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Riparian buffer zone widths, windthrows and recruitment of dead wood

– A study of headwaters in northern Sweden

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Abstract

Riparian buffer zones, that is vegetated strips that are left surrounding streams, are today the general management practice to protect our running waters during forestry. They are created with the intent of preserving a variety of important ecological functions, including provision of dead wood. In this study, I wanted to investigate how buffer width affects windthrows and recruitment of dead wood in the buffer zones of 29 headwater streams in Västerbotten, Sweden. I registered and measured all dead trees rooted within the buffer zones. I also measured original and current buffer width. The original width was given by the uprooted outer edge trees and the current width was given by the current standing outer edge trees. Further, I gathered landscape properties such as clear-cut size, harvest year, clear-cut slope, stream direction and buffer zone soil wetness to use for statistical analysis. A weak, near significant relationship of decreasing buffer zone loss with increasing buffer zone width was found. Although weak, this result could indicate that narrower buffer zones are more prone to wind damage and managers should create wider buffer zones to minimize windthrows. I found similar amounts of dead wood in the buffers regardless of the buffer width. This implies that the buffer widths used today for headwaters in Sweden today are equally vulnerable to windthrows and that narrower buffers are experiencing the same loss of retained trees as the wider buffers. No other measured parameter was significantly affecting the amount of dead wood in the buffers. Further studies are needed to increase knowledge on how windthrows affect the buffer zones intended ecological functions.

Keywords: Fixed-width buffers, wind disturbance, small streams, nature consideration

Preface

I want to thank my supervisor Lenka Kuglerová who has been a tremendous support throughout this process and guided me in writing this thesis.

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Abbreviations

Dbh	Diameter at breast height
Buffer zones	Vegetated strips left unharvested around streams in Swedish forestry
LW	Large dead wood

1. Introduction

1.1. Background

The Swedish forests contain about 2.5 million kilometres of streams and waterways (Ågren & Lidberg 2019). Although dynamic and everchanging, headwater streams (small streams) represents an extensive part of our running water network (Bishop et al. 2008; Ågren & Lidberg 2019). Through the groundwater input and riparian vegetation dynamics, small streams are closely linked to the riparian zone and the adjacent terrestrial areas (Kuglerová et al. 2017). They also have a high stream edge to stream surface area ratio (Richardson & Danehy 2007), which highlights the importance of riparian area for number of stream functions.

A riparian zone is the forest adjacent to a stream that constitutes the transitioning between land and water. This area often has a high species richness and harbours species with specific demands and niches which improves the beta diversity in the area (Hylander 2004; Sabo et al. 2005). Further, it provides the streams with different services such as shading and temperature regulation, litter input and stream bank stability (Barling & Moore 1994). Riparian zones are amongst the most productive and diverse ecosystems in the world, but they are also heavily impacted by humans (Nilsson & Berggren 2000). Activities such as stream channelization, alteration of flow regimes and commercial forestry are examples of human activities that can have a negative impact on water bodies (Hjältén et al. 2016).

Streams can be affected in several different ways by forestry operations. It has been shown that clear-cuts can change hydrological dynamics such as increasing springtime runoff due to increased snow accumulation contra decreasing summertime runoff due to higher levels of evapotranspiration (Ide et al. 2013; Schelker et al. 2013). Removal of the canopy close to stream channels also impairs leaf litter provisioning the years following harvest, affecting the food webs of the stream, and increasing light input (Hoover et al. 2011). Clear-cuts have further been shown to temporarily increase nitrogen levels in headwater streams due to leaching (Schelker et al. 2016) and DOC levels which further amplifies following site preparation (Schelker et al. 2012). Sedimentation has also been shown to increase after logging and soil preparation due to higher water discharge and overland runoff (Palviainen et al. 2014).

In order to mitigate these negative effects and protect the waterways, leaving vegetated riparian buffer zones around the streams are today common practice in forestry. They are most often of constant width along the whole stream, usually referred to as fixed-width buffers (Richardson et al. 2012). This is most likely because it is an easy and convenient method to protect these sensitive areas, although it is not the most efficient or ecologically sound. The functionality and success of the buffer zones in sustaining important ecosystem functions is associated with various parameters such as riparian zone width (Broadmeadow & Nisbet 2004), vegetation structure (Kreutzweiser et al. 2012) and species composition (Hoover et al. 2011), none of which is constant across the landscape.

Countries have different approaches to riparian zone management in forestry. In the United States, minimum widths and a minimum amount of residual trees are common practice, although the specifics vary amongst the states (Blinn & Kilgore 2001). In British Columbia – Canada, recommendations for large fish-bearing streams are 20-50 m wide buffer zones. Smaller streams, although providing similar ecosystem services like bigger streams are however left without buffer zone requirements (Kuglerová et al. 2020b). Finland's legislation is fairly unspecified and the protection of streams largely relies on forest certifications (Ring et al. 2017). In Sweden, riparian buffer zone management are characterized by voluntary guidelines and forest certifications and required minimum buffer widths does not exist. The Swedish Forest Agency's guidelines focus on functionality, which essentially means that managers have a responsibility to create riparian buffer zones with adequate widths in order to protect their ecological functions for the streams (Andersson et al. 2013). In reality, this means that sometimes wide large buffer zones are needed, sometimes selective cuttings are called for and in some cases it can be acceptable to cut all the way to the stream edge (Andersson et al. 2013; Kuglerová et al. 2017).

Headwaters have received very little protection historically. This has been due to, for example, a lack of knowledge of their existence (Bishop et al. 2008), stream alterations, and unclear information from authorities on how to manage them (Hasselquist et al. 2020). This management has resulted in small streams in Sweden being surrounded with even-aged, mature production forest, which means that in addition to having a uniform width, the buffer zones protecting headwater streams in general also consist of similar aged trees of 1-2 species together forming only one story (Kuglerová et al. 2020a).

1.2. Dead wood and riparian buffer zones

Since the 1980's, large dead wood and its importance for biodiversity has been getting increased attention by forest managers (Jonsson & Kruys 2001; Stokland 2012). Dead wood in different decay stages forms a large variety of habitats for a broad range of species and is a key component in boreal forests biodiversity (Esseen et al. 1997). Managed forests are typically known to have low volumes of dead wood (Stokland 2012). In Sweden, the average total volume of dead wood in managed forests is 7.6 m3/ha (Jonsson et al. 2016).

In a Finnish study published in 2002 comparing managed and unmanaged areas within the same catchment, it was found that the quantities of large dead wood in and around streams were 10-100-fold times higher in the unmanaged areas compared to the managed ones, with an average of 331.6 m3/ha for the un-manged stream-side forests (Liljaniemi et al. 2002). A Swedish study found that streams located in old-growth forests held double the amount of dead wood pieces and 4 times the volume compared to streams in managed forests (Dahlström & Nilsson 2004). In a study on lakeside riparian forests it was found that, riparian forests hold a larger amount of woody debris than upland forests and a more diverse fungi community (Komonen et al. 2008). Although riparian zones are thought to be excluded from management, these areas adjacent to headwater streams has not been given this protection historically (Hasselquist et al. 2020). The results of this is that the mature stands of single-species dominated forests situated next to small streams also have very little dead wood due to the previous management interventions (Kuglerová et al. 2020a).

This is however changing due to the contemporary riparian buffer management in Sweden, which largely apply fix-width narrow buffers (Kuglerová et al. 2020b). Trees retained within buffer zones are exposed to increased wind levels and both managers and ecologists have raised concern about the problems associated with this. Windthrows have negative consequences on the functionality of the created buffer zones (shading, erosion, water quality etc.), but a positive effect on the production of large dead wood (Wolff & Grizzel 1998).

Wind disturbance in boreal forests has since the millennial shift gained increased interest by scientists (Rich et al. 2007). Susceptibility to wind disturbance has been shown to be influenced by various complexly interacting factors such as wind speed (Elie & Ruel 2005), tree species (Canham et al. 2001), diameter and stand age (Rich et al. 2007) and soil characteristics (Everham & Brokaw 1996). Additionally, trees with a high height/diameter at breast height ratio are exposed to a higher risk of windthrows (Schelhaas 2008). Further, stand density seems to be of high significance. In dense stands the sheltering effect and support of the neighbouring trees lowers the risk of wind damage (Schelhaas et al. 2007). Another aspect to stand density is also that wind is able to penetrate deeper into stands with wide spacing between trees (Gardiner et al. 1997).

There has been some research on riparian buffer zones width and the resilience to wind. Mäenpää et al (2020) found that the amount of windthrown threes were on average the same in buffer zones of 10 m compared to 30 m wide buffers. However, the wider buffer zones retained a larger proportion of the original number of trees, due to the protection of the inner zone. Another study conducted in British Columbia found that post-harvest windthrows were more common in a narrower (10 m) buffers than wider ones (30 m). They also found that most of the windthrows took place in the immediate years after harvest (Bahuguna et al. 2010).

Harvesting on both sides of streams, as well as the size of the clear-cuts, has been shown to further affect the amount of windthrows. The risk of windthrow was larger at bigger clear-cuts in Finland since the potential wind speed is higher with more open space (Mäenpää et al. 2020). However, this type of research has not been thoroughly conducted along riparian buffer zones protecting small streams in Sweden. Since the buffer management differs largely between Finland and Sweden (Kuglerová et al. 2020b) the Finnish examples might prove hard to apply in a Swedish context since headwater buffers are generally narrower in Sweden. Further, compared to Finland when streams typically experience harvest only on one side, Swedish streams have typically disturbance on both banks (Kuglerová et al. 2020b). This calls for research on windthrows along Swedish headwaters to increase our knowledge of the fate of buffer zones that we leave around small streams.

1.3. Aims of the study

The effect of forestry on headwater streams has recently gained increasing attention by the scientific community. However, windthrows and dead wood in buffer zones of small streams in Sweden is currently a blind spot. The purpose of this study is to investigate if riparian buffer zone width affects the amount of windthrows and the large dead wood in the buffer zones. These objectives will be answered through three questions.

1. Does a wider riparian buffer zone have a larger resistance towards windthrow events than a narrower buffer zone?
2. Does riparian buffer zone width affect the amount of blown down dead wood in the buffer zone?
3. Are other landscape properties (i.e. clear-cut size, slope, stream direction, years since harvest, and soil moisture) associated with windthrows in riparian buffer zones?

First, I hypothesized that wider buffer zones would have less windthrows than narrower buffers. Secondly, I expected that there would be most large dead wood (LW) in the medium sized buffer zones. This is because in the narrower buffer zones there is a low potential for dead wood input (less retained trees) and in the wider buffer zones the inner zone is protected. Thirdly, I hypothesized that there would be a positive relationship between clear-cut size and amount of LW at the sites. I did not expect to find any relationship between clear-cut age or soil moisture and amount of LW.

2. Method

2.1. Study sites

The field work was conducted during September 2020 at 29 sites located in Västerbotten county, Sweden (figure 1). The streams selected for this study has been used in previous work (Kuglerová et al. 2020b) and were selected to represent headwater streams (catchment area < 10 km^2, or width typically <3 m bankful) and all were situated in production forest stands. The clear-cuts were harvested between 2010 and 2020 and the clear-cut sizes ranges from 1.6 hectare (ha) to 62.1 ha. At some sites adjacent clear-cuts of similar age were included as they affected wind movement and possible wind speeds. All sites were situated on land owned by forest companies (i.e., Holmen skog, SCA and Sveaskog).

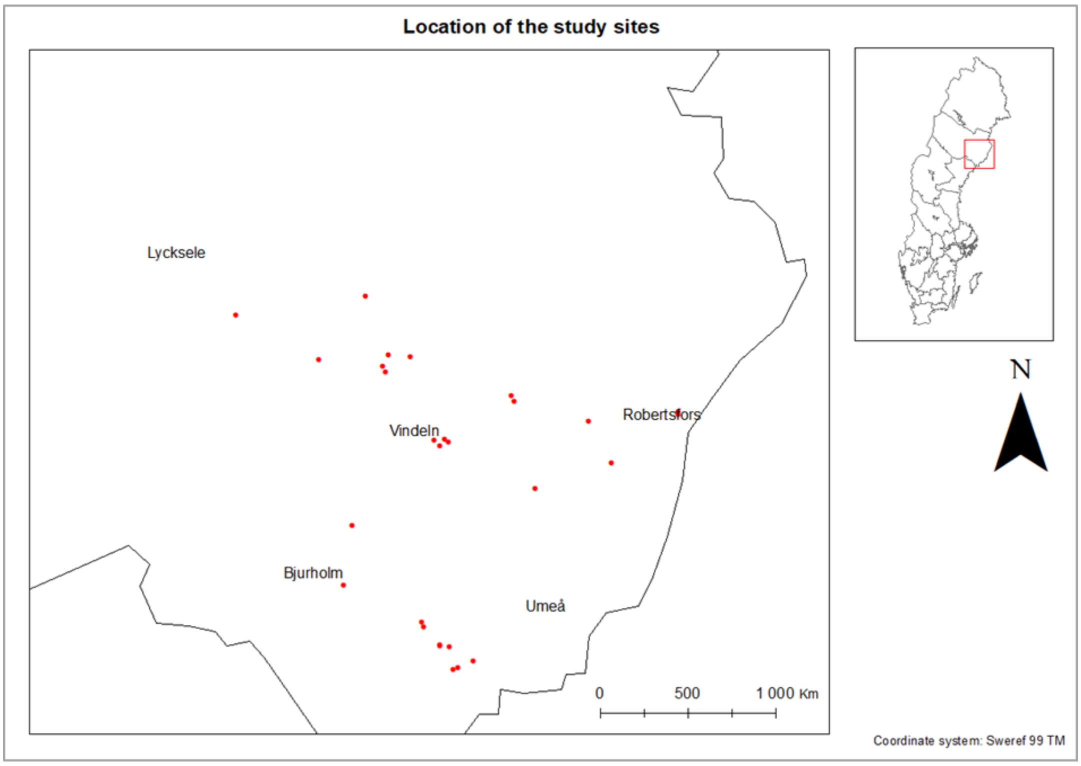

Figure 1: The location of the study sites (red dots) within Västerbotten county, Sweden

2.2. Field work

At each site, a 50-meter stretch of the buffer zone that was determined to be representative of the site was measured with a meter tape along which the different measurements were taken. The original buffer width and current buffer width was measured at 0 m, 25 m and 50 m at both sides of the stream with measuring tape. The original buffer width was set as the original locations of uprooted or broken trees (if present) perpendicular to the stream. The current buffer width was set as the standing trees furthest way from the stream. The average of the six measurements for original and current buffer width were used in the data analyses.

The diameter at breast height (dbh) was measured on all large dead wood which was wind felled but rooted within the buffer zone, using a caliper. Dead wood with a dbh below 5 centimeters was excluded from the study. The length, tree species, type (snag or log), cause (uprooted or steam breakage) and the stage of decomposition was also registered for all dead wood.

The stage of decomposition was visually assessed by using Thomas et al. (1979) decay classification system for snags and logs (figure 2). For logs all the classes (1-5) was used, for snags stage 6 was used. The reason for only using stage 6 for the snags was that broken stems can describe wind damage unlike the other 8 stages.

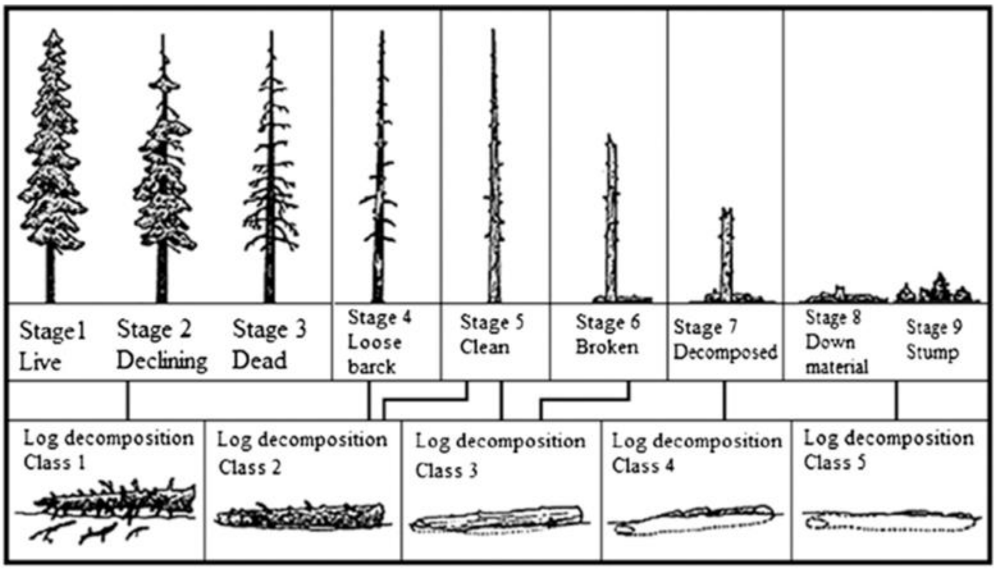

Figure 2: Visual representation of Thomas et al. (1979) decomposition classification system

2.3. Calculations

The volume of the dead wood was calculated by the following functions in which *V* = volume, *d* = diameter at breast height, *h* = height.

Spruce (Näslund, 1947):

$$V = 0{,}1202 * d2 + 0{,}01504 * d2 * h + 0{,}02341 * d * h2 - 0{,}06590 * h2$$

Birch (Näslund, 1947):

$$V = 0{,}03715 * d2 + 0{,}02892 * d2 * h + 0{,}004983 * d * h2$$

Pine (Näslund,1947):

$$V = 0{,}09314 * d2 + 0{,}03069 * d2 * h + 0{,}002818 * d * h2$$

Aspen (Eriksson, 1973):

$$V = 0{,}01548 * d2 + 0{,}03255 * d2 * h - 0{,}000047 * d2 * h2 - 0{,}01333 * d * h + 0{,}004859 * d * h2$$

Black alder (Eriksson, 1973):

$$V = 0{,}1926 * d2 + 0{,}01631 * d2 * h + 0{,}003755 * d * h2 - 0{,}02756 * d * h + 0{,}000499 * d2 * h2$$

For tree species that do not have an existing volume function, volume was determined by existing functions for other species. Grey alder by Eriksson's (1973) function for black alder and rowan by Näslund's (1947) function for birch.

Number of pieces was used in the data analyses because it is more ecologically relevant. Volume is presented in table 1 and is included because it is a more common forestry metric.

2.4. Data and statistical analysis

The collected data were compiled and entered in Microsoft Excel. All statistical analysis were conducted with the Minitab 19 software. In order to only analyze the dead wood recruited after the buffer zones were created, analyzes were done on dead wood in decomposition classes 1 and 2. Dead wood of decomposition class 3-5 was analyzed only for descriptive summary statistics, to assess how much dead wood there was prior to harvesting (old dead wood).

Landscape properties such as clear-cut slope in degrees, clear-cut size, buffer zone soil wetness and stream orientation were created with the tool Zonal statistics in ArcMap 10.7 (ESRI 2019). Buffer zone soil wetness, an index in which 0 is dry and 100 is wet, was based on SLU's Markfuktighetskarta version 1.0. Harvest year, clear-cut size and slope of the clear-cut was extracted from data obtained from the web of the Swedish forest agency (Skogsstyrelsen 2020).

For the first question, I calculated the difference (in meters) between the original buffer width and the current buffer width, creating a variable called buffer zone loss. For the sites which experienced buffer zone loss (i.e. > 0, $n = 16$), I created a linear regression model between buffer width loss (response variable) and original buffer width (explanatory variable) and evaluated the trend. Buffer zone loss variable was log-transformed to fulfill the assumption of normal distributed data, while buffer width was normally distributed. Both statistical significance (p-value) and model performance (r^2) was assessed.

For questions 2 and 3, six separate linear regression models were constructed with the amount (number of pieces) of dead wood in decomposition classes 1 and 2 as a response variable. The following explanatory variables were used: Original buffer width, current buffer width, average clear-cut slope, clear-cut size, harvest year and buffer zone soil wetness. Clear-cut size was log-transformed to fulfill the assumption of normal distributed data. Both statistical significance and model performance was assessed for each model, accounting for multiple testing (i.e. Bonferroni correction of p-values). Separate regression models were used instead of multiple regression due to collinearity between some of the explanatory variables.

A one-way ANOVA was created with amount (number of pieces) of dead wood in decomposition classes 1 and 2 as dependent variable and stream direction as factor (4 levels: south, south east, south west and west/east). Statistical significance (p-value) was assessed, also accounting for multiple testing.

3. Results

Figure 3: Examples of riparian buffer zones and windthrows that are investigated in this thesis.

3.1. Buffer zone and dead wood conditions

The average original buffer zone widths in this study ranged from 1.4 m to 14.8 m. 16 of the 29 study sites had a current average buffer zone width that was less than the original whilst 13 remained the same as the original. However, all sites had experienced windthrows and had records of large dead wood (table 1).

Table 1: Study site location, measured average buffer widths, dead wood amount, total volume and calculated volume per hectare.

Site id	Coordinates (WGS84)	Average original buffer width	Average current buffer width	Dead wood pieces	Total volume m3	Total volume m3/ha
1	64.1541, 20.1023	10,8 m	10,8 m	11	2,4	44,5
2	64.1501, 20.1055	1,8 m	1,8 m	10	0,6	66,4
3	64.2095, 19.4341	3,3 m	3,3 m	26	2,4	151,9
4	64.2906, 19.3228	6,4 m	5,9 m	45	4,0	128,3
5	64.2741, 18.5605	13,2 m	13,1 m	21	3,0	45,3
6	64.2156, 19. 1826	9,5 m	8,7 m	29	2,8	60,5
7	64.0623, 20.3625	13,2 m	13,2 m	6	1,3	20,0
8	64.1140, 20.5530	9,5 m	9,5 m	10	1,8	39,5
9	64.1156, 20.5553	7,7 m	7,4 m	9	1,6	42,0
10	64.1148, 20.3093	3,0 m	3,0 m	24	1,7	118,9
11	64.1941, 19.3628	8,0 m	6,4 m	31	3,2	81,9
12	64.2013, 19.3556	14,8 m	14,8 m	39	5,1	68,8
13	64.2141, 19.3748	7,0 m	6,6 m	20	1,9	54,6
14	64.1801, 19.8530	6,6 m	5,7 m	30	12,7	386,0
15	64.1726, 19. 8660	5,5 m	5,5 m	28	2,7	99,5
16	63.4388, 19.5421	11,0 m	10,2 m	22	9,9	179,6
17	63.4303, 19.4871	4,2 m	3,6 m	14	2,5	122,5
18	63.4330, 19.4996	4,0 m	2,5 m	17	6,8	345,6
19	63.4603, 19.4566	9,2 m	7,5 m	19	7,1	154,8
20	63.4613, 19.4548	5,2 m	4,4 m	16	5,5	212,8
21	63.4586, 19.4795	6,9 m	6,9 m	18	1,2	35,1
22	64.0130, 19.2406	1,9 m	0,3 m	21	4,5	472,6
23	63.4848, 19.4158	7,0 m	4,2 m	20	7,0	204,0
24	63.4911, 19.4103	8,5 m	8,5 m	15	1,6	39,3
25	63.5403, 19.2086	10,1 m	10,1 m	11	2,2	43,5
26	64.0401, 20.1478	1,4 m	1,4 m	8	1,4	212,2
27	64.1000, 19.4983	4,9 m	0,7 m	15	3,1	128,1
28	64.1066, 19. 4823	13,7 m	13,1 m	28	15,4	225,7
29	64.2861, 19.3220	9,6 m	9,6 m	13	1,1	22,8

The dead wood that was registered in the buffer zones were mostly spruce and birch. Spruce was the dominant species, constituting 62 % of the total dead wood count and birch 29 %. Species identification was not possible due to moss coverage and/or the advanced decomposition state for 17 pieces (table 2).

Table 2: Distribution of species of the dead wood (number of pieces) across all study sites.

Species	Count
Spruce (*Picea abies*)	359
Birch (*Betula* spp.)	172
Grey Alder (*Alnus incana*)	17
Pine (*Pinus sylvestris*)	9
Aspen (*Populus tremula*)	1
Rowan (*Sorbus aucuparia*)	1
Unknown	17

In total, 576 pieces of dead wood was measured across all sites. Logs of class 2 was dominant with 311 findings, which makes up for 53.9 % of the total dead wood. 99 logs of class 1 was found (17.1 %), by adding these with logs of class 2 (i.e. dead wood that are most likely to have fallen after the creation of the buffer zone) they together make up for 71.1 % of the total amount.

Further, 93 logs were registered in class 3 (16.1 %). Older dead wood (class 4 and 5) were rare with a total of 31 individuals in class 4 (5.3 %), and 13 logs in class 5 (2.2 %) across all 29 study sites. Together classes 3-5 make up for 23 % of the total amount. Additionally, stumps (class 6) accounted for 5 % (figure 4).

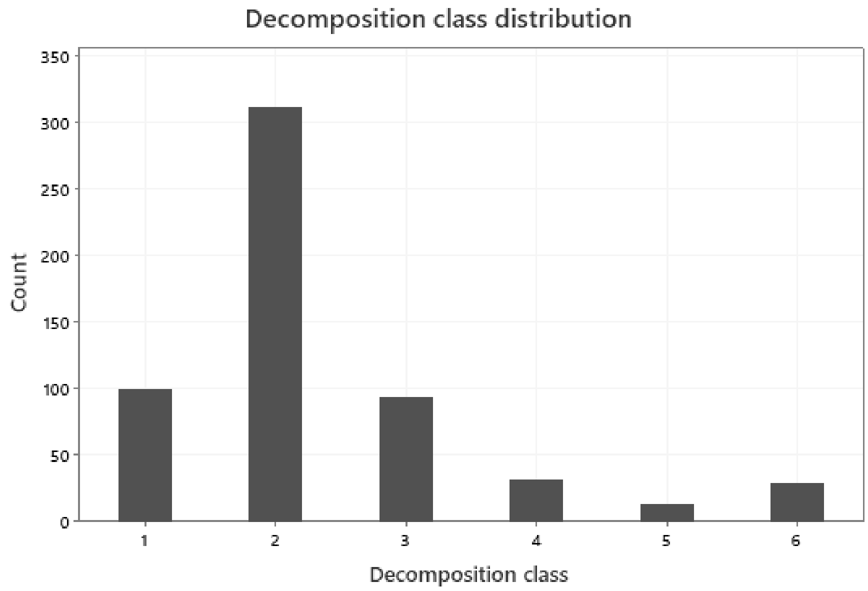

Figure 4: Histogram displaying the distribution of the decomposition classes across all study sites of all dead wood pieces recorded (y-axis).

3.2. Relationship between riparian buffer zone widths and dead wood

The average buffer zone loss in this study was 0.6 m, with a 4.1 m loss as the highest and several sites were the average buffer zone loss was 0 m. Only two sites had a buffer loss larger than 2 meters. There was near-significant negative exponential relationship (p-value = 0.07) between buffer zone loss and average original buffer zone width. The results show a weak negative trend of decreasing buffer zone loss with increasing buffer width ($r^2 = 0.23$, figure 5).

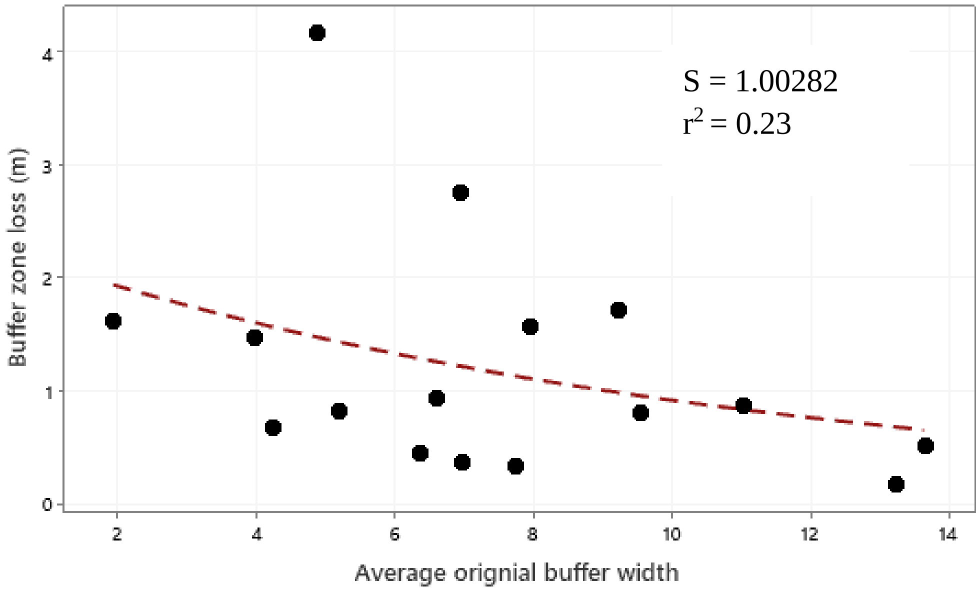

Figure 5: Buffer zone loss plotted against the original buffer width of the buffer zone of the sites that experienced loss. S = 1.00282, and r^2= 0.23 are parameters obtained from the negative exponential trend indicated by the dashed line.

The pieces of dead wood at the study sites ranged from 6 at the site with the least amount to 45 to the site with the highest amount of dead wood, with an average of 19 pieces of dead wood/site. No relationship was found between the amount (pieces) of dead wood in decomposition class 1 and 2, found in the buffer zones (figure 6a, figure 6b) with the average original buffer zone width nor the average current buffer zone width ($p > 0.05$, Table 3).

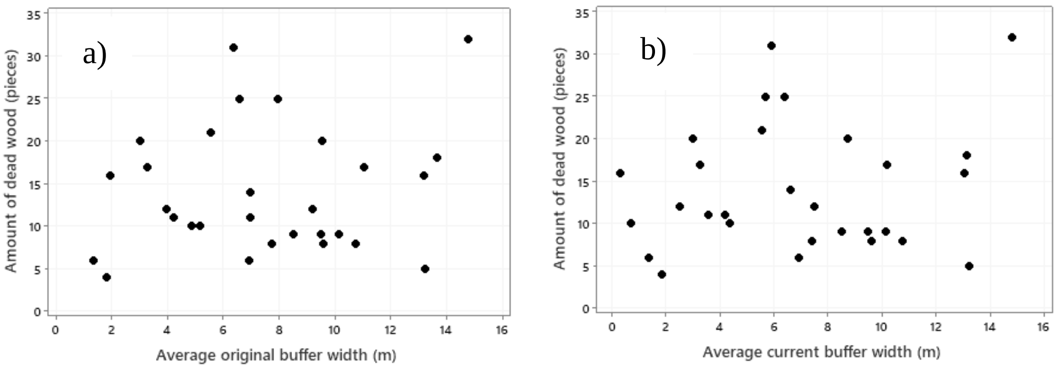

Figure 6: Amount of dead wood (pieces) in the decomposition classes 1 and 2 in the buffer zones plotted against the original buffer zone width (a) and current buffer zone width (b)

3.3. Dead wood in riparian buffer zones and other landscape properties

The average slope of the clear-cuts was at the lowest 2.5 degrees and at the highest 7.4 degrees. No relationship ($p > 0.05$, Table 3) was found between the amount of dead wood in decomposition classes 1 and 2 in the buffer zones and the average slope of the clear-cuts (figure 7).

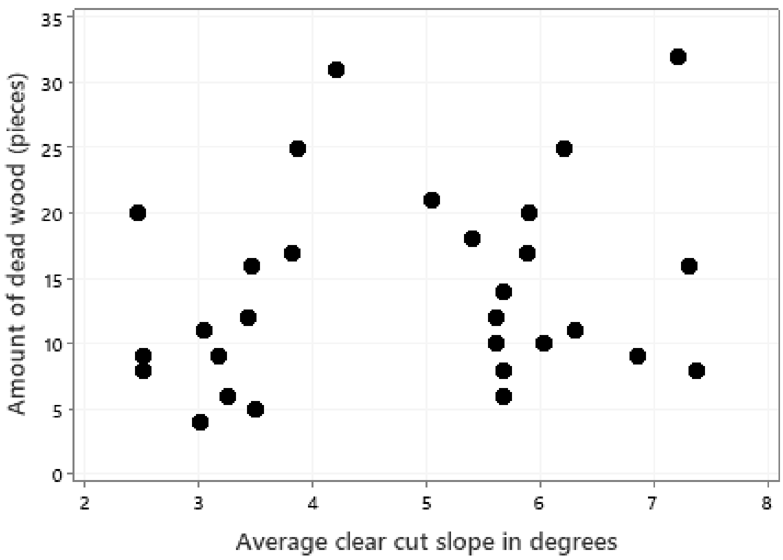

Figure 7: Amount of dead wood in decomposition classes 1 and 2 in the buffer zones plotted against the average slope of the clear-cuts in degrees

The size of the clear-cuts and (if present) adjacent clear-cuts ranged between 1.9 ha to 72.6 ha. 14 clear-cuts were between 1-10 ha, 11 clear-cuts were between 11-20 ha and 4 were 21 ha or bigger. Both the amount of dead wood in decomposition classes 1 and 2 and the buffer zone loss showed a large variation independent ($p > 0.05$, Table 3) of the clear-cut size (figure 8).

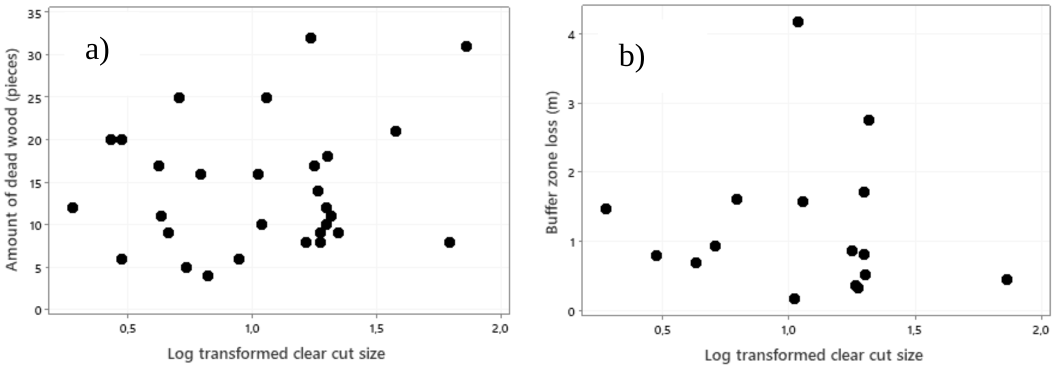

Figure 8: Scatter plots with amount of dead wood in decomposition classes 1 and 2 (a) and buffer zone loss (b) plotted against the log transformed size of the clear-cuts.

Three streams had east-to-west or west-to-east direction, south and south-to-east had 9 streams, and 8 streams had a south-to-west direction. No statistically significant difference ($p > 0.05$. Table 3) in the amount of dead wood in decomposition classes 1 and 2 were found by the stream directions (figure 9).

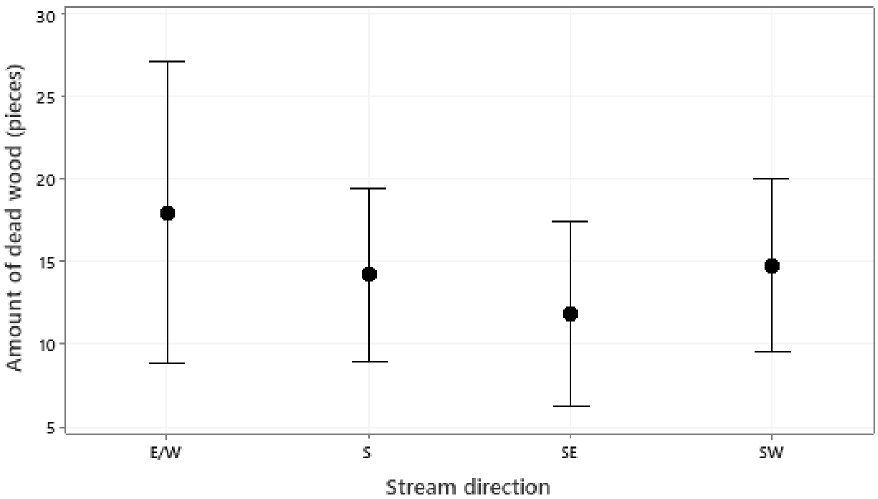

Figure 9: Average (± SD) of amount of dead wood in decomposition classes 1 and 2 for each stream direction and E/W = East or West, S = South, SE = South east, SW = South west.

The clear-cuts in this study were harvested between 2010 and one as late as 2020 (one month before the field inventories). No relationship ($p>0.05$, Table 3) was found between the age of the clear-cut and the amount of dead wood in decomposition classes 1 and 2 found in the buffer zone (figure 10).

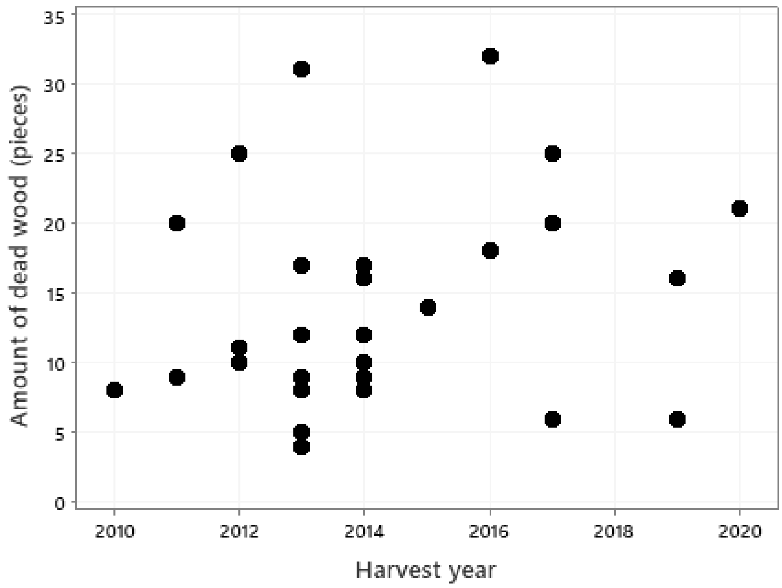

Figure 10: Scatter plot with amount of dead wood in decomposition classes 1 and 2 plotted against the harvest year of the clear-cut. No trend was found.

Soil wetness is expressed as an index in which 0 is dry and 100 is wet. No significant trend ($p>0.05$, Table 3) was found between the amount of dead wood in decomposition classes 1 and 2 and the average soil wetness of the buffer zones (figure 11).

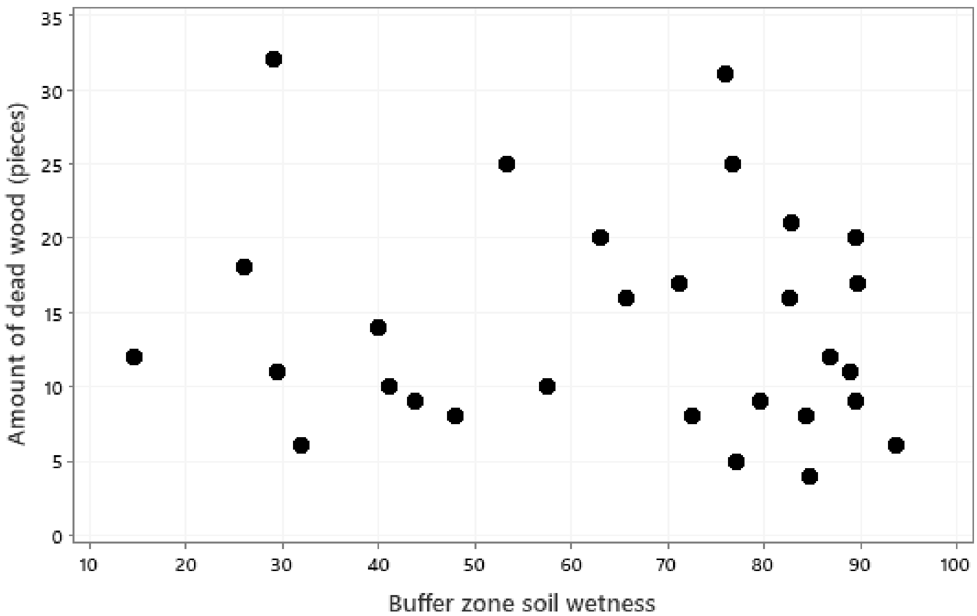

Figure 11: Amount of dead wood (class 1 and 2) in the buffer zones plotted against the average soil wetness in the buffer zone. No trend was found.

P-values and r^2 -values for the different models created are found in the following table (table 3).

Table 3: P-values and r^2 values for the linear regression models testing the amount of dead wood (pieces) and buffer zone loss against different explanatory variables.

Parameters	p-value	r^2
Amount of dead wood vs Average original buffer width (fig 6a)	0.635	0.034
Amount of dead wood vs Average current buffer width (fig 6b)	0.724	0.025
Amount of dead wood vs Average clear cut slope in degrees (fig 7)	0.484	0.054
Amount of dead wood vs log transformed clear cut size (fig 8a)	0.385	0.071
Buffer zone loss vs log transformed clear cut size (fig 8b)	0.734	0.046
Amount of dead wood vs Stream direction (fig 9)	0.683	-
Amount of dead wood vs Harvest year (fig 10)	0.264	0.046
Amount of dead wood vs Buffer zone soil wetness (fig 11)	0.658	0.021

4. Discussion

4.1. Original buffer zone width and buffer loss

I hypothesized that there would be a negative relationship between original buffer width and buffer zone loss. In other words, the wider the buffer zone the less windthrows and less reduction of the buffer width. Smaller retention patches are more susceptible to windthrows than larger retention patches (Beese et al. 2019) and narrower buffers have been shown to be more prone to wind disturbance (Mäenpää et al. 2020). The results showed a near-significant negative exponential relationship (p-value 0.07) with a weak negative trend of decreasing buffer zone loss with increasing buffer zone width ($r^2 = 0.23$, figure 4). Although weak, the trend could imply that managers should consider wider buffers in order to minimize windthrows and create functioning protection for small streams. Wider buffers has been shown previously to support more functions (Broadmeadow & Nisbet 2004) and are needed to maintain ecological integrity of headwaters (Sweeney & Newbold 2014), so the goal for managers should be to retain wider buffers over time. Since the narrower buffer zones have less to lose, the negative consequences for the ecological functions the buffer is intended to uphold might also be greater the narrower the buffer is to begin with.

I also expected to see a bell-shaped relationship between amount of dead wood (number of pieces) and buffer width. The idea behind this hypothesis was that narrow buffer zones have little potential for recruitment to begin with, so even if the retained trees blow down, the amount could not be very high (Bahuguna et al. 2010; Mäenpää et al. 2020). Wide buffers would protect the inner zone, and be generally more resistant to wind, and therefore dead wood provision would be low. Intermediate buffer widths would however be narrow enough to not protect its inner zone whilst harbouring a larger number of retained trees to be blown down compared to the narrowest buffers. No trend was however found, not for original buffer width nor current buffer width (figure 6a and 6b, table 3). This is most likely because of the range of the buffer widths investigated in this thesis.

The widest average buffer zone width in this study was 14.8 meters. In previous studies comparing buffer widths carried out in British Columbia and Finland (Bahuguna et al. 2010, Mäenpää et al. 2020), the wide buffers have usually been 30 meters wide (and proven to be very wind resistant). This range was not possible to investigate in Sweden, simply because such buffer widths rarely exist, at least along headwater streams (Kuglerová et al. 2020b). Nevertheless, the results in this study implies that the amount of dead wood is unaffected by buffer widths, and this is supported by Mäenpää et al.'s (2020) findings. Although no significant relationship was found between buffer width and dead wood, these results are of high importance. It documents that similar amounts of wood are blown down in the narrow buffers and the wider buffers in this study. This means that in the narrow buffers, very little trees are left standing which heavily impairs or even eliminates the ecological functions the trees are left for to begin with. The functions that are most heavily affected when buffers are blown down, are the ones connected to removal of canopy such as leaf litter input and shading (Hoover et al. 2011), windthrows also induces heavy sediment loading (Wolff & Grizzel 1998)

The riparian buffer zones chosen for this thesis are very typical headwater buffers in northern Sweden which means that they are representative for small stream buffer zones in the area (Kuglerová et al. 2020b). Leaving trees unharvested means lost revenue for the landowners (Tiwari et al. 2016). The results in this study points towards that a lot of the retained trees are blown down within a couple of years which makes little sense both ecologically and economically.

4.2. Landscape properties and dead wood

As expected, no relationship was found between amount of dead wood and harvest year (figure 10, table 3). The literature supports this result. Most windthrows in new stand edges following harvest occurs during the immediate years following harvest (Jönsson et al. 2007; Bahuguna et al. 2010).. The age distribution of the clear-cuts in this study is ranging from 2010 to 2020. One site was harvested 2020 and two sites were harvested in 2019. These three sites might still experience some major windthrow events, which could affect the results if one were to revisit these sites in one or two years from now.

The results in this study do not support the hypothesis that clear-cut size affects the amount of dead wood in the buffer zones (figure 7a, table 3). There was no relationship between buffer zone loss and clear-cut size either (figure 7b, table 3). This is not what was expected based on that previous studies, which have shown that wind speed affects wind disturbance (Elie and Ruel 2005) and that risk for windthrows increase with clear-cut size (Meänpää et al. 2020). One possible explanation to this could be that the production forest landscape of Sweden is becoming increasingly fragmented and composed of small adjacent stands of different ages (Axelsson & Östlund 2001; Kempe & Nilsson 2011), which makes clear-cut size of one stand of less relevance.

Retention patches in forestry located in moist areas should be planned based on topography and prevailing wind directions (Vanha-Majamaa & Jalonen 2001). It has been previously shown that wind disturbance is influenced by topographic conditions. Stands located lower in a slope are often less susceptible to wind damage than stands locate higher up (Ruel et al. 1998). However, in this study no relationship was found for average clear-cut slope in degrees and amount of dead wood (figure 7, table 3).

No significant difference between the different stream directions was found either. According to the Swedish Meterological and Hydrological Insitute, both south-southwestern winds and north-northwestern winds are common in the studied area (SMHI 2020) which probably is the reason to why no differences was found. If there is no prevailing wind, then no stream direction is of higher exposure.

The risk for windthrows are typically associated with local soil characteristics, especially soil wetness (Everham & Brokaw 1996). However, riparian zones have in general a high level of soil moisture. This is because of the shallow ground water movement and the presence of surface water in the adjacent streams (Mikkelsen & Vesh 2000). Therefore, I did not expect to see a relationship between buffer zone soil wetness and amount of dead wood, simply because I did not expect this parameter to vary that much across the study sites. Indeed, no relationship was found between amount of dead wood and buffer zone soil wetness (figure 10, table 3).

4.3. Alternative management options

In the managed boreal forests of Sweden, there is very little dead wood in the riparian zones of headwaters due to historical management (Kuglerová et al. 2020a). In this light, windthrows in buffer zones creates necessary substrate to uphold biodiversity and provide important habitat (Esseen et al. 1997; Bragg & Kershner 1999). Although this function is provided by the contemporary buffer management, as documented in this thesis, the other desired functions outlined by the Swedish Forest Agency (Andersson et al. 2013) cannot be sustained if majority of the buffer blows down. It is also important to keep in mind that a severe wind events causing a large amount of windthrows in one pulse do not replace the long-term continuous recruitment of dead wood that is largely missing from Swedish forests. Severe windthrows can also stimulate large amounts of fine sediment transport to the streams which have different negative consequences for the aquatic environment (Wolff & Grizzel 1998).

The results of this thesis can certainly contribute to refining the guidelines for riparian buffer management along Swedish headwaters. As an alternative to the current standardized fixed width buffers, hydrologically adapted buffer zones have been proposed by researchers (Kuglerová et al. 2014). They can basically be described as buffer zones which have widths that changes with local site conditions. In areas where the groundwater table is close to the soil surface buffers are to be wider and areas of less significance allows harvesting closer to the stream. These types of buffer are in addition more cost-efficient than fixed with buffers (Tiwari et al. 2016) and would most likely alter the spatial recruitment of dead wood.

Another management option to the standardized fixed width buffers that has been proposed is emulating natural disturbances (END). END-management promotes biodiversity and creates a larger heterogeneity of habitats through variations in buffer widths, harvest intensity and vegetation structures (Kreutzweiser et al. 2012). Buffer zones like this where the width is dynamic along the stream might also have positive effects for windthrows and dead wood recruitment. In narrower parts, windthrows would be expected (and wanted) while in wider zones trees are better retained and the full range of services are provided.

Stand density and gap size between neighbouring trees also affect a forest stands susceptibility to wind disturbance (Schelhaas et al. 2007, Gardiner et al. 1997). Planning riparian buffer zones at an early stage in a stand's rotation period, as early as the cleaning phase, would make it possible to create full storied, diverse in age structure, multi-species riparian zones protecting the streams. This is also supported by the fact that forest stands with a diverse age structure has been found to have a low probability of windthrows and lower extents of vulnerable edges (Pukkala et al. 2016). Riparian forests of this type would also be beneficial for other ecosystem functions such as resource subsidies between the stream and the terrestrial environment (Richardson & Sato 2015).

4.4. Conclusions and future research

What other parameters could influence the results in this study? Measuring standing trees in the buffer zone would have been interesting and could provide valuable information on the magnitude of wind disturbance relative to standing stock. Mäenpää et al. (2020) found that a larger proportion of the original stems retained was affected by wind disturbance in narrower buffers and it would have been interesting to see if the situation is the same in the sites in this study. It is also known that height/dbh ratio and crown size is a strong driver of windthrow susceptibility of individual trees (Schelhaas et al. 2007; Schelhaas 2008), this information would also have improved the study. Unfortunately, due to time limitations of the field surveys this was not achievable. However, most sites in this study were chosen to be similar in respect to the riparian forest conditions; typical northern Swedish stands that are dominated by mature spruce. A potential source of error to the study is the choosing of representative stretches for the sites, however since all the field work was done by the author this minimizes the possible negative effect.

In conclusion, the results in this study shows a weak relationship that points to that original buffer zone width affects the future width of the buffer which could imply that managers should aim for wider buffers to minimize wind damage. In addition, when ranging from 0 – 15 meters, buffer zone width does not affect the amount of windthrown trees in the buffers of headwaters in northern Sweden. This could mean that any buffer zone width between 0 - 15 m are vulnerable to wind disturbance and to ensure that the ecological functions are kept in the near stream area, wider buffers are needed. Wind resistance of headwater buffer zones is a question that affects both the long-term ecological status of our running water and biodiversity issues.

Leaving unharvested strips of trees is an economic cost for the landowners. According to the results in this study is this a reduction in income that generate very little ecological value. Severe wind events and narrow buffers could further be problematic for landowners since the forestry law in Sweden regulates the amount of fresh dead wood one can leave un-salvaged (SFS 1979:429.). Salvage loggings of buffers might be necessary in the future if we continue with this management.

Future research should focus on how wind disturbance affects the proportion of retained trees in headwater buffers to further gain knowledge on how the buffers are affected in respect to other ecological functions such as shading and resource subsidies.

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2020:06	Författare: Nils Södermark Inverkan av trädslagsval och plantstorlek på tall- och granbestånds anläggningskostnad, skadeutveckling och tillväxt i norra Sveriges kust- och inland	
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