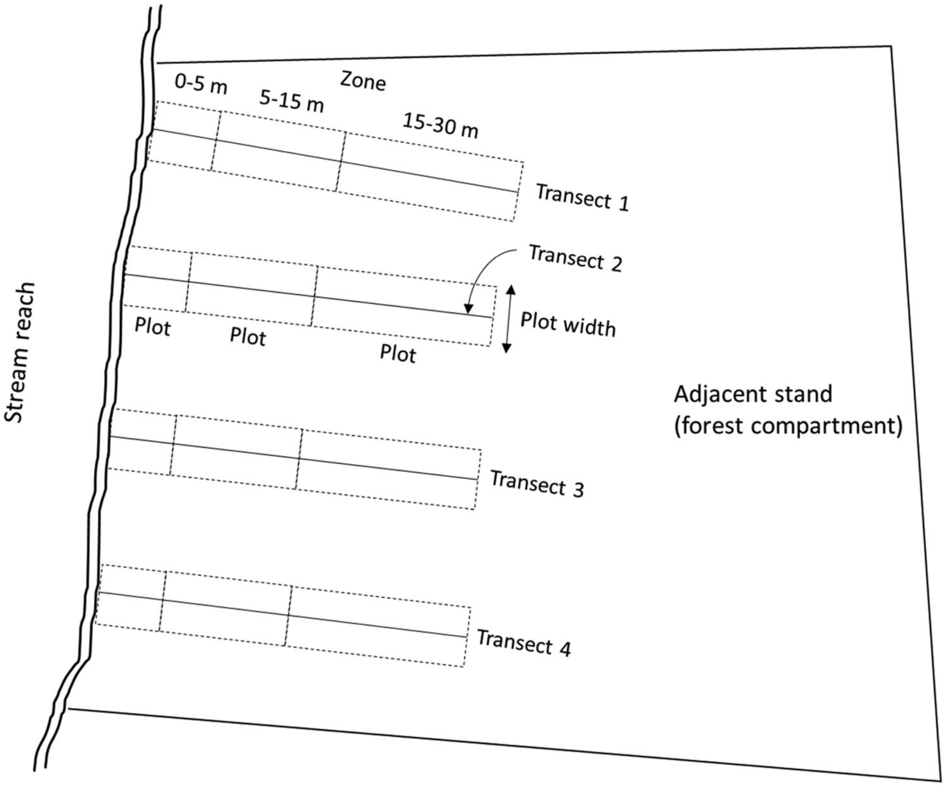

**Figure 1.** Sampling design schematic for a selected stream reach with four transects. The distance between the transects is one quarter of the length of the stream reach, and the distance between the edge transects and the compartment border is one eighth of the length of the stream reach. Plot width was 4 m when the adjacent stand was 0–25 years old, 7 m when the stand was 26–75 years old and 10 m when the stand was >75 years old. From Ring et al. (2018).

before broadleaved trees. In each of the three landscapes the stand and site data for plots within each zone (0–5, 5–15, 15–30 m) was assumed to represent the entire area covered by buffer zones within the landscape. For the tree landscapes entire forest maps and stand registers as well as zones 0–5, 5–15 and 15–30 were imported to Heureka (zonal areas withdrawn from the original compartments). For each landscape and each zone management alternative a long-term (100 years) management plan was created by optimizing the NPV, calculated according to Faustmann (1849), of the entire landscape. The discount rate was set to 2.5% real interest rate, and we used a restriction on a maximum 10% difference in logging volume between two consecutive five-year periods.

## Results

The standing volume in the buffer zone was generally highest in the first 0–5 m from the stream (Figure 2). This zone also had a higher share of Norway spruce and broadleaves than the 5–15 m and 15–30 m zones, while Scots pine was more common in the two latter zones. The differences in stem volume, in total and by tree species, between the 0–5 m zone and the two outer zones were statistically significant (Ring et al. 2018). The average standing volume for the entire zone (0–30 m) was 180, 198 and 129 $m^3$/ha respectively, for the southern, central and northern sites based on our sample plots. The average standing volume taken from available stand registers, for all landscapes, was 115, 151 and 134 $m^3$/ha respectively, for the southern, central and northern sites.

The Heureka simulations resulted in management programs based on optimization of the NPV of the entire landscape, for the different management alternatives for the buffer zone (Table 3). The reduction in NPV with increased width of the buffer zone (from 0 to 30 m wide) was between 4 and 10% for the widest unmanaged buffer (UUU) compared with no buffer at all (CCC). The intermediate buffer widths (UCC and UUC) showed lower reductions in NPV, between 1 and 5%. The alternatives with repeated selective loggings in the buffer (USC, USS and UUS) increased the NPVs as compared to the same buffer widths with unmanaged forest (UCC, UUC and UUU). A 30 m buffer zone with just the 0–5 m zone unmanaged and the rest selectively logged (USS) resulted in a higher NPV than a 15 m unmanaged buffer (UUC) for all three sites. The reductions in NPVs were largest for the central site and smallest for the northern site.

The mean annual possible wood harvest from the three landscapes, with different management alternatives for the buffer zone, is shown in Table 4. The reduction in potential future timber harvest at landscape level largely follows the same patterns as for the NPVs but with slightly smaller effects. The exception is the alternative with selective logging in the central site, where the reduction in wood harvest is slightly larger than in the NPVs.

The two factors related to the ecological impacts of buffer zones – the amount of broadleaves and hard dead wood –

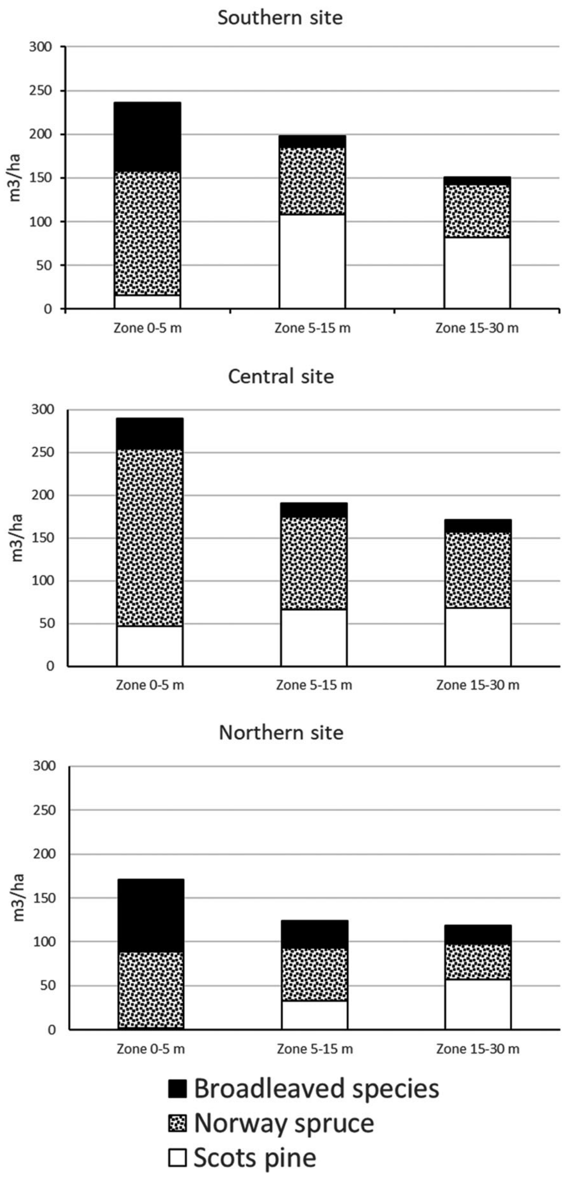

**Figure 2.** Average standing stem volume of different tree species and in total for the three zones on the three sites.

showed different effects for the three management alternatives (clearcut, unmanaged and selective logging) for the different zones (Figures 3 and 4). The proportion of broadleaves was increased by selective logging as defined. In the 5–15 m and 15–30 m zones the share of broadleaves increased from 5–20% initially to 20–55% after 100 years. The increase was larger for the northern site than for the southern and central sites. Clearcutting followed by mechanical site preparation hasinitially favored natural regeneration of broadleaves. But after 20–40 years when the planted conifer seedlings had been promoted in precommercial thinnings, the broadleaved share was reduced to levels equal to or lower than before clearcutting. These effects were also most pronounced for the northern site. Leaving the buffer zone unmanaged mostly preserved the volume share of broadleaves or slightly reduced it over the 100 years simulation horizon.

When the buffer zone was left unmanaged the amounts of hard dead wood were predicted to increase over time, from a few cubic meters per hectare to levels of 30–90 $m^3 ha^{-1}$ at the end of the 100 years scenario period (Figure 4). For the clear-cut alternative there were only limited changes in the hard dead wood volume over time. For selective logging there was a slight increase in the volumes of hard dead wood as compared to the initial state (Figure 4).

## Discussion

Our results demonstrate that the costs, in reduced NPV, of leaving unmanaged buffer zones along watercourses, is generally of the same magnitude as the area proportion of buffer zones compared to the total area of managed forest land in the landscape (Table 3). Similar results have been obtained by Lundström et al. (2018) in a study of the same landscape as our northern site but which was based on remote sensing data. Our results, which were assessed from simulations based on empirical field data, indicate that this conclusion also seems valid for the landscapes in southern and central Sweden. However, our study and Lundström et al. (2018) analyzes buffer widths of 5–30 m, if even wider buffers are applied, an increase in logging costs can be expected because of the fragmentation of remaining areas available for wood production and logging (Bren 1997).

When the riparian zone holds more stem volume per hectare than the average in the landscape which was the case for the southern and central sites the relative cost in reduced NPV was slightly higher than the area proportion of buffer zones to the total productive forest land area. With lower stem volume in the buffer zone the cost reduction was more moderate, which was the case in the northern site. The high proportion of broadleaves at the northern site

**Table 3.** Net present values (NPVs) per hectare from wood production in the three landscapes studied with different management alternatives for the riparian buffer zones.

| Management | Southern site | | Central site | | Northern site | |
|---|---|---|---|---|---|---|
| alternative | NPV (EUR/ha) | Difference (%) | NPV (EUR/ha) | Difference (%) | NPV (EUR/ha) | Difference (%) |
| CCC | 4014 | | 4236 | | 2548 | |
| UCC | 3967 | −1.2 | 4163 | −1.8 | 2526 | −0.9 |
| UUC | 3904 | −2.8 | 4042 | −4.8 | 2487 | −2.4 |
| UUU | 3807 | −5.5 | 3860 | −9.7 | 2450 | −4.0 |
| USC | 3956 | −1.5 | 4138 | −2.4 | 2519 | −1.1 |
| USS | 3923 | −2.3 | 4102 | −3.2 | 2513 | −1.4 |
| UUS | 3877 | −3.5 | 4006 | −5.7 | 2480 | −2.7 |

Note: Differences between no buffer zone (CCC) and the different management alternatives with buffers given in terms of percentage loss.

**Table 4.** Mean annual wood harvest (WH100) per hectare for the coming 100 years in the three landscapes studied with different management alternatives for the riparian buffer zone.

| Management | Southern site | | Central site | | Northern site | |
|---|---|---|---|---|---|---|
| Alternative | WH100 ($m^3\ ha^{-1}\ yr^{-1}$) | Diff. (%) | WH100 ($m^3\ ha^{-1}\ yr^{-1}$) | Diff. (%) | WH100 ($m^3\ ha^{-1}\ yr^{-1}$) | Diff. (%) |
| CCC | 5.64 | | 5.31 | | 3.25 | |
| UCC | 5.59 | −0.9 | 5.23 | −1.5 | 3.23 | −0.6 |
| UUC | 5.53 | −2.0 | 5.08 | −4.5 | 3.18 | −2.2 |
| UUU | 5.44 | −3.7 | 4.87 | −9.0 | 3.14 | −3.5 |
| USC | 5.58 | −1.1 | 5.17 | −2.7 | 3.22 | −0.9 |
| USS | 5.54 | −1.8 | 5.10 | −4.1 | 3.22 | −0.9 |
| UUS | 5.50 | −2.6 | 5.01 | −6.0 | 3.18 | −2.2 |

Note: Differences between no buffer zone (CCC) and the different management alternatives with buffers given in terms of percentage loss for the entire 100-year period.

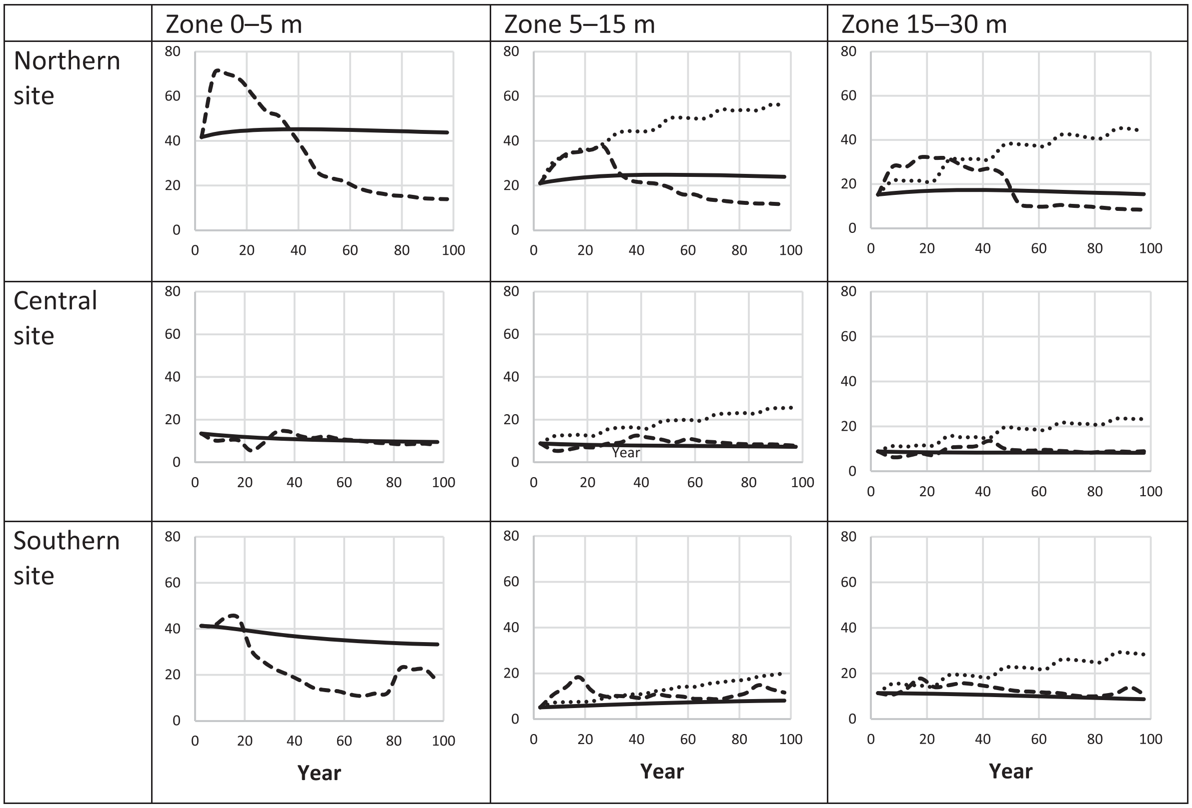

**Figure 3.** Development over the coming 100 years of the proportion (%), by stem volume, of broadleaved trees in the riparian buffer, divided into three zones: 0–5, 5–15 and 15–30 m from the water and on the three sites studied. The three management options are unmanaged (solid line), clearcut followed by regeneration and management as the adjacent stand (dashed line) and selective logging with repeated thinnings promoting broadleaved species (dotted line).

(Figure 2) also contributed to a lower cost for leaving unmanaged buffers, since the wood price for broadleaves was lower than for conifer wood. The loss in wood available for harvest was closely connected to the loss in NPV at all three sites (Table 4).

As expected, the scenario alternatives with selective logging in the 5–15 m and 15–30 m zones reduced the cost for having buffer zones with a continuous tree cover (Table 3). In the study by Lundström et al. (2018), in which selective logging in the buffer zone was analyzed, the same conclusion was drawn. In our study it was assumed that the logging operation in the buffer zone could be carried out independent in time to the operation in the adjacent compartment. Lundström et al. (2018) compared independent and dependent timing of logging operations in the buffer zone and concluded that the difference in NPV was negligible. However, they did not account for additional costs for more frequent movement of machinery between sites, which could have increased costs for time-independent buffer management.

It is notable that a 30 m buffer with the first 5 m unmanaged and 5–30 m managed with selective logging favoring broadleaves was slightly more cost-efficient than a 15 m unmanaged buffer for all three sites (Table 3). Oldén et al. (2019b) studied the communities of vascular plants and mosses in an experiment in Finland and found that a 15 m wide buffer was not sufficient to protect the plant communities but they found no changes in 30 m wide buffers, whether selectively logged or not. On the other hand, when studying the microclimate in the same experiment Oldén

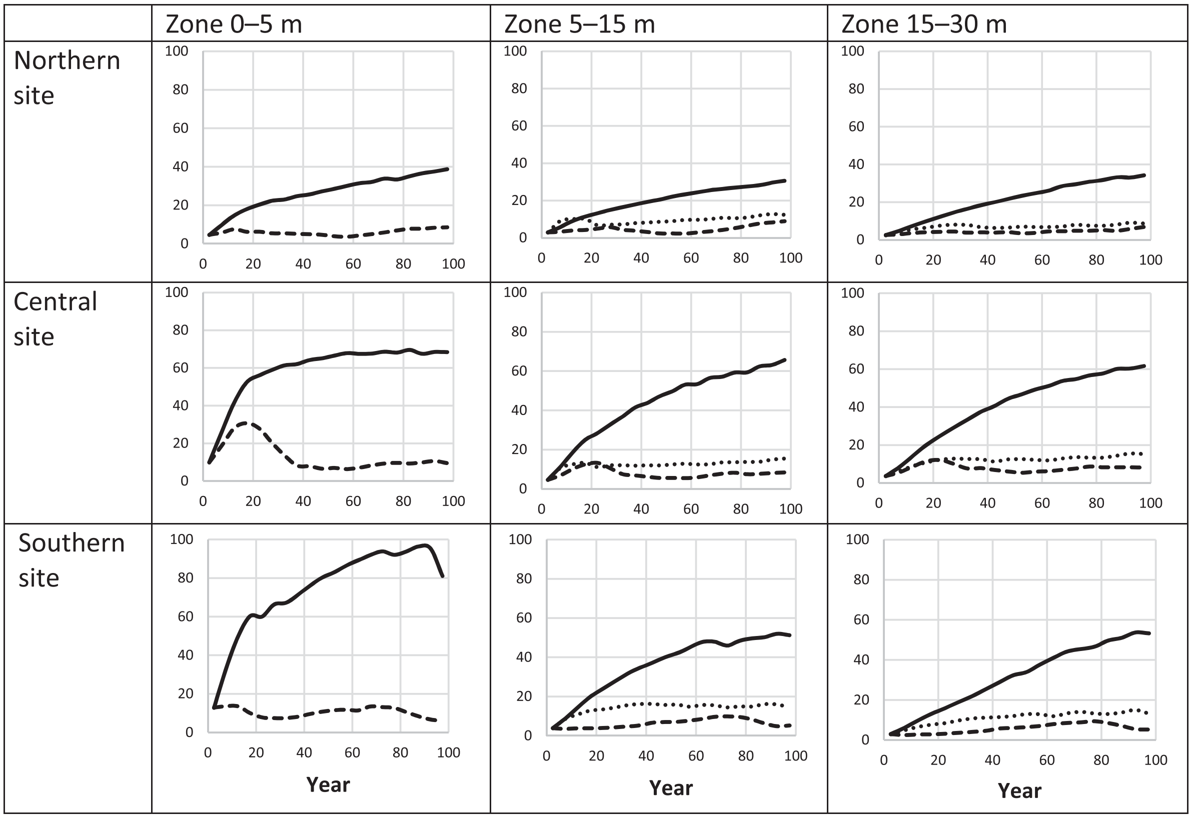

**Figure 4.** Development over the coming 100 years of the volume (m$^3$) of hard dead wood per hectare in the riparian buffer, divided in three zones: 0–5, 5–15 and 15–30 m from the water and on the three sites studied. The three management options are unmanaged (solid line), clearcut followed by regeneration and management as the adjacent stand (dashed line) and selective logging with repeated thinnings favoring broadleaved species (dotted line).

et al. (2019a) found that even the 30 m buffer did not preserve the cool and humid climate if selectively logged. The choice between an unmanaged narrow buffer and a selectively logged wider buffer can thus be dependent on which particular function of the buffer is most desirable. Our results indicate that an unmanaged buffer will produce and accumulate a large amount of dead wood over time (Figure 4), while the volume share of broadleaved trees is relatively constant. In contrast, selective logging favoring broadleaves will increase the volume share of broadleaved trees, but the increase of dead wood will be more moderate than in the unmanaged alternatives. Selective logging favoring broadleaves is also one of the methods for management of riparian forests recommended by the Swedish Forest Agency (SFA 2014). However, it does not seem to be possible to establish a broadleaf dominated stand within 100 years with the simulated type of selective logging if the share of broadleaves at the starting point is too low. In the southern and central sites, in the 5–30 m zone, the broadleaves only represent 5–10% of the standing volume (Figure 3), and after 100 years of selective logging favoring broadleaves, the share has increased only to 20–30%.

The Swedish forestry certification standards FSC (2018) and PEFC (2017) both require a certain amount of admixture of broadleaved trees within stands as well as some stands dominated by broadleaved trees. One possibility for future development of buffer zones along streams is to focus on increasing the number of broadleaved trees, thus combining benefits for watercourses with benefits for the terrestrial values targeted by the certification standards.

The concept of varying the buffer width is proposed as a cost efficient mean for conservation of ecological and environmental values (Hylander et al. 2005; Kuglerová et al. 2014b; Tiwari et al. 2016). Hylander et al. (2005) studied bryophytes in riparian buffer strips and proposed to increase the buffer width at sites with large amounts of woody debris or boulders to favor red-listed species. Kuglerová et al. (2014b) suggested wider buffer zones in groundwater discharge areas to conserve species richness of vascular plants and bryophytes. Tiwari et al. (2016) analyzed hydrologically adapted buffer zones, delineated using a cartographic depth to water (DTW) index (Murphy et al. 2008) and concluded that this method allowed more effective protection of the parts of the riparian zone that are ecologically and bio-geochemically important without forest landowners incurring any additional costs than fixed width buffers. The slightly lower costs for the hydrologically adapted buffers were mainly since the groundwater discharge areas had lower site productivity and thus lower standing timber volumes (Tiwari et al. 2016). To vary buffer width makes good sense for both economic, ecological, and environmental reasons. However, decisions on where to apply wider buffers are not always easy as exemplified in the studies mentioned above. The location of groundwater discharge, boulders and large amounts of dead wood do not always coincide.

The strength of this study is the detailed field inventory data that gave us the opportunity to simulate stand development at different distances from the watercourse. The sampling design with plots at fixed distances from the stream does not, however, allow us to test management alternatives with variable width buffers, as suggested by Kuglerová et al. (2014b). A study with partly similar scope by Lundström et al. (2018), conducted in the same area as our northern site, has the benefit of varying buffer width but relies on data on the tree layer from remote sensing. Our study also includes the results from two sites in southern and central Sweden, adding to our understanding of these questions in other parts of the country.

We conclude that the costs, in terms of reduced NPV, of leaving unmanaged buffer zones along watercourses, are generally of the same magnitude as the area proportion of buffer zones compared to the total area of managed forest land in the landscape. This is valid both for the NPVs and long-term timber harvest opportunities. These costs can be reduced substantially by allowing selective logging in the buffer zone to promote broadleaved trees. Favoring broadleaves also promotes some important ecological functions, mainly connected to leaf litter input to the streams. On the other hand, unmanaged buffers will provide more dead wood in the streams, supporting other ecological functions. There are obvious trade-offs between costs, timber production and differing ecological goals, forming a complex information structure that is of vital importance when making decisions regarding the effective and appropriate management of riparian buffer zones.

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