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The role of riparian buffer width on sediment connectivity through windthrow in a boreal headwater stream

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ABSTRACT

Riparian buffers are commonly used to mitigate the negative effects of forestry operations near water, particularly sediment transport to streams. In Sweden, current practices typically involve 5-7 m wide riparian buffers along small streams. Historical forest management, which favored conifers up to the channel edge, has resulted in these narrow buffers having a simplified tree species composition and structure, making them prone to windthrow. While windthrow can contribute large wood (LW) to streams, windthrow also risks increasing sediment inputs if rootwads are exposed near stream edges. This disturbance affects sediment connectivity, or the movement of particles through the fluvial system, but the interaction between LW dynamics and sediment connectivity in small boreal streams is not well understood. We investigated sediment connectivity at the Trollberget Experimental Area in northern Sweden, where six 100 m stream reaches had either 5 m or 15 m wide riparian buffers. Pre-harvest and one-year post-harvest data on windthrow, hydrology, and sediment yields were collected. Forest harvesting increased sediment connectivity in the streams regardless of buffer width, indicating that buffers wider than 15 m are necessary to reduce sediment input impacts in small headwater streams. Windthrow affecting stream channels was more common in the 5 m buffers, leading to significantly higher deposition of very fine sediments (<250 μm) compared to the 15 m buffers. Coarse (>1 mm) and fine sediments (250 μm – 1 mm) were also higher in the 5 m buffers. We found that sediment connectivity in streams was closely linked to LW dynamics, negatively before harvest but positively after harvest. Before harvest, LW trapped sediment and prevented downstream transport, but after harvest, the increased sediment input overwhelmed this function. Our results highlight a trade-off between the recruitment of LW and minimizing sediment connectivity, two key objectives in riparian buffer management.

1. Introduction

Headwater ecosystems are critically important for local as well as downstream biodiversity, ecological functions, transport of solutes and biogeochemical cycling (Wohl, 2017). Headwaters are tightly connected to their adjacent riparian zones that provide a number of ecological functions, securing healthy aquatic ecosystems. Among others, two of the most important functions that the riparian zone has is to prevent excessive sediment transport to the streams through filtering overland flow and stabilizing streambanks (Polvi et al., 2014), as well as to supply large wood (LW). In fact, LW in streams is one of the most important controlling environmental factors on channel geomorphology and ecosystems (Gurnell et al., 1995; Jackson and Sturm, 2002; Hassan et al., 2005; Gomi et al., 2006; Wohl et al., 2018; Wohl et al., 2019). LW increases the diversity of flow velocities and spatial heterogeneity of channel form, increases hydraulic roughness and habitat complexity, provides substrate and food for aquatic invertebrates, decreases velocities and traps sediment and organic matter (Martens et al., 2020; Poeppl et al., 2024). However, most of the research on the functions of LW in streams concerns fish-bearing large streams and the effects of LW in headwaters is still not well known (Jackson and Sturm, 2002) especially when it comes to LW and sediment connectivity interactions (Poeppl et al., 2024). Further, this interaction remains underexplored in boreal headwaters affected by intensive land use because the majority of research has been conducted in temperate and coastal forests (e.g., Boggs et al., 2016; Gomi et al., 2005; Grizzel and Wolff, 1998; Merten et al., 2010).

To protect the functioning of streams, including the sources and

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supply of LW, the allocation of riparian buffers was developed as a strategy to reduce or prevent negative effects caused by land use. Forested riparian buffers should serve as physical, biogeochemical and ecological barriers between managed uplands and streams, and should secure the provision of functions that streams depend on (Kuglerová et al., 2023a). In forestry, the premise has been that if enough trees along streams are retained, they will mitigate the effect of forest harvest in the uplands (Richardson et al., 2012). These effects including removal of tree biomass that alters evapotranspiration and thus alters hydrology, decomposition of branches and roots that releases nutrients, and rutting caused by harvesters and timber-laden forwarders moving trees to roads that can expose and release sediment (Richardson et al., 2012). Whether riparian buffers prevent the adverse effects of forestry on streams depends on local conditions, buffer characteristics, properties of the affected streams (Kuglerová et al., 2023a), as well as hillslopes and roads (Rachels et al., 2020). In terms of preventing sediment transport to streams, the assumption is that the sediment that reaches streams after forestry operations originate in the harvested area that is beyond the riparian buffer. However, riparian buffers may also be a source of sediment when windthrow occurs within the buffer, especially when falling trees uproot along the streambank or within the channel. This is because sediment under the rootwad as well as loose sediment in and around the roots are exposed and can be exported to the stream more easily directly from the riparian buffer. While windthrow can increase LW in streams and riparian areas, its potential effect on sediment connectivity, i.e., the potential of particles to move through the fluvial system (Hooke, 2003), are not well known (Grizzel and Wolff, 1998; Boggs et al., 2016).

While streambank erosion is a natural process that shapes channel form (Florsheim et al., 2008), excessive sediment erosion and subsequent deposition in streams can have adverse effects on aquatic communities (Wood and Armitage, 1997). Sediment burial was found to have a large negative impact on the autotrophic productivity in boreal streams (Myrstener et al., 2023). Further, deposition of fine sediment can reduce fish eggs and fry survival (Sutherland et al., 2002), change invertebrate community composition (Kreutzweiser et al., 2005), smother endangered freshwater pearl mussels (Denic and Geist, 2015), and degrade biochemical exchange processes (Brunke and Gonser, 1997). Riparian buffers can protect channel beds from excessive sedimentation and further downstream transport if they are wide enough. Gomi et al. (2006) found that 20 m wide buffers are associated with relatively little sedimentation compared to unharvested reference. Kreutzweiser et al. (2009) further showed that if wide buffers are retained (30–100 m), it is possible to carefully harvest within them and still prevent sediment transport from the upland to streams. Wider buffers are also more effective in preventing windthrow (Kuglerová et al., 2023b) that may increase sediment connectivity. Thus, whether buffers function as a filter for sediment delivered from the harvested upland or source of sediment due to windthrow, is likely dependent on their width.

In Sweden, the guidelines for riparian buffer management state that well-functioning riparian buffers should prevent an increase in erosion and sediment reaching the stream above natural levels, as well as should provide LW to the streams and riparian zones (Andersson et al., 2013). Riparian buffers around small streams in Sweden are usually 5–7 m wide and typically consists of 1–2 rows of trees (Kuglerová et al., 2020; Ring et al., 2023). These streams are lacking LW because, historically, Swedish forest management has suppressed LW in production stands (Dahlström and Nilsson, 2004; Kuglerová et al., 2023b). The riparian forests around small streams are also typically dominated by Norway spruce, a consequence of a legacy of forest management and fire suppression that promoted production stands all the way to the edges of small streams (Hasselquist et al., 2021). Mäenpää et al. (2020) questioned the ecological function of such narrow spruce-dominated buffers because they are more likely to be affected by windthrow (Kuglerová et al., 2023b), and thus, are more likely to expose sediment to erosion rather than prevent it. The trade-off between the two ecological functions – prevention of excessive sediment entering the stream and consequent sediment connectivity, and provision of LW – is relatively unexplored. Using the Trollberget Experimental Area in northern Sweden (Laudon et al., 2021), that includes a replicated riparian buffer width experiment along the length of one headwater stream, we asked how sediment connectivity in streams is affected by adjacent clear-cut harvest operations. Furthermore, we asked whether riparian buffers of different widths, a ‘Narrow’ (5 m buffer) or ‘Wide’ (15 m buffer), mitigate sediment connectivity or are a source of sediment due to recruitment of LW following windthrow. We hypothesized that the wide buffers (15 m) would act as sediment filter by preventing transport from uplands into the channel, therefore decrease downstream sediment connectivity. On the other hand, the narrow (5 m) buffers might act as a sediment source due to extensive windthrow, increasing downstream sediment connectivity. We further hypothesized that the LW in the channel would have a negative effect on sediment connectivity because it will trap sediment before harvest. However, after harvest, LW will be associated with increased sediment connectivity because the higher volume of LW will be associated with windthrow that provides a larger sediment source to the channel. Finally, we hypothesize that sediment connectivity will increase downstream due to increasing stream size (catchment area) and discharge, and thus stream power, and this trend will be stronger after the harvest because of the general increase of sediment in the stream that can be mobilized.

2. Methods

2.1. Site description

The study stream (Torrkällsbäcken) has a catchment area of 0.17–0.63 km^2 and is situated in the Trollberget Experimental Area in northern Sweden, about 45 km northwest of Umeå (Laudon et al., 2021). The channel width varies between 0.3 and 1 m, and bankfull depth varies between 0.2 and 0.7 m, with an average bed slope of 0.04 m/m. At Trollberget, the forest was harvested in July–August 2020 and February 2021 (Fig. 1A). The harvest was carried out as final felling (clearcutting) of most commercial trees with some retention forest patches left on site (Fig. 1A). Riparian buffers were either 5 ($n = 3$) or 15 (n = 3) m wide strips of unharvested forest on each side of the channel along six ca 100 m long stream reaches (Fig. 1A). The forest surrounding the study stream was, before the harvest, dominated by conifers, such as Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). The riparian forests were, and still are, dominated by Norway spruce (Kuglerová et al., 2023b). The surficial geology is dominantly till, and the soils are commonly iron podzol of 10–20 cm depth on the hillslopes and 30–70 cm depth in the riparian areas (Marcus Klaus, personal communication). Soils are dry to moist and closer to the stream, peat is common. Bedrock in the area consists of paragneiss. While we do not have discharge data from our study stream (logger failure), we present flow data from a gauge that is located on a small tributary (drainage area: 0.084 km^2, Laudon et al., 2021) that drains into our study stream directly downstream of position 9 (Laudon et al., 2021; Fig. 2). We assumed that the flow regimes in respect to fluctuation of the two streams are similar due to their proximity. However, we do not use the discharge data in the analyses, because the magnitude and timing could be different.

2.2. Large wood inventory

We inventoried large wood (LW) in each of the six stream reaches with buffer treatments. Details of the LW inventories can be found in Kuglerová et al. (2023b). In this study, we focus on LW that could directly affect the stream channel, i.e., either submerged in the stream or located within the bankfull width, because this subset of LW is assumed to have an effect on sediment deposition relevant for the time frame of this study. Thus, we did not include LW that were bridges and thus not

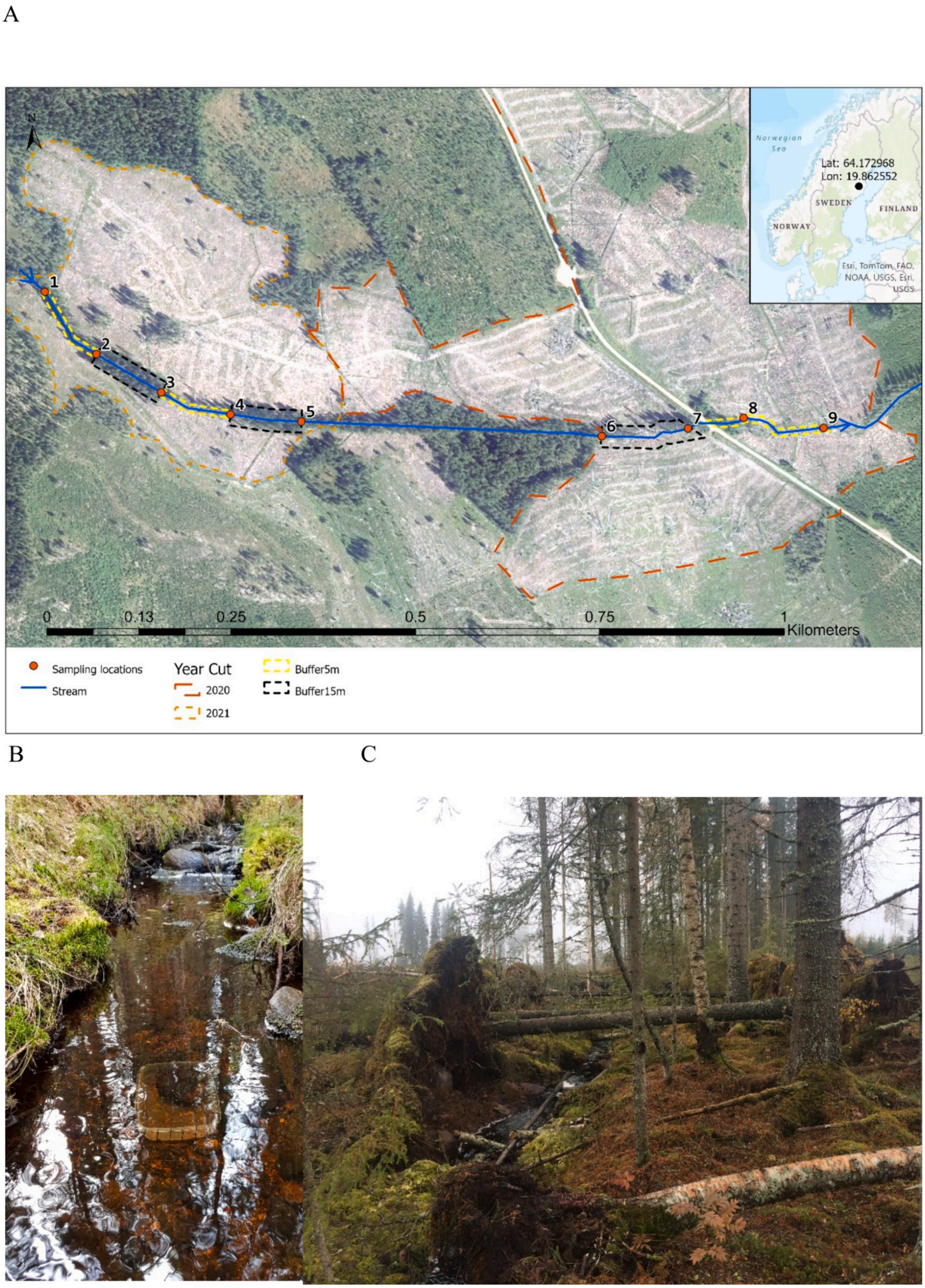

Fig. 1. A) The Torrkällsbäcken stream (blue line) situated in Trollberget Experimental Area in northern Sweden (inset map in A) included six reaches that received either narrow (5 m, yellow dashed line) or wide (15 m, black dashed line) riparian buffers when the adjacent forest was harvested. The boundary of the clear-cut harvest in 2020 (red) and 2021 (orange) is displayed over an aerial photo taken after the harvest was complete. The downstream positions of the sediment traps are indicated by the red points 1–9. B) Photo of a sediment trap (13 × 17 cm) used in this project and the study stream. C) Windthrow and rootwads affecting the streambank after a storm in fall of 2020; the right side of the photograph shows that nearly the entire 5 m wide buffer was blown down.

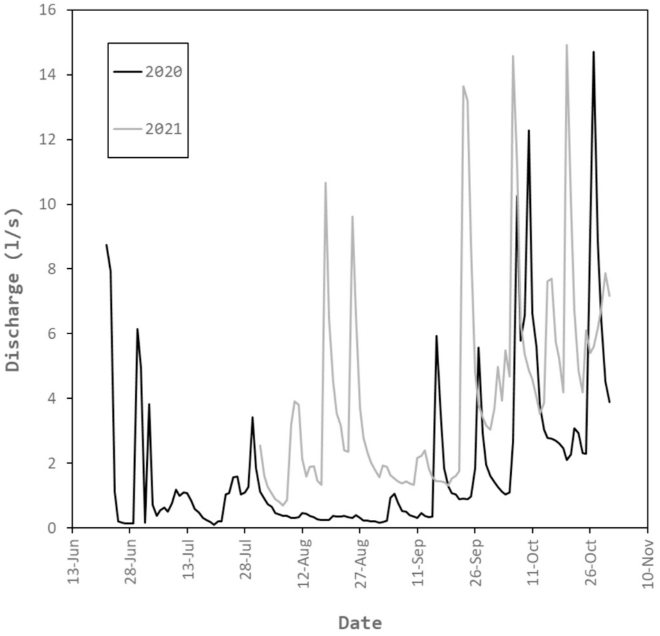

Fig. 2. Discharge (l/s) over the studied period from the gauging station on an adjacent catchment that flows into our study stream.

likely to interact with the stream for decades (Bahuguna et al., 2010; Rossetti de Paula et al., 2020). For all LW pieces that were > 1 m long and > 5 cm mid-diameter, we measured length and mid-diameter and calculated volume (m^3) based on an assumption of a cylindrical shape (Wohl et al., 2010). We conducted the inventories twice, once before the harvest and creation of the buffers (July 2020) and once after the harvest. It is important to note that soon after the two most downstream buffers were created in August 2020, there were two large storms in October and November 2020, with high wind speeds and a record high stream flow (Laudon et al., 2021). Though landowner removal of most wood recruited by these storms precluded the inclusion of that wood in our 2021 inventories, we were able to use exposed rootwads on the channel banks - which are left behind in the salvage-logging process - as a proxy for LW recruitment by the late 2020 storms.

2.3. Sediment measurements

To assess sediment connectivity downstream from the experimental buffer reaches, sediment traps were used to determine bedload sediment yield (sensu Kreutzweiser et al., 2009). The traps consisted of plastic boxes that were 17 cm long, 13 cm wide and 5 cm deep. The traps were dug into the channel bed so that the top edge of the plastic box was level with the bed (Fig. 1B). The tops of the traps were open and weighed down by a cobble (diameter: ca 7 cm) and secured with a 15 mm mesh net that was attached to the channel bed with metal tent stakes, thus any sediment over 15 mm was excluded from the traps. The open tops allowed sediment to be deposited but also re-suspended during different flow conditions (Kreutzweiser et al., 2009). At each downstream position (1–9), we placed three traps in the thalweg, ca 1 m apart longitudinally. Traps were placed longitudinally, because it was not possible to place them laterally at all positions, due to the stream being <1 m wide. The traps were placed directly downstream of each experimental buffer reach (position 2, 3, 4, 5, 7 and 9) as well as directly upstream of the first buffer reach (position 1), after a wetland complex that separated the study reaches (position 6), and directly downstream of a culvert at a road crossing (position 8). While positions 1, 6 and 8 are not associated with any of the experimental buffers and not used in the statistics for determining the effect of buffer width and LW, they are informative from a longitudinal connectivity perspective.

The traps were installed in June 2020 and then sampled monthly until ice-covered conditions occurred October in 2020. Traps were opened and sampled again in July 2021 and sampled monthly until October 2021. The samples collected in July and August 2020 serve as a pre-harvest control at all nine positions. Samples from September and October 2020 at positions 6, 7, 8 and 9 represent post-harvest samples because the first harvest at the downstream part of the study reach was completed (Fig. 1A, Table 1), while September and October 2020 at positions 1–5 represent pre-harvest period. Samples from August, September and October 2021 represent the post-harvest period at all positions (Table 1). During each sampling occasion, we emptied each trap into a 1 L storage container, moved the container to a freezer within 4 h, and stored it frozen until lab processing. Emptied traps were put back into its position and secured until the next sampling occasion.

Each sediment sample was sieved to obtain the sediment size distribution based on three sediment sizes: i.e., coarse sediment (1–15 mm), fine sediment (250 μm - 1 mm) and very fine sediments (1.6 μm - 250 μm). We acknowledge that these categories do not align exactly with standard sediment size classes (Blair and McPherson, 1999), but given our aim of examining whether the buffers allow forests to meet environmental goals, we chose ecologically meaningful sediment size classes. Sediment sizes <1 mm are known to impact salmon egg survival (Jensen et al., 2009) as well as freshwater pearl mussel (Denic and Geist, 2015), and 250 μm was used for very fine sediments based on Kreutzweiser et al. (2009). The maximum sediment size measured was 15 mm. Sediments washed through the 250 μm sieve were suspended with the water from the storage container and filtered through a pre-ashed Whatman grade glass-fibre filter (1.6 μm pore size). The samples were then dried for two days at 60 °C. After two days, all sediments were weighed and then combusted in a muffle furnace (2 h at 500 °C) to obtain ash-free dry mass and an estimate of the organic vs. inorganic mineral fraction from each sample and sediment size class.

2.4. Statistical analyses

To test the effect of forest harvest and buffer width on sediment connectivity as quantified through sediment yield, we used linear mixed-effect models (LMM), specifically the function *lmer* in the *lme4* package (Bates et al., 2015) in R (version 4.3.1, R Core Team, 2023). Response variables were the yield (grams) of each sediment size (coarse - CS, fine - FS, and very fine -VFS) and fractions (organic —O vs. inorganic —I, and total-T) and the explanatory fixed factors were buffer width (narrow and wide) and harvest period (before and after), and their interaction. Since the sites were located along the same stream, we included downstream position (1–9) and time (month of sampling) as random factors. To determine differences of Least Squares Means for the fixed factors of our mixed-effect models when interactions were significant we used the function *emmeans* (Lenth, 2021). The statistical significance of the interactions and individual factors was tested using restricted maximum likelihood with significance levels of α = 0.1 and 0.05. Data were log transformed prior to analysis.

To assess how LW affects sediment connectivity in our study stream, we performed correlation analyses between average volume of LW pieces found in each reach and the yield of the three sediment sizes (coarse, fine, and very fine) and fractions (organic vs. inorganic, and total) at each downstream position that had an associated upstream experimental buffer reach. Thus, data from positions 1, 6 and 8 were excluded from these analyses. We used sediment data from July and August 2020, and August, September and October 2021. Our objective with the correlation analyses was to assess whether the relationship between LW and sediment connectivity changed due to forest harvest and as such, using data from September and October 2020 was not possible as only half of the stream reaches were harvested then (Fig. 1A). Thus, we excluded those two months from the correlation analyses. We then correlated the sediment yield in the traps downstream of each experimental buffer reach with the volume of LW separately for each of

Table 1

Catchment areas for each of the sampling positions (from upstream to downstream), mean volume of LW pieces (total volume per reach in parenthesis), and number of rootwads counted in each stream reach before and after harvest. Note that sampling positions 1, 6 and 8 are not associated with an upstream riparian buffer experimental section (see methods and Fig. 1A for details) hence we did not inventory LW and rootwads in their upstream reaches.

Downstream position	Catchment area (km^2)	Harvest completed	Upstream buffer reach	Buffer width (m)	LW in 100 m upstream (m^3)		Rootwads (#)	
					Before	After	Before	After
1	0.17	Feb-21						
2	0.22	Feb-21	3 Narrow	5	0.01 (0.15)	0.02 (0.14)	0	8
3	0.24	Feb-21	3 Wide	15	0.01 (0.26)	002 (0.37)	0	3
4	0.29	Feb-21	2 Narrow	5	0.03 (0.14)	0.04 (0.12)	0	0
5	0.3	Feb-21	2 Wide	15	0.01 (0.06)	0.02 (0.17)	0	0
6	0.6	Aug-20						
7	0.6	Aug-20	1 Wide	15	0.004 (0.04)	0.23 (2.54)	0	0
8	0.62	Aug-20						
9	0.63	Aug-20	1 Narrow	5	0.01 (0.29)	0.39 (7.37)	0	0

the five months. The sediment yield was averaged for the three traps at each sampling position. Spearman correlations tests were used because data were not normally distributed.

Spearman correlation tests were also used to test the relationship between sediment yield and catchment area. Since all sampling positions are situated along the same stream, we used catchment area as a proxy for downstream connectivity and increasing stream size (Kuglerová et al., 2015). Catchment area of each of the nine positions was generated from a flow accumulation model based on a 2 m digital elevation model (Arc GIS Pro 3.1.1). We used the same months as in the correlations with LW (July and August 2020, and August, September and October 2021) to be able to compare the effect of catchment area on downstream sediment connectivity before and after harvest. Similar to the previous correlations, the yield of coarse, fine and very fine sediments, as well as the organic/inorganic fractions were correlated with the catchment area of each of the nine downstream positions.

3. Results

3.1. Forest harvest and buffer width

We found that forest harvest increased sediment connectivity as shown by an increase in the sediment yield of all sizes and for organic and inorganic fractions (fixed effect of 'harvest', $p < 0.1$, Fig. 3, Supplementary Information Table 1) except for total very fine sediment (VFST, $p = 0.1$) and the inorganic fraction of very fine sediment (VFSI, $p = 0.12$). In general, we found higher sediment yield of all sediment sizes and organic and inorganic fractions in narrow buffers compared to wide buffers after harvest (interaction of the fixed effect of 'harvest*buffer', $p < 0.05$, Fig. 3, Supplement Information Table 1), but this was only statistically significant for total yield of very fine sediment (VFST, $p = 0.02$) and the inorganic fraction of very fine sediment (VFSI, $p = 0.03$).

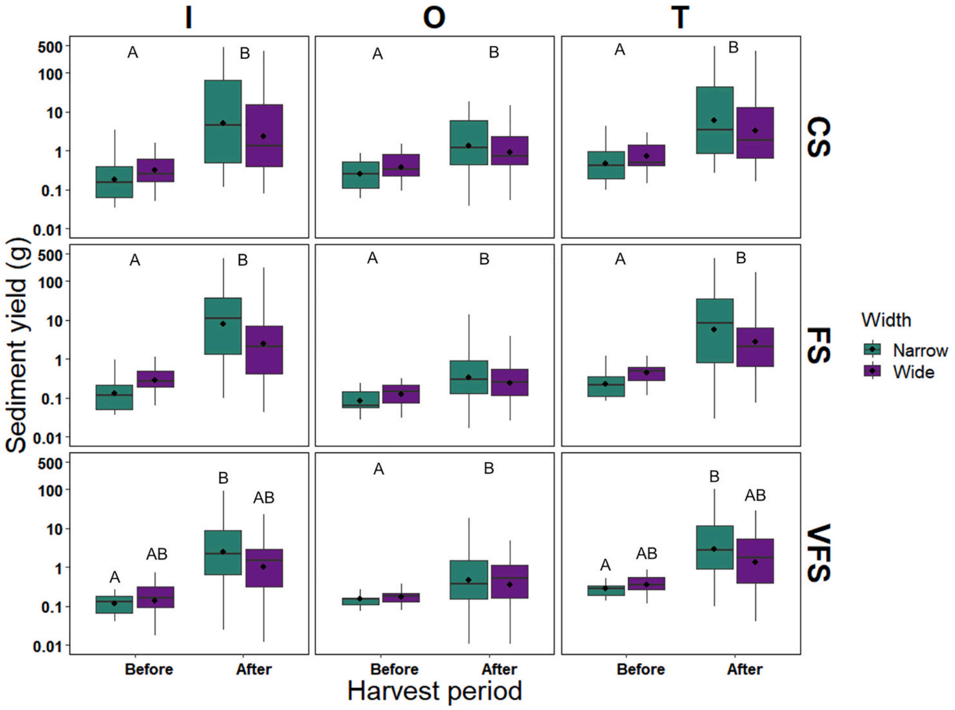

Fig. 3. Sediment yield (g) measured per 100 m stream reach before and after the adjacent forest was harvested and three reaches each of narrow (5 m) and wide (15 m) buffer widths were established at the Trollberget Experimental Area. Deposited sediment was collected on a monthly basis and separated into different sediment sizes (coarse sediment – CS, fine sediment – FS, very fine sediments VFS), and organic fractions (total- T, inorganic – I, organic - O). Horizontal lines represent medians, black points represent averages, and quantiles are indicated by the boxes. Error bars represent minimums and maximums. Significant differences between before and after the harvest are designated with different letters at the top of the panels, while significant interactions between harvest and buffer width are shown with different letter combinations just above individual boxes. If boxes share a letter, they are not significantly different from each other (p < 0.1).

3.2. *Large wood and large wood recruitment*

Before the harvest, LW in the stream affected sediment connectivity negatively (negative correlations with CS and FS) for all fractions (organic, inorganic, and total). After harvest, there was a positive relationship between LW and sediment yield with correlations that were consistently high for all sizes and fractions (Table 2). In particular, in July 2020, the coarse sediment (CS) yield was negatively correlated with LW volume (Table 2). Although not statistically significant, we found the same trend in August. Before harvest, fine sediment (FS) was also negatively correlated with the LW volume, however, these correlations, albeit high, were not statistically significant (Table 2). The correlations between very fine sediment (VFS) and LW volume were low, non-significant but still negative. After harvest, we found most correlations between sediment yield and LW high and significant, however, compared to the before-harvest trends, all of the correlations were positive after harvest. The yields of most size classes as well as organic and inorganic fractions increased with increasing volumes of LW in the water (Table 2).

3.3. *Downstream position*

Catchment area, here representing downstream position and increasing stream size, had a strong positive effect on sediment connectivity (Fig. 4). In the two months before the forest harvest, we saw strong correlations between the coarse and fine sediment yields, and catchment area, with both size classes significantly increasing downstream (Table 3, Fig. 4). In contrast, the yield of very fine sediment (VFS) had no relationship with downstream position, indicated by the weak and non-significant correlations between all VFS fractions and catchment area in July and August 2020. After the harvest, the trends persisted for the coarse (CS) and fine (FS) sizes, and most of the VFS fractions also became significantly positively correlated with catchment area (Table 3). During September and October 2021, which had relatively high flow events (Fig. 2), the significant correlations between a few organic/inorganic fractions of some size classes and catchment area became non-significant (CSO and VFSO in September 2021, and CST and VFSI in October 2021); however, the correlations were still relatively high ($r > 0.6$).

4. Discussion

4.1. *Forest harvest and riparian buffer width*

We tested the effect of leaving mature Norway spruce adjacent to a headwater stream in either a 'narrow' (5 m on either side of the stream) or 'wide' (15 m on either side) fixed-width buffers. Our data partially supported our hypothesis that wider buffers act as sediment filters to adjacent clear-cut forestry operations, while narrow buffers act as sediment sources due to more windthrow affecting the channel in narrow buffers in addition to less area to filter overland flow. The harvest affected instream sediment yield, regardless of buffer width, except for very fine sediment (VFS) that only increased where narrow buffers were present (Fig. 3). Though not statistically significant, observably higher sediment yields in narrow buffers in all sediment sizes and organic fractions, suggest that the wide buffers were able to filter at least VFS or that only narrow buffers increase the connectivity of this sediment size with the channel. In Kreutzweiser et al. (2009), VFS were also less responsive to forest management than the other sediment size fractions after the riparian buffers of their study streams were partially harvested. While our method is not well developed to collect VFS (Kreutzweiser et al., 2009), the results we obtained aligned with our hypothesis and with previous research findings (Gomi et al., 2005; Kreutzweiser et al., 2009), confirming its usefulness within the framework of this study.

Table 2

Spearman correlation coefficients between mean volume of large wood (LW) in each of the six experimental reaches and yield of different sediment sizes (coarse sediment – CS, fine sediment – FS, very fine sediments VFS), and fractions (total-T, inorganic – I, organic - O). The correlations were calculated separately for the months before harvest (July, August 2020) and months after harvest (August, September, October 2021). Statistically significant correlations at α = 0.05 are marked with * and in bold.

Sediment size/ fraction	July 2020 Before	August 2020 Before	August 2021 After	September 2021 After	October 2021 After
CST	**−0.89***	−0.77	**0.89***	**0.89***	**0.89***
CSI	**−0.89***	−0.77	**0.89***	0.71	**0.89***
CSO	**−0.94***	−0.31	**0.94***	0.83	**1***
FST	−0.66	−0.66	**0.89***	**0.94***	**0.94***
FSI	−0.66	−0.66	**0.89***	**1***	**0.94***
FSO	−0.71	−0.77	**0.94***	0.83	**1***
VFST	0.086	−0.2	**0.94***	**1***	**0.89***
VFSI	−0.29	−0.03	**1***	**0.88***	0.77
VFSO	−0.6	−0.66	0.71	**0.88***	**1***

Our findings that wide (15 m) buffers are better at preventing changes in the sediment connectivity than narrow buffers agree with Gomi et al. (2005), showing that buffers between 10 and 20 m produced less sediment. It is unclear how long these effects on increased connectivity will last in our study stream; we only measured one year post harvest of the adjacent stand, and thus, just initial effects. Chellaiah and Kuglerová (2021) found no relationship between the portion of channel bed sediment <2 mm and buffer width in a snapshot survey. However, they acknowledge that they might have missed the peak in sediment connectivity caused by harvesting as their study was done 3–8 years after harvesting and did not assess the pre-harvest status of the channel beds. Other studies have found that it takes >10 years for fine sediments in channels exposed to forest harvest to return to pre-harvest levels (Merten et al., 2010). Further, Macdonald et al. (2003) found that suspended sediments in streams have been found to return to normal levels within 3 years or less. As changes in flow after harvest can last for years (Schelker et al., 2013a, 2013b), it is possible that increased bank erosion from newly exposed rootwads could continue until the new forest has enough volume (and thus evapotranspiration) to affect stream flow, riparian plants reestablish and stabilize the sediment, and/or LW currently occurring as bridges decompose enough to interact with the channel bed and affect sediment connectivity.

The weak relationships with the coarser sediment sizes could be due to the less mobile nature of the coarse sediment sizes or potentially the effects of a large storm that increased sediment connectivity, but only in the two downstream sections. Since sediment typically moves downstream at varying rates depending on their size (Topping et al., 2018), the short time scale of our measurements may not have captured the full effect of the change in sediment connectivity of coarse grain sizes, which mareuqire longer time scales (i.e., several years) to be detectedyears. Furthermore, high variation in the windthrow among replicates may have led to masking of general trends; most windthrow occurred in just one replicate for each of the buffer widths. In the wide buffers, the windthrow occurred outside of the channel, with half the number of rootwads affecting the channel than in the narrow buffer; thus, the windthrow that did occur in the wide buffer was not as susceptible to bank erosion (Table 1). As stated previously, some erosion is a natural part of channel processes, but too much can be detrimental to instream organisms, particularly populations of endangered freshwater pearl mussels and salmon when they are smothered by fine sediments (< 1 mm, Sutherland et al., 2002, Denic and Geist, 2015). Our study shows the potential for downstream deposition of sediment with increased connectivity associated with windthrow in narrow riparian buffers; we need even wider buffers to fully protect streams from this potential threat to instream biodiversity and to ensure a more steady and gradual recruitment of LW and thus connectivity in the future.

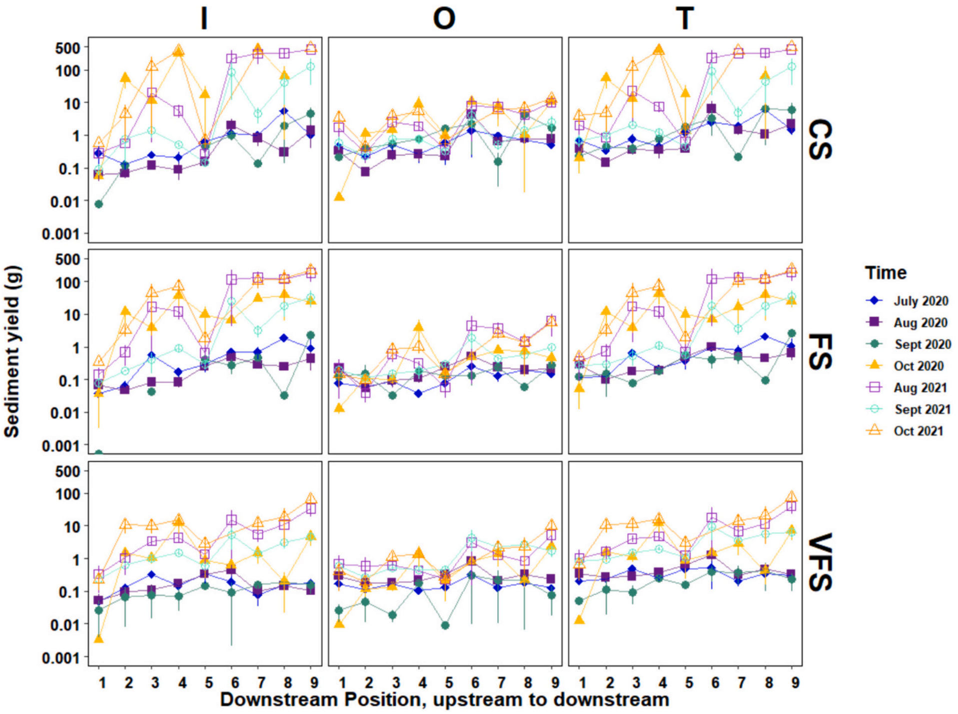

Fig. 4. Mean (+/1 standard error) sediment yield (g) measured along the length of the study stream at the Trollberget Experimental Area. Sediment was collected on a monthly basis and separated into different sediment sizes (coarse sediment – CS, fine sediment – FS, very fine sediments VFS), and fractions (total- T, inorganic – I, organic - O). July and August 2020 were before harvest measurements for all sampled downstream distances, and August – October 2021 were after harvest for all sampling sites. September–October 2020, just the downstream distances 6–9 were impacted by harvest.

Table 3
Spearman correlation coefficients between catchment area of each sampled positions and average yield of different sediment sizes (coarse sediment – CS, fine sediment – FS, very fine sediments VFS), and fractions (total- T, inorganic – I, organic - O). The correlations were calculated separately for the months before harvest (July, August 2020) and months after harvest (August, September, October 2021). Statistically significant correlations at α = 0.05 are marked with * and in bold.

Sediment size/ fraction	July 2020 Before	August 2020 Before	August 2021 After	September 2021 After	October 2021 After
CST	**0.81***	**0.71***	**0.80***	**0.79***	0.69
CSI	**0.79***	**0.89***	**0.81***	**0.82***	**0.79***
CSO	**0.69***	**0.70***	**0.80***	0.60	**0.81***
FST	**0.93***	**0.75***	**0.83***	**0.98***	**0.86***
FSI	**0.93***	**0.84***	**0.85***	**0.92***	**0.86***
FSO	**0.76***	0.37	**0.80***	**0.82***	**0.88***
VFST	0.36	0.37	**0.87***	**0.88***	**0.81***
VFSI	0.33	0.42	**0.92***	**0.77***	0.79
VFSO	0.14	0.49	0.63	0.64	**0.81***

4.2. *Large wood and large wood recruitment*

The importance of LW for trapping sediment and thus decreasing sediment connectivity has been recognized for decades (Gurnell et al., 1995; Gomi et al., 2006; Poeppl et al., 2024). Our results from the pre-harvest period confirm this pattern in a headwater stream situated in a mature production forest stand in northern Sweden. Before the harvest, in-channel LW caused sediment dis-connectivity (Poeppl et al., 2023) indicated by the strong negative correlations between the coarse sediments (both organic and inorganic fractions) sampled downstream of the experimental buffer reaches and LW volume, and similarly, the strong (but not significant) negative correlation between LW and fine sediment. While we did not measure sediment deposition directly around the LW, our results suggest that LW was effectively trapping particles, mitigating downstream transport. The correlations were stronger in July 2020 but similar in August 2020. The difference between these two pre-harvest months were likely caused by the different flow magnitudes. August was a very dry month with very low flow (Fig. 2), while July 2020 included several rain events causing increased flow and hence the potential for bedload transport and collection in our traps. Interestingly, the very fine particles had weaker correlations (still negative) with the LW volume during the pre-harvest months. This is likely because LW is not efficient in trapping such small sediment sizes (Allan et al., 2021) but also because the proportion of VFS was extremely low in the stream in general, before harvest.

We were able to confirm our hypothesis that there is a certain trade-off between provision of LW and prevention of erosion and potential for sediment to be exported to the stream, two functions that should be provided by riparian buffers (Andersson et al., 2013). After the harvest, we found strong positive correlations between all sediment sizes in the traps downstream of each experimental buffer reach and LW volume during all the sampled months. All three months sampled after the harvest were characterized by several rain events and associated high flows (Fig. 2), contributing to initiation of sediment mobilization from the newly exposed sediment in the riparian zone and consequently increased connectivity within the channel (Hassan et al., 2005; Croke and Hairsine, 2006). The strong positive correlations between LW volume and sediment were not caused directly by the LW in the channel, but the indirect effect of windthrow of the riparian trees that also increased LW volumes (Kuglerová et al., 2023b) and sediment mobilization from the disturbed sediment that overwhelmed any potential dampening effect of the LW (Fig. 1). So far, these cascading effects of buffer management on LW recruitment and consequent sediment connectivity increase in streams has only been speculated (e.g., Hasselquist et al., 2021; Kuglerová et al., 2023b). This study is the first to provide evidence in a managed boreal forest context. The largest sediment yields were measured in the traps situated at the downstream ends of the two reaches that experienced the highest windthrow and had the largest numbers of rootwads directly within the bankfull channel (Table 1). Importantly, the VFS also increased after the harvest, which poses a concern because those are the size fractions that are problematic for drinking water quality and can be transported the longest distance (Wood and Armitage, 1997) and are not effectively trapped by LW as shown by our pre-harvest results.

From our results, we cannot say when or if the increased volumes of LW associated with the post-harvest windthrow will start functioning as sediment traps. However, in another study, most of the wood that was recruited by windthrow formed bridges over the channel, rather than being deposited into the channels (Kuglerová et al., 2023b). It will take decades before this wood is incorporated into the channel and provides a beneficial dis-connectivity function (Rossetti de Paula et al., 2020). A long-term evaluation of the interaction of LW as it ages and the channel stabilizes in relation to sediment yield should be made to understand the time frame that is necessary for LW and sediment dynamics to reach a new equilibrium. In the meantime, our results provide direct evidence that the current riparian buffer management in Sweden is insufficient to provide these two functions simultaneously in the short term post-harvest.

4.3. Effect of downstream position on sediment connectivity

Generally, sediment connectivity increased with catchment area, i.e., downstream position along the stream. This trend was expected because along this ca 1.2 km long channel affected by adjacent forest harvest, the catchment area nearly quadruples. Such an increase in catchment area is associated with an increase in discharge and thus stream power, and this in turn, has a positive effect on sediment mobility and transport (Hassan et al., 2005). We observed an increasing trend of sediment connectivity with downstream position for coarse (>1 mm) and fine (250 μm - 1 mm) sediment sizes as well as all organic and inorganic fractions both before and after harvest. However, the magnitude of the increase was much lower before the harvest compared to after the harvest. Before harvest (2020), the total coarse sediment yield increased from the most upstream (position 1) to the most downstream (position 9) position by a factor of two in July and by a factor of 5.5 in August, while over the same channel length, fine sediments increased by a factor of 9.6 in July and by a factor of 2.3 in August. After the harvest (2021), the corresponding increase in sediment yield for total coarse sediment was by a factor of 212 in August, 178 in September and 127 in October; and for the total fine sediment yields, they increased by a factor of 533 in August, 121 in September and 495 in October. This underscores the enormous increase in sediment supply to the streams caused by the harvest and the windthrow in riparian buffers (Grizzel and Wolff, 1998) and the consequent potential for downstream propagation. While the wide buffers appear to be relatively more adept at mitigating the harvest/windthrow effects, the narrow buffers failed at this function. It is likely that the particles that entered the streams in the reaches with narrow buffers traveled further than the 100 m associated with each sediment trap and that is why we see such a large increases of sediment connectivity downstream after the harvest.

The fact that we found that the very fine particles had no relationship with catchment area before harvest suggests that our studied stream potentially rarely transported such small size particles, likely due to lack of sources (Wood and Armitage, 1997). However, the way we sampled was likely less effective in catching the smallest fractions, as mentioned previously (Kreutzweiser et al., 2009). However, the VFS yields significantly increased after harvest and also with catchment area after harvest indicating that even this sediment size was able to reach the stream and was able to be transported downstream. The downstream propagation of harvest effects has been shown for temperature (Roon et al., 2021), dissolved organic carbon (Oni et al., 2015) and several ecological parameters (Erdozain et al., 2022) but not explicitly for sediment connectivity. Yet, since sediment can have many adverse effects on aquatic ecology (Sutherland et al., 2002; Kreutzweiser et al., 2005; Myrstener et al., 2023) and biogeochemical process (Brunke and Gonser, 1997), our study has large implications for the way we manage our forests in vicinity to small streams.

5. Conclusion

Many streams affected by forest management have reduced levels of LW within channels and their associated riparian zones. Forest buffers are intended to remedy this by providing a long-term source of LW, as well as a range of other ecosystem services (e.g. biodiversity, filtering nutrients). Some of these functions are undermined by windthrow (e.g. shade, water quality, streambank stability), but some may be improved (e.g. LW recruitment, sediment capture). In this study, it is evident that with current management of riparian buffers in Sweden, which are typically 5–7 m wide, more sediment is transported into the streams from the harvested uplands than before the adjacent forest was harvested. We found that at short time scales, the disturbance to channel banks when LW was recruited via windthrow increased the potential for sediment to be transported downstream by at least two orders of magnitude, overwhelming any trapping function that LW had before the harvest. Furthermore, there were strong trends for all sediment sizes and statistically significant trends for the very fine sediments, that wider buffers provided less sediment input to streams. Excessive sediment mobilization and extirpation of instream organisms has been previously identified as one of the most serious impairments of water quality in managed boreal forests (Futter et al., 2016). Negative impacts of forest management on water quality and ecology should be buffered by leaving intact riparian forest along streamside edges. Here we show that with current management practices for riparian buffers, we cannot satisfy the two functions that riparian buffers should provide to streams at the same time, provision of LW and prevention of erosion and potential for sediment transport to downstream reaches, at least not in the short term. Riparian buffers need to be wider or managed differently to maximize LW and reduce sediment connectivity.

CRediT authorship contribution statement

Eliza Maher Hasselquist: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lina E. Polvi:** Writing – review & editing. **Rasmus Staaf:** Writing – review & editing, Methodology, Formal analysis. **Malgorzata Winkowska:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Ruben Baan Hofman:** Writing – review & editing, Methodology, Investigation, Data curation. **Lenka Kuglerová:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to condense the abstract down to <300 words. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.geomorph.2024.109320. These data include the Google maps of the most important areas described in this article.

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