AGU ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR026381

Cutting Edge: A Comparison of Contemporary Practices of Riparian Buffer Retention Around Small Streams in Canada, Finland, and Sweden

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Key Points:

- We conducted regional-scale field surveys in Canada, Finland, and Sweden to evaluate conditions of riparian buffers along small streams
- Riparian buffers along 286 small streams in Canada, Finland, and Sweden were on average 8.9, 15.3, and 4 m wide, respectively
- A revision and re-evaluation of present forestry guidelines and regulations are needed in order to better protect small, forest streams

Supporting Information:

- Supporting Information S1

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Citation:
Kuglerová, L., Jyväsjärvi, J., Ruffing, C., Muotka, T., Jonsson, A., Andersson, E., Richardson, J. S. (2020). Cutting edge: A comparison of contemporary practices of riparian buffer retention around small streams in Canada, Finland, and Sweden. *Water Resources Research*, *56*, e2019WR026381. https://doi.org/10.1029/2019WR026381

Received 28 SEP 2019
Accepted 31 AUG 2020
Accepted article online 10 SEP 2020

Abstract Forested riparian buffers are recommended to mitigate negative effects of forest harvesting on recipient freshwater ecosystems. Most of the current best practices of riparian buffer retention aim at larger streams. Riparian protection along small streams is thought to be lacking; however, it is not well documented. We surveyed 286 small streams flowing through recent clearcuts in three timber-producing jurisdictions—British Columbia, Canada (BC), Finland, and Sweden. The three jurisdictions differed in riparian buffer implementation. In BC, forested buffers are not required on the smallest streams, and 45% of the sites in BC had no buffer. The average (±SE) width of voluntarily retained buffers was 15.9 m (±2.1) on each side of the stream. An operation-free zone is mandatory around the smallest streams in BC, and 90% of the sites fulfilled these criteria. Finland and Sweden had buffers allocated to most of the surveyed streams, with average buffer width of 15.3 m (±1.4) in Finland and 4 m (±0.4) in Sweden. Most of the streams in the two Nordic countries had additional forestry-associated impairments such as machine tracks, or soil preparation within the riparian zone. Riparian buffer width somewhat increased with stream size and slope of the riparian area, however, not in all investigated regions. We concluded that the majority of the streams surveyed in this study are insufficiently protected. We suggest that a monitoring of forestry practices and revising present forestry guidelines is needed in order to increase the protection of our smallest water courses.

1. Introduction

The importance of riparian buffer retention along freshwater systems during forestry operations has been recognized for decades (Castelle et al., 1994; Richardson et al., 2012; Sweeney & Newbold, 2014). When upland forests are harvested, riparian buffers can mitigate the impacts of vegetation removal and soil disturbance on receiving waters. For example, forested buffers have been shown to help avert excessive amounts of fine sediment and nutrients delivered from disturbed upland soils (Hill, 1996; Kreutzweiser et al., 2009), riparian trees and shrubs shade streams to prevent rising water temperatures (Gomi et al., 2002; Kreutzweiser et al., 2009), and their roots increase bank stability (Beeson & Doyle, 1996). Moreover, maintaining diverse riparian vegetation provides resource subsidies for aquatic organisms in the form of leaf litter and other organic materials (Richardson & Sato, 2015). Some studies have documented that retention of riparian buffers can also provide suitable habitat and corridors for species movement and dispersal (Marczak et al., 2010; Spackman & Hughes, 1995).

The effectiveness of riparian buffers depends on a number of factors such as the conditions of the buffer (e.g., width, forest structure and composition, and level of tree retention), the properties of adjacent harvested areas, and the properties of the streams themselves (Kreutzweiser et al., 2010; Lidman et al., 2017; Richardson et al., 2012). Stream properties vary across the fluvial network as they are related to stream size and network position. For example, headwater streams (the smallest streams in the network) usually differ from higher order streams into which they flow in topographical, hydrological, and ecological aspects, including gradient, discharge, and/or dominant sources of water, and riparian vegetation (Benda et al., 2004; Kuglerová et al., 2015; Montgomery, 1999). Importantly, the smaller the streams, the more directly coupled they are to their surrounding contributing areas (Church, 2002; Wallace & Eggert, 2015). As such, small streams might be the most sensitive parts of the stream network to any changes in the riparian areas associated with forestry operations. Nevertheless, in many countries, larger streams usually receive protection in the form of forested riparian buffer zones.

Small streams, on the other hand, are generally regarded to receive minimal protection (Kuglerová et al., 2017; Olson et al., 2007; Wohl, 2017) for several reasons. For example, small streams are abundant in forested landscapes (Bishop et al., 2008), and retaining riparian buffers along all of them would impose a large cost on forest owners. Further, small streams are often missing from property maps and are sometimes difficult to visually locate during harvest operations, especially in winter (Ågren et al., 2015; Meyer & Wallace, 2001). Finally, small streams do not present recreational-fishing possibilities, and thus, protecting their habitat for cold-water adapted species (e.g., salmonids) is not prioritized (Olson et al., 2007). Overall the ecological and/or biochemical importance of small streams on both local and downstream scales has been underappreciated by land managers in the past (Hasselquist et al., 2019; Kuglerová et al., 2017). However, small streams are important at the catchment scale. In many regions, they represent up to 80% of the total stream network length (Bishop et al., 2008; Leopold et al., 1964). They deliver water, nutrients, carbon, and sediments to downstream ecosystems, and they can function as sources and/or refuge for populations of aquatic organisms (Gomi et al., 2002; Wipfli et al., 2007). It also has been reported that small streams harbor unique organisms, which are rarely found in larger streams (Richardson, 2020). As such, downstream systems directly depend on their small tributaries, and these linkages should be acknowledged in land-use planning, including forestry operations. Although many researchers and government agencies have speculated for a long time that small streams are neglected when allocating buffers (Hylander et al., 2002; Kuglerová et al., 2017), there are very few data on regional scales to test this contention. Only a few local reports (Ahonen, 2017, in Finnish; Olsson, 2009, in Swedish) or studies conducted within single catchments (Hasselquist et al., 2019) have somehow evaluated buffer presence (or width) around small streams. Scientific evidence is needed to understand the current status of riparian protection for small streams, especially if we aim to protect our water resources from sources to outlets in landscapes managed for production forestry.

Currently, policy approaches for delineating and applying riparian buffer zones and regulation of forestry operations within those zones vary greatly among countries (Lee et al., 2004; Ring et al., 2017). The variation in riparian buffer requirements across jurisdictions is driven by factors such as land ownership, forest certification schemes, legal requirements, and/or voluntary actions, as well as the quantity and quality of watercourses. For example, Sweden and Finland, two of the top wood-producing countries in the world (Food and Agriculture Organization of the United Nations (FAO), 2019), have a similar proportion of land area covered by forest (around 70%), similar percentage of private forest land (around 70%), and both rely on voluntary actions and forest certification, rather than on law enforcement, for riparian buffer management. However, the stream network characteristics differ substantially between the two jurisdictions. In Finland, a large number of the smallest watercourses have been ditched, whereas Sweden has about five times the number of small streams on forest land (Ring et al., 2017). This difference in the quantity of natural (Sweden) versus modified (Finland) small channels might cause a large difference in how their protection is applied. Ring et al. (2017) reported that recommendations for riparian buffers in both countries vary between 5 and 50 m for all running waters, but natural or close-to-natural streams are typically prioritized (Finnish Forest Act, 2013; Skogsstyrelsen (The Swedish Forest Agency), 2014). British Columbia (BC), Canada, another top wood-producing jurisdiction (Food and Agriculture Organization of the United Nations (FAO), 2019), recommends riparian reserves of 20–50 m on the largest streams, particularly those that bear fish to avoid deteriorating habitat for cold-water adapted species. There are however, no requirements for leaving forested buffers on smaller, non fish-bearing streams (British Columbia Ministry of Forests, 1995). The differences in the degree of prescriptiveness is remarkable, given that small streams provide similar ecosystem services and have similar hydroecological functions across forested regions (Gundersen et al., 2010; Wallace & Eggert, 2015; Wipfli et al., 2007). Moreover, although many instructions for how to design riparian buffers are available, there is limited information on their implementation over regional scales and across jurisdictions, especially for the smallest streams.

This study aims to evaluate the current practices of riparian buffer implementation along small, forested streams in BC, Finland, and Sweden. We specifically evaluated buffers along small streams because they are acknowledged as important hydroecological parts of stream networks by scientists, yet they appear to be overlooked by practitioners (e.g., Kuglerová et al., 2017; Olson et al., 2007; Wohl, 2017). Our first objective was to determine how riparian buffers are implemented along small streams in each jurisdiction. We expected that the differences in legislation (e.g., BC has no mandatory buffers along small streams), voluntary actions (e.g., Sweden and Finland highly rely on voluntary set-aside forests and forest certification), and the character of small, fluvial features (e.g., number of small, natural streams) will cause differences in the presence and width of buffers among the three jurisdictions. We expect that BC streams receive the least protection (no buffers) due to the lack of legislative requirement. In Finland and Sweden, buffers are recommended along all natural or close to natural streams, regardless of size. However, we expect that Finland would have more streams with buffers (or wider buffers) compared to Sweden because natural small streams that should have a buffer are less frequent in Finland; thus, their riparian protection could be economically feasible. Our second objective was to determine whether there are properties of the local landscape or streams that explain buffer width in each jurisdiction. We predicted that buffer width would scale with stream size. However, we aimed at small streams, and thus, it is possible that our stream size gradient has too small a range to see wider buffers at the upper end of the stream size gradient. Moreover, we predicted that the size of the harvested area around the stream will determine the buffer width, with larger clearcuts associated with wider buffers. Finally, because many riparian buffer guidelines recommend avoiding steep slopes during harvest operations (British Columbia Ministry of Forests, 1995; Skogsstyrelsen (The Swedish Forest Agency), 2014), we expected a positive relationship between riparian slope and buffer width. Our third objective was to assess forestry-associated impairments in the riparian area, other than harvest, including drainage ditches connected to the stream, machine tracks, stream crossings with machines, blown-down trees, and partial harvests within the buffer, and whether their occurrence differs among the three jurisdictions.

2. Methods

2.1. Site Selection and Spatial Analyses

In each jurisdiction (BC, Finland, and Sweden), we selected two climatically contrasting regions to account for potentially different type of forests and forestry practices, yet with the same national policies. In Finland and Sweden, sites were located in southern and northern parts of the country, while in BC, sites were distributed across the coastal and interior regions (Figure 1). We acknowledge that there are jurisdictional differences in climate, geology, and topography. However, our aim was to evaluate whether practitioners follow national guidelines and policies for buffer allocations, and this should be independent of jurisdictional environmental differences. In all three jurisdictions, the dominant harvest practice is clearcutting of even-age forests. In Finland and Sweden, the dominant commercial tree species are Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*), and those species usually grow all the way to the water's edge of small streams. In BC, the dominant commercial tree species are western red cedar (*Thuja plicata*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and lodgepole pine (*Pinus contorta*). Other non-commercial tree species are found in the riparian zones along small streams, with downy birch and silver birch (*Betula pubescens* and *Betula pendula*) in the Nordic countries and red alder (*Alnus rubra*), vine maple (*Acer circinatum*), and cottonwoods (*Populus* sp.) in BC.

The approach for locating study sites was based on analyses of spatial data of clearcuts, small streams, and roads. Each jurisdiction varied in the availability of spatial data during site selection, and thus, the methods for site selection differed somewhat (details in supporting information Text S1). In general, spatial data of clearcuts harvested between 2010 and 2016 were obtained from forestry companies, national forestry agencies, or satellite images. Small streams (catchment size <15 km^2) were obtained from terrain and property maps or they were generated based on digital elevation models (DEMs). We used catchment area as a descriptor of stream size, rather than stream order, because stream order is dependent on map resolution and might not be comparable among jurisdictions (Richardson, 2020). The upper limit of 15 km^2 was chosen based on our experiences to include only wadeable streams, <3 m bankfull width. Nevertheless, smaller streams (~1 m wide) were prioritized during field work when possible. Roads were also obtained from property maps or as vector files from national GIS data sets. Candidate sites were identified by intersecting the small streams with clearcuts that were within ~200 m from the nearest road (Figure S1), and they were ground-truthed during the summers of 2017 and 2018. During field visits, sites that were evaluated by the field personnel as a man-made ditch, too disturbed to measure (i.e., stream channel was not obvious due

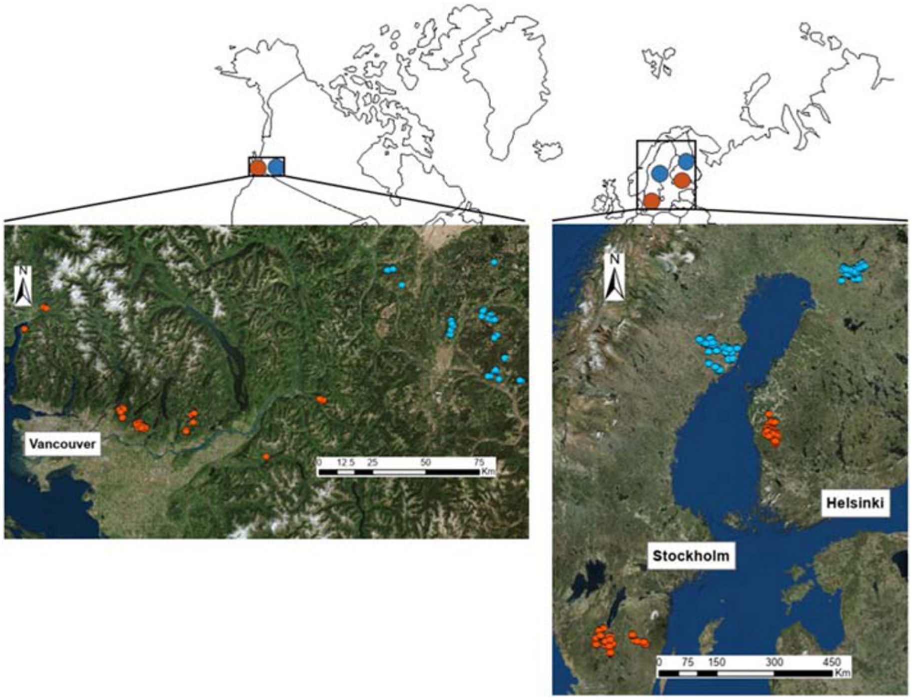

Figure 1. The locations of the 286 study sites in the coast (orange) and interior (blue) of British Columbia, Canada (to the left), and in northern (blue) and southern (orange) Sweden and Finland (to the right). The map in the background displays the location of the study regions within the northern hemisphere.

to extensive driving over the stream with heavy machines, <3% of cases) or completely missing (false positive), were excluded. Ditches (ca. 15% of sites) were excluded during field visits only in Sweden because in Finland and BC such sites were excluded prior to field work based on map evaluation. The stream segments that were further investigated (Figure S1) were selected from all the potential candidates based on driving distances between them (shorter distances were preferred) and accessibility (e.g., no gates on roads or difficult terrain). The land area (calculated by drawing a polygon containing all sites in each region) where surveyed sites were distributed was ca. 7,800, 4,000, and 12,200 km^2 in BC, Finland, and Sweden, respectively. With this site selection approach, we obtained a data set of streams that represent typical conditions for each region.

For each sampling site, we calculated catchment area, area harvested, and riparian slope. Catchment areas were derived from flow accumulation maps by using the D_8 algorithm (O'Callaghan & Mark, 1984) of pre-processed DEMs. In Sweden, the DEM had 2 × 2 m resolution and was generated from LIDAR point cloud data. In Finland, a 2 × 2 m DEM was used for the southern region and 10 × 10 m DEM for the northern region. The best quality DEM available for BC had a coarser resolution of 25 × 25 m. The size of clearcuts was calculated by extracting the size of each harvested polygon. In BC, the Ministry of Forests, Lands, Natural Resource Operations and Rural Development maintains spatial data describing clearcuts and forest tenure. After calculating catchment areas from the DEMs, we noticed that in Sweden and Canada, all surveyed sites were within the range of the predefined catchment area (<15 km^2) and a majority of streams were much smaller (<1 km^2, Table 1). In Finland, where DEM was not available upon site selection, we found that 16 sites had catchment area >15 km^2 (the average catchment area of those 16 sites was 24.6 km^2). Average slope of the riparian areas was calculated from the respective DEMs within a 30 m buffer on each side of each sampled stream reach. If this buffer intersected with a road, the road pixels were removed when calculating slope to avoid flat pixels. All spatial analyses were performed in ArcGIS (ArcMap 10.5, ESRI 2017), R (R Developmental Core Team, 2018) and Whitebox GAT (Lindsay, 2016).

2.2. Rapid Assessment Surveys (RAS)

At each site, an *RAS* protocol was performed on a 50 m-long stream reach situated within the clearcut, right before the stream entered a downstream forest patch or crossed a road. This most downstream part of the

Table 1
Summary of the Physical Attributes of the Streams Investigated in British Columbia (Canada), Finland, and Sweden

	British Columbia			Finland			Sweden		
Variable	Mean ± SE (median)	Range	*p*	Mean ± SE (median)	Range	*p*	Mean ± SE (median)	Range	*p*
Catchment area (km^2)									
North/Coast	0.14 ± 0.02 (0.09)	0.01–0.64		7.33 ± 1.26 (3.6)	0.13–47.30		1.41 ± 0.30 (0.44)	0.10–11.14	
South/Interior	1.34 ± 0.41 (0.65)	0.01–15.84	**<0.001**	9.30 ± 1.42 (6.50)	0.15–36.51	0.199	1.04 ± 0.29 (0.42)	0.11–12.13	0.93
Clearcut size (ha)									
North/Coast	9.53 ± 1.2	6.00–27.1		4.46 ± 0.67	0.82–28.54		15.61 ± 2.32	1.04–99.97	
South/Interior	77.22 ± 10.38	16.00–208.0	**<0.001**	5.86 ± 1.89	0.21–84.48	0.210	6.34 ± 1.6	0.41–34.77	**<0.001**
Riparian slope									
North/Coast	14.61 ± 1.43	2.96–41.6		3.46 ± 0.36	0–12.57		5.24 ± 0.29	1.91–14.23	
South/Interior	7.92 ± 0.57	1.76–15.1	**<0.001**	1.91 ± 0.28	0–7.31	**<0.001**	5.58 ± 0.37	2.32–13.27	0.40
Stream width (m)									
North/Coast	2.25 ± 0.14	1.08–5.20		1.82 ± 0.18	0.5–5.5		0.79 ± 0.09	0.2–5.0	
South/Interior	1.27 ± 0.12	0.37–4.00	**<0.001**	2.22 ± 0.18	0.3–5.0	**0.043**	0.95 ± 0.11	0.22–4.67	**0.004**
Substrate silt (%)									
North/Coast	42.00 ± 3.58	0–100		16.72 ± 3.56	0–100		43.05 ± 4.51	0–100	
South/Interior	31.69 ± 5.59	0–100	**0.024**	18.87 ± 3.34	0–100	0.232	76.70 ± 5.15	0–100	**<0.001**
Substrate sand (%)									
North/Coast	6 ± 1.66	0–40		18.38 ± 3.44	0–80		20.64 ± 3.30	0–90	
South/Interior	23.58 ± 3.66	0–86.67	**<0.001**	50.97 ± 4.40	0–100	**<0.001**	11.92 ± 3.25	0–80	**0.009**
Substrate gravel + pebbles (%)									
North/Coast	16.50 ± 1.96	0–75		21.47 ± 2.81	0–70		21.95 ± 3.09	0–100	
South/Interior	30.99 ± 4.4	0–100	**0.049**	16.39 ± 2.92	0–62.5	0.097	5.80 ± 2.05	0–60	**<0.001**
Substrate rocks + boulders (%)									
North/Coast	38.01 ± 2.75	0–80		31.39 ± 3.93	0–85		14.22 ± 2.27	0–85	
South/Interior	12.16 ± 2.80	0–70	**<0.001**	13.99 ± 3.07	0–70	**<0.001**	5.19 ± 1.59	0–50	**0.02**
Large wood (# of pieces)									
North/Coast	27.15 ± 4.2	4–150		6.90 ± 1.11	0–32		7.72 ± 0.60	0–23	
South/Interior	43.4 ± 5.4	0–162	**0.011**	11.02 ± 2.65	0–110	0.466	4.70 ± 0.50	0–15	**<0.001**

Note. For the differences between the two regions in each jurisdiction, a Wilcoxon test was used for averages of the values recorded at each site. Statistically significant differences at $\alpha = 0.05$ are presented in bold. Median values are presented for catchment areas to demonstrate the positive skewness of the stream sizes.

stream was chosen to capture the accumulated effects of harvest operations across the clearcut. The protocol was designed to efficiently (within 1 hr) evaluate stream physical conditions, riparian buffer widths, and the occurrence of impairments connected to the harvest operations. Only mature trees were considered when evaluating buffer width; that is, if only saplings (<2 m tall or <2 cm DBH) were present, they were not measured as a buffer. At 10, 30, and 50 m marks upstream from the reach beginning (0 m mark), stream bankfull width was measured. Within each of the three sections (i.e., 0–10, 10–30, and 30–50 m), buffer width was measured at each side of the stream, and the average of these six observations was used in further analyses. If timber harvest occurred only on one side of the stream (while the other side was forested), measurements were made only on the harvested side (i.e., three observations for buffer width). Stream substrate composition (proportions of silt, sand, gravel/pebbles, and rocks/boulders) was recorded as proportion of each grain size in each section based on visual evaluation. Pieces of large wood (LW: >1 m long and >10 cm in diameter) within the bankfull channel were counted along the entire 50 m section. The magnitude of impairments associated with forestry operations, other than harvest, were assessed for both sides of the stream combined (if both sides were harvested) along the entire 50 m reach and 30 m lateral distance from the stream, irrespective of buffer width. Briefly, we evaluated (a) the presence of ditches used for draining forest land or roadsides, (b) tracks caused by heavy machine driving, (c) soil preparation (typically scarification) to improve regeneration, (d) stream crossing, (e) blown-down trees, and (f) partial harvest indicated by the presence of stumps within the buffer. The classification of impairments was based on a 4-level scoring system (0 = no marks, 1 = low, 2 = medium, 3 = severe marks) for machine tracks, stream crossings, and blown-down trees, or on a 2-level scoring system (0 = absence, 1 = presence) for drainage ditches, soil preparation, and partial harvest. For stream crossings, Scores 1 and 2 indicated stream crossing with permanent or temporary bridge, respectively, and Score 3 indicates a stream crossed without a bridge. For machine tracks, Score 1 indicated one or two shallow tracks, Score 2 indicated a few shallow tracks or one or two deep (>50 cm) tracks, and Score 3 indicated numerous shallow or a few deep tracks. For blow-down trees, Score 1 indicated one or two trees blown down, Score 2 indicated up to 50% of trees blown down, and Score 3 indicated >50% of trees blown down.

2.3. Statistical Analyses

First, we used descriptive summary statistics to describe stream physical properties among the jurisdictions and regions within them. To assess the statistical differences in the stream physical properties, catchment area, clearcut size, and riparian slope between the two regions within each jurisdiction, we used Wilcoxon tests because of the non-normally distributed data. Analyses of variance (ANOVAs) were used to compare buffer widths among the three jurisdictions with average buffer width per site as the dependent variable and jurisdiction and region as the explanatory variables. ANOVA was followed by a Tukey post hoc test to assess the pair-wise differences among jurisdictions and between the two regions in each jurisdiction. Since buffer widths differed significantly among the three jurisdictions, and regions within each jurisdiction were also mostly significantly different, all following analyses were performed for each region within a jurisdiction separately.

Catchment area, clearcut size, and riparian slope were used as explanatory variables in multiple regression models with average buffer width as a response variable. None of the independent variables were highly collinear ($r < 0.5$); thus, it was possible to use them in multiple regressions. The multiple regression models were constructed separately for each jurisdiction and each region (in total six regression models). All three independent variables were log transformed before analyses to meet test assumptions. We did not include interactions among the variables, and we did not perform model simplifications because we had hypotheses about the effects of all three variables. To account for the effect of many zeros (i.e., no buffer) in the BC data, we performed the analyses for the entire data set as well as a subset of the sites that had any buffer present (Table S1). In Finland, we performed the analyses with all data as well as excluding the 16 sites with catchment areas $>15\ \text{km}^2$ (Table S1). No site was excluded from the analyses of the Swedish data set.

For the six impairments related to harvest operations (i.e., drainage ditches, machine tracks and soil preparation within 30 m from the stream, partial harvest within the buffer, stream crossing, and blown-down trees), we first calculated the proportion of streams in each jurisdiction and region with different scores for the individual impairments. Second, to assess whether these impairments are connected to buffer width (and to each other), we created an Impairment Index for each site by summing the scores for all impairments except blown-down trees. We excluded blown-down trees from the Impairment Index because an increasing number of blown-down trees must result in a narrower riparian buffer, and thus, these two variables are inherently linked. We then related the Impairment Index to buffer width in each region using generalized regression model with Poisson errors, because the impairment index represents counts. All statistical analyses were performed in R (R Developmental Core Team, 2018).

3. Results

3.1. Properties of Investigated Streams

In total, we investigated 286 stream reaches flowing through recent (harvested 2–8 years ago) clearcuts: 80 in British Columbia (40 at the coast and 40 in the interior), 95 in Finland (46 in the south and 49 in the north), and 111 in Sweden (46 in the south and 65 in the north). The study streams had some general differences among the jurisdictions and between the two regions in each jurisdiction (Table 1). On average, Finnish streams had larger catchment areas (average of 7.3 and 9.3 km^2 in the north and south, respectively) compared to BC and Sweden, which had streams with similar catchment sizes (averaging around 1 km^2; Table 1). The catchment areas were positively skewed in all three jurisdictions (medians < means; Table 1) indicating that majority of the streams were on the lower end of the size gradient in all three jurisdictions. Due to the geomorphological and hydrological differences among the jurisdictions, the bankfull widths of the streams in BC and Finland were similar (averaging between 1.2 and 2.2 m), despite the different catchment sizes. Swedish streams were on average narrower (<1 m width) compared to the other two jurisdictions (Table 1).

In BC, the streams investigated in the interior region had significantly larger catchment areas compared to the coast, while in Sweden and Finland, the streams in the south and north were of similar size (Table 1). Finer substrates (sands and/or silts) were dominant in all three jurisdictions, but there were some differences in proportions of bottom substrates within the jurisdictions. In BC, the coastal streams had significantly higher proportions of silt and large rocks/boulders while lower proportions of sand and gravel/pebbles compared to the interior sites. Streams in southern Finland had significantly higher proportions of sand and lower proportion of coarser materials (rocks/boulders) compared to the north. Streams in southern Sweden had significantly higher proportions of silt while northern streams had more sand and, similar to the Finnish northern streams, coarser substrates (Table 1). Streams in northern Sweden had significantly more pieces of large wood (LW) in the channels compared to the southern sites, while in Finland, there was no difference between the north and south in LW. In BC, sites in the interior had significantly more LW compared to the coastal streams (Table 1).

3.2. Riparian Buffer Widths

The riparian buffer widths were significantly different across the three jurisdictions (ANOVA: $F = 38.39$, d.f. $= 280$, $p < 0.001$; Figure 2). Considering all sites within each jurisdiction, the buffers were the widest in Finland with average (±SE) buffer width of 15.3 (±1.4) m on each side of the stream (Figures 2b and 3b). This was significantly wider (Tukey post hoc test: $p < 0.001$) than buffers in BC with average width of 8.9 (±1.2) m, as well as buffers in Sweden (Tukey post hoc test: $p < 0.001$) with average buffer of 4 (±0.4) m (Figures 2c and 3c). BC buffers were also significantly wider (Tukey post hoc test: $p = 0.001$) than Swedish buffers. Excluding the 16 streams with catchment area >15 km^2 from the Finnish data set did not change the statistical differences among buffer widths in the different jurisdictions as the average buffer width in Finland only marginally increased then, to 15.5 (±1.5) m.

Among the streams sampled in BC, 45% had no buffer at all, that is, no mature trees remaining along the stream reach (Figure 2a). After excluding the 36 sites with no buffers in BC, the average width of buffers was similar (Tukey post hoc test: $p = 0.97$) in the coastal (14.8 ± 2.3 m) and the interior (17 ± 1.8 m) regions. In Finland, five streams (6%) lacked any buffer, and 51 streams (53%), including the five without buffer, had buffer widths below the average for the whole data set (Figure 3). The average buffer width in Finland, considering all 95 sites, was significantly higher (Tukey post hoc test: $p < 0.001$) in the northern region with buffer width averaging 21.1 (±2) m and 9.2 (±1.4) m in the north and south, respectively. After excluding the 16 sites with catchment areas >15 km^2, buffers in northern Finland (20.2 ± 2.2 m) were still significantly wider (Tukey post hoc tests: $p < 0.001$) than the buffers in the south (9.4 ± 1.7 m). Finnish streams had a high

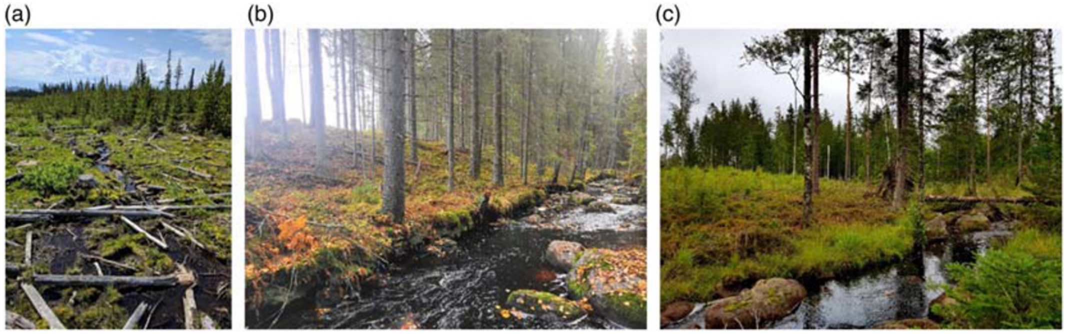

Figure 2. Examples of typical riparian buffer management observed along small streams in (a) British Columbia, Canada (no buffer), (b) Finland (buffer >10 m wide), and (c) Sweden (buffer <5 m wide).

proportion of one-sided buffers, with 79% of the streams being clearcut on one side of the stream while the other side remained unharvested. In Sweden, five streams (5%) had no buffer at all, and 71 streams (64%), including the five without buffer, had buffer width below the average for the whole data set (Figure 3). The average buffer width was higher in northern (5.3 ± 0.6 m) compared to southern (2.3 ± 0.3 m) Sweden, but the difference was not significant (Tukey post hoc test: $p = 0.54$). In contrast to Finland, only eight stream reaches (7%) had a clearcut solely on one side of the stream in Sweden.

When including all sites in BC in the multiple regression models, riparian buffer widths increased with stream size (measured by catchment area) in the interior streams ($estimate = 2.92$, $t = 3.15$, $p = 0.003$), while coastal streams had no significant relationship between buffer width and stream size ($estimate = 0.69$, $t = 0.74$, $p = 0.47$; Figure 4a). In Finland and Sweden, average buffer width increased significantly with catchment area in the north (Finland: $estimate = 3.5$, $t = 2.44$, $p = 0.019$; Sweden: $estimate = 1.31$, $t = 3.38$, $p = 0.001$) but not in the southern streams (Finland: $estimate = 1.25$, $t = 1.14$, $p = 0.26$; Sweden: $estimate = 0.34$, $t = 0.87$, $p = 0.39$; Figures 4b and 4c). Riparian buffer widths along northern Swedish streams were also significantly positively related to the riparian slope ($estimate = 4.05$, $t = 3.53$, $p < 0.001$; Figure 4f), and a significant but opposite trend was found in BC coastal streams ($estimate = -6.82$, $t = -2.7$, $p = 0.01$). Streams in the BC interior ($estimate = -0.06$, $t = -0.02$, $p = 0.99$), southern Sweden ($estimate = -0.23$, $t = -0.23$, $p = 0.82$), and both southern ($estimate = -0.05$, $t = -0.11$, $p = 0.91$) and northern ($estimate = 0.83$, $t = 0.76$, $p = 0.45$) Finland had no significant relationship between riparian slope and buffer width (Figures 4d–4f). Riparian buffer widths in no region had a significant relationship with clearcut size (BC coast: $estimate = -0.24$, $t = -0.13$, $p = 0.89$; BC interior: $estimate = -2.88$, $t = -1.86$, $p = 0.07$; Finland north: $estimate = -1.42$, $t = -0.5$, $p = 0.62$; Finland south: $estimate = 1.47$, $t = 1.15$, $p = 0.26$; Sweden north: $estimate = 0.19$, $t = 0.4$, $p = 0.7$; Sweden south: $estimate = 0.49$, $t = 1.13$, $p = 0.27$). When the sites without buffers were removed from the BC data set, none of the explanatory variables had a

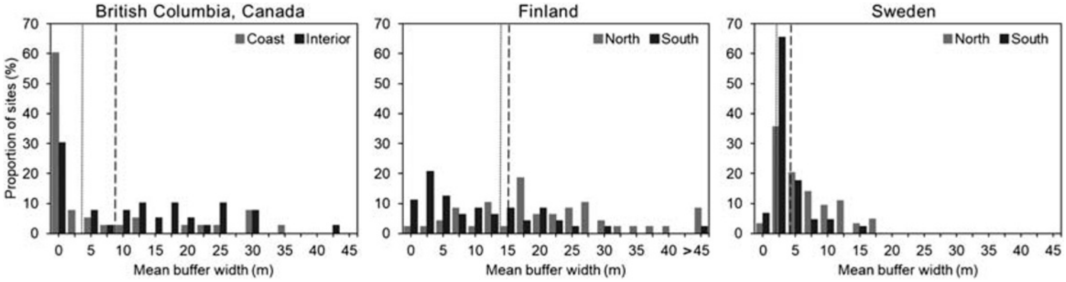

Figure 3. Histograms showing the proportion of sites with different riparian buffer widths retained around small streams in British Columbia, Canada ($n = 80$), Finland ($n = 96$), and Sweden ($n = 111$). The vertical dotted and dashed lines indicate the median and average buffer width on each side of the stream per jurisdiction, respectively. Note that for 79% of the Finnish streams, only the harvested side of the stream was assessed (see text for more details).

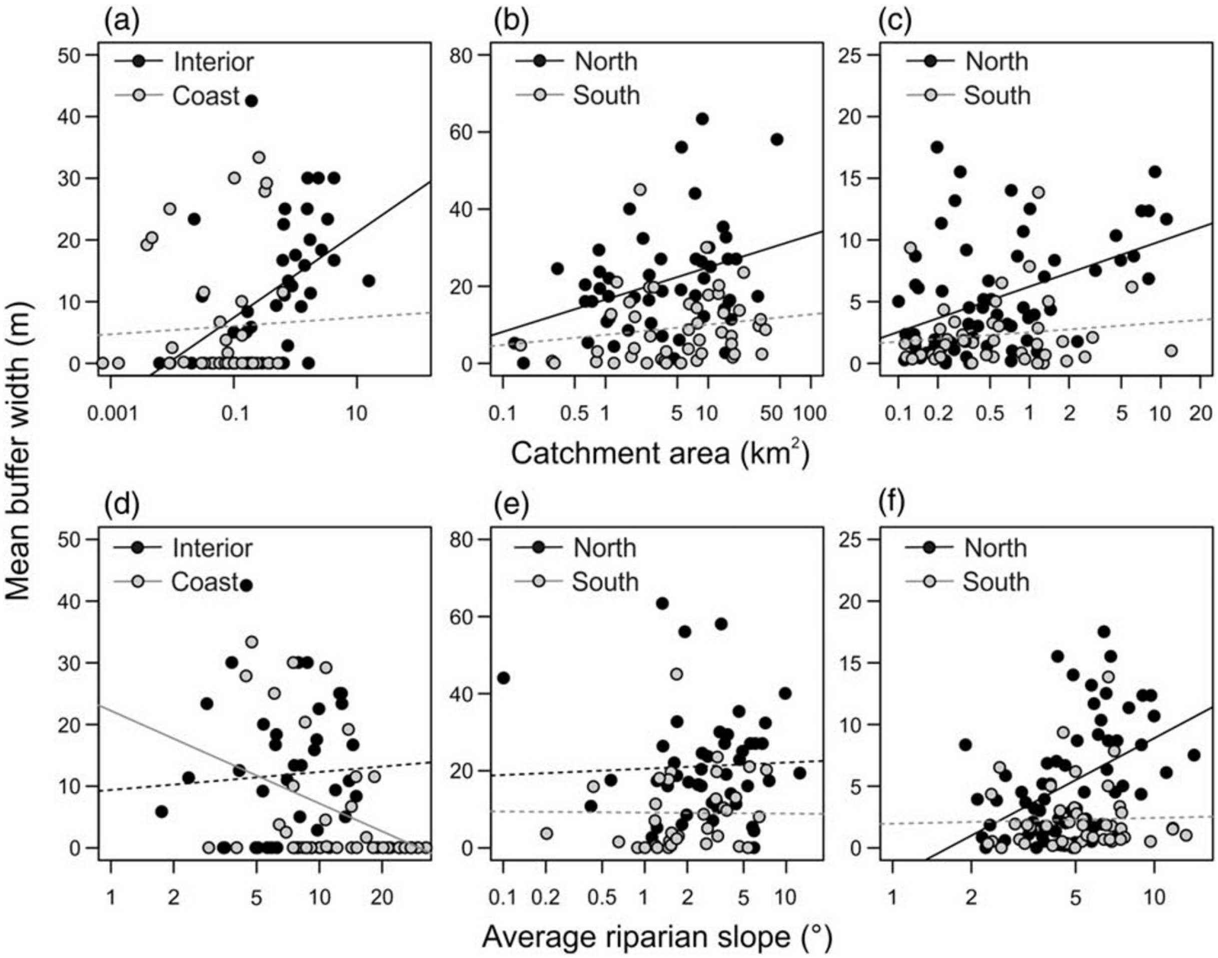

Figure 4. The relationship between riparian buffer width and stream size, measured by catchment area (top panels), and riparian slope (bottom panels) for stream reaches investigated in British Columbia, Canada (a, d), Finland (b, e), and Sweden (c, f). Note that all *x*-axes are on logarithmic scales. Statistically significant trends (see text for test results) are displayed with solid lines while non-significant trends are dashed.

significant relationship with the average buffer width (Table S1). After removing the 16 Finnish sites with catchment areas >15 km^2, the results stayed the same as for the whole data set (Table S1).

3.3. Impairments

The three jurisdictions differed substantially in the type of impairments associated with forestry operations observed at the investigated stream reaches. In Finland and Sweden, more than 50% of the streams had soil preparation performed within the 30 m zone on each side of the stream channels; in Finland, this was more prominent in the south, and in Sweden in the north (Table S2). No soil preparation was observed in BC. Similarly, in Finland and Sweden, some machine tracks within 30 m distance from the streams were observed for nearly all streams, with a majority of streams having either medium or severe marks (Table S2). In BC, >90% of streams had no machine tracks recorded within 30 m distance from the stream. In Sweden, 46% and 36% of the streams in the north and south, respectively, had marks of stream crossing, with 35% of the investigated streams in the north having streams crossed without a bridge (Score 3). In BC and Finland, stream crossings with (Score 1 for permanent and 2 for temporary bridge) or without a bridge were found less frequently (<10% sites in Finland and <25% in BC). Blown-down trees were most common in Sweden with >80% of streams in the north and 59% in the south having some trees blown down. In Finland, 65% of the streams in the north and 47% of the streams in the south had blown-down trees. In BC, blow-down trees were observed at 40% of streams in the coast and 60% streams in the interior. Ditches directly draining into the study reaches were observed relatively seldom in Sweden (12% and 9%

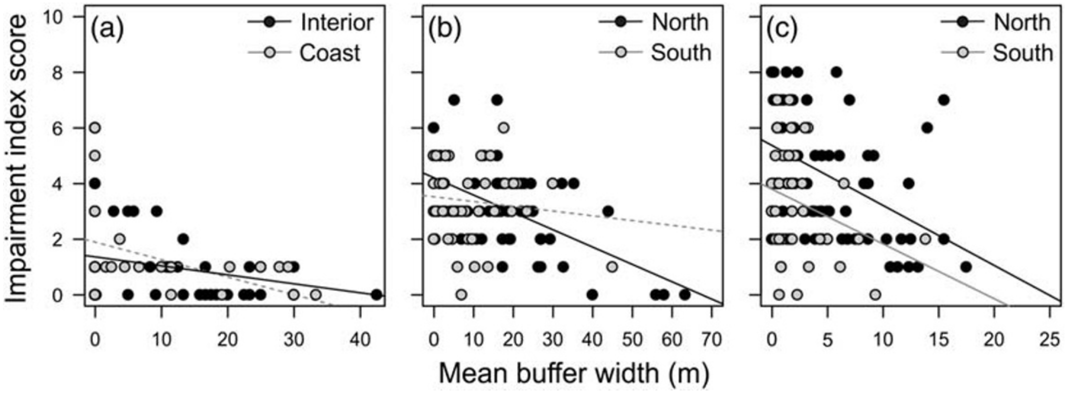

Figure 5. The relationship between Impairment Index (sum of scores for ditches, soil preparation, partial harvest, machine tracks, and stream crossing) and mean buffer width per site for British Columbia, Canada (a), Finland (b), and Sweden (c). Regression lines for the two regions in each jurisdiction are displayed separately. Statistically significant trends (see text for test results) are displayed with solid lines while non-significant trends are dashed. Note different scaling of x-axes.

of streams in the north and south). Southern Finnish streams were the most impacted by connected drainage ditches (28% of sites), and similarly, interior BC had 22% of sites with drainage ditches observed. Finally, the majority of investigated streams in Sweden had evidence of partial harvest (stumps) within the riparian buffers (63% of streams in the north and 87% of streams in the south), while in Finland, partial harvest was observed only on 6% and 15% of streams in the north and south, respectively. In BC, buffers were partially harvested in 30% of coastal streams and 58% of interior streams (Table S2).

When we combined the scores for individual impairments into an Impairment Index (sum of scores for ditches, soil preparation, partial harvest, machine tracks, and stream crossing), we found that the Impairment Index was significantly negatively related to buffer width in the interior region (glm: *estimate* = −0.08, $z = 3.87$, $p < 0.001$) of BC but not in the coastal region (glm: *estimate* = −0.04, $z = -1.85$, $p = 0.07$; Figure 5a). In Finland, the Impairment Index was negatively related to buffer width in the northern region (glm: *estimate* = −0.03, $z = -3.54$, $p < 0.001$), but not in the southern region (glm: *estimate* = −0.01, $z = -0.59$, $p = 0.56$; Figure 5b). The impairment index was significantly lower with increasing buffer width in both regions of Sweden (glm: north: *estimate* = −0.06, $z = -3.81$, $p < 0.001$; south: *estimate* = −0.07, $z = -1.97$, $p = 0.05$; Figure 5c).

4. Discussion

By using a high number of on-the-ground evaluations across a large spatial area, we demonstrate here that small streams often receive poor protection during harvest operations in BC, Finland, and Sweden. Many studies have found that well-functioning riparian buffers should be at least 20–30 m wide (Broadmeadow & Nisbet, 2004; Castelle et al., 1994; Sweeney & Newbold, 2014), and similar numbers can be found in policy and guideline documents (Lee et al., 2004; Olson et al., 2007; Ring et al., 2017). The majority of streams in Sweden had buffers narrower than 5 m, the average buffer width in southern Finland was 9.2 m and nearly half of the streams in BC had no buffers at all. Further, large number of sites in all three jurisdictions had other forestry associated impairments recorded within the riparian zones, including machine tracks, stream crossings, soil preparation, or blown-down trees. It is worrisome that we observed these poor practices along a large number of small streams, because this can likely lead to downstream cumulative effects and propagation of impairments throughout the entire stream network (Kuglerová et al., 2017; Seitz et al., 2011). Further, since our sites were distributed across large areas in each jurisdiction (4,000–12,200 km^2), we are confident that our data set represent a standard practice. Importantly, this is the first study to demonstrate a discrepancy between forestry guidelines and practice of riparian buffer retention and other forestry related disturbances around small streams across regional and jurisdictional scales.

Small (or non fish-bearing) streams are excluded from buffer (retention) recommendations in BC, but not in Sweden and Finland. Thus, our findings, to some degree, demonstrate that practitioners do not follow the guidelines of forest agencies. In Finland, buffer retention was generally better, with buffers on average being 15.3 m wide, and >20 m wide in the northern region. Further, most of the harvest was performed only on one side of the Finnish streams. This is because streams in Finland are frequently used as boundaries between individual forest stands which usually belong to different forest owners. This practice, although not based on intentional planning but rather on independent management decisions by different land owners, may prove to be useful in mitigating the adverse impacts of clearcutting on stream ecosystems. Nevertheless, the ecological benefits of one-sided buffers, and whether they represent a better practice than double-sided buffers, are currently unclear and should be investigated further. The streams in Finland were on average twice as large compared to Sweden and BC, which is a likely reason for wider buffers. Such small streams as we investigated in Sweden and BC are rare in Finland due to large-scale modification of the smallest streams to drainage ditches to improve forest growth on peat soils. Modified streams or ditches are not typically prescribed to receive buffers and have different rules for forestry practices (Hasselquist et al., 2017). Thus, although the streams in Finland differed from the other two jurisdictions size-wise, they do represent the smallest natural, or close to natural, channels and therefore are essentially comparable, from a management perspective, to the small streams in BC and Sweden. In BC, if buffers were retained, their widths were similar to those in Finland (15 m on average). The reasons for why practitioners voluntarily keep such reserves in BC are unclear. It could be because of operational unfeasibility to harvest steep ravines where streams in BC are often situated.

The finding of wider buffers in Finland, where streams were generally larger, as well as the positive relationship between stream size and buffer width in northern Sweden and Finland and interior BC, supports the view that larger streams may receive better protection (Hylander et al., 2002; Kuglerová et al., 2017). Despite the abundance of scientific evidence about the importance of small streams on a catchment scale (Bishop et al., 2008; Gomi et al., 2002; Richardson, 2020), legislation and management practices have not yet fully incorporated this into their guidelines. However, riparian buffer retention targeted to larger streams, although implemented to protect the habitat for cold-water adapted fish, might not be as important for some ecosystem functions as if the buffers were retained along small streams. For example, shading by riparian trees is generally higher in small compared to larger channels (Warren et al., 2016). Therefore, organisms in and around larger streams in forested landscapes are already exposed to higher levels of incoming radiation. As such, they might be less sensitive to light increments associated with riparian harvesting compared to organisms in canopy-closed smaller streams. Similarly, resource subsidies provided by riparian vegetation are more likely to be locally retained and utilized by organisms in small streams, while they are likely transported further downstream with higher discharge typical of larger streams (Quinn et al., 2007). Temperature increases in small streams after having their shade removed can exceed 8°C above expected and violate water degradation laws in some places while sending warmer water to fish-bearing reaches downstream (e.g., Gomi et al., 2006; Groom et al., 2017). Small streams are also affected by groundwater contributions to a larger degree—due to the low surface water volume (Gomi et al., 2002). Groundwater fluxes are typically altered after upland forest harvest (Schelker et al., 2013), and this will have relatively larger effects on small streams. Taken together, there is enough evidence that allocation of riparian buffers only to larger streams, while ignoring the small ones, is not environmentally justified if good water quality and protection of ecology should be achieved on a catchment scale.

We did not find the positive stream size-buffer width relationship across all studied regions. We did not aim to compare small streams to larger ones, and most of our streams are considered small from a management perspective. The few replicates along the upper limit of the stream size gradient were not enough to allow such a comparison. Even in Finland, where 16 sites had catchment areas larger than 15 km^2, the trends for buffer widths remained the same after excluding those sites. Overall, this suggests that there might be differences within jurisdictions of how stream sizes are evaluated by practitioners. Further, differences in land use and/or forest ownership between the two regions within each jurisdiction can also partly explain the different buffer practices. In Sweden, the forest ownership was similar for the southern and northern regions; however, local managers are responsible for the planning and implementation of the harvest operations for a given area, and thus, practices can differ even within the same forest company.

We found no effect of clearcut size on buffer width in any of the studied regions. We did notice that clearcuts were on average larger in interior BC and in northern Sweden and those regions also had on average wider buffers compared to their counterparts in the coast (BC) and the south (Sweden), respectively. It is therefore possible that clearcut size has some effect on the buffer management considering a country-wide scale. More surprisingly, we found little evidence (only in northern Sweden and coastal BC) that riparian buffer widths are related to slope. Many guidelines recommend leaving wide buffers on steep slopes to prevent high rates of material transport to the streams (Lee et al., 2004; Ring et al., 2017). At the same time, very flat areas around streams typically have wet soils, and forest practitioners tend to not operate on these areas to avoid trapped machines. The trend in coastal BC contradicts the notion that buffers would be retained in steep areas since many of the streams in this region without any buffer were associated with the steepest slopes. Overall, our data contain streams with both steep and flat riparian zones, which might explain why no strong patterns were observed for riparian buffer widths and slope.

While the evaluation of riparian buffer width in this study was based on the presence of mature trees, forested protection zones are not always mandatory. For example, BC legislation prescribes mandatory machine-free zone of about 20–30 m wide around small streams, but tree retention is not a requirement (British Columbia Ministry of Forests, 1995). In Sweden and Finland, forest-certification and voluntary actions are the dominant drivers of buffer allocation, and an operation-free zone, even if a forested buffer was not retained, is also suggested (Skogsstyrelsen (The Swedish Forest Agency), 2014). Our evaluation of forestry-associated impairments, regardless of presence and width of the buffers, also shows poor practices around small streams. First, the machine-free, or operation-free, zone should prevent driving and soil preparation within the near-stream area. In Sweden and Finland, >50% of all sites had medium or severe scores for machine tracks within 30 m from the stream. Similarly, soil preparation to improve regeneration was observed on >50% of streams in the two Nordic countries. Further, in 35% and 16% of the sites in northern and southern Sweden, respectively, streams were crossed with forestry machines without a bridge (Score 3), which does not correspond with the national regulation of “damage to soil and water must be prevented or mitigated” (Skogsstyrelsen (The Swedish Forest Agency), 2014). Temporary (Score 2) or permanent (Score 1) bridges are strongly recommended to be built if streams are to be crossed, which has been agreed upon by a large part of the forest sector (Skogsstyrelsen (The Swedish Forest Agency), 2014), and this was observed in 11% and 20% of cases in northern and southern Sweden, respectively. In BC, no soil preparation was observed, likely because it is not a typical regeneration practice in the province. Furthermore, the majority of the BC streams (90%) had no marks associated with driving of machines. This confirms that the legal prescription of a machine-free zone is largely followed in British Columbia.

Partial harvesting within riparian buffers has been suggested as a potential strategy to balance economic and environmental goals in forestry (Sibley et al., 2012). Although upland harvesting will necessarily lead to some changes within the aquatic ecosystems, and no type of buffer can prevent them all; partially harvested buffers, if wide enough, seem to be an effective protection measure (Kreutzweiser et al., 2009, 2010; Oldén et al., 2019). In addition, partial harvesting has been suggested to emulate natural disturbance (END) in the riparian corridor (e.g., forest fire) which may promote some ecosystem processes such as biodiversity, recruitment of broadleaf species in conifer-dominated stands, and more variable forest structure, which in turn may have positive feedback on aquatic ecosystems (Lidman et al., 2017; Mallik et al., 2014). As such, the high numbers of streams with partial harvest within the riparian buffer documented here corresponds with the current END paradigms (Sibley et al., 2012). On the other hand, it is highly unlikely that the Swedish streams with already narrow buffers benefit from having their buffers also partially harvested. Forestry interventions within buffers <5 m wide result in one to two rows of trees sparsely situated along the streams (see Figure 2c for an example). This in turn leads to an increase of windthrow because the root systems of the few remaining trees are not adapted to an open landscape (Grizzel & Wolff, 1998). Not surprisingly, we recorded the highest number of streams with blown-down trees in Sweden, where the buffers were the narrowest and had the highest levels of partial harvest. Although provision of LW to streams is one of the desired functions of riparian buffers, the blown-down trees along small streams are typically suspended far above the water (Bahuguna et al., 2010). It will take decades before these trees break apart and fall into the channels contributing to the instream habitat structure (Grizzel & Wolff, 1998). Our data on LW further suggest that wider riparian buffers provide more deadwood to the channels because significantly more LW and wider buffers were found in northern Sweden compared to the south, and in the interior of BC streams compared to the coast. Finland and BC also had many streams with records of blown-down trees, especially along the streams with narrower buffers. Finally, the impairment index, combined from all individual impairments, increased with decreasing buffer width in four out of the six regions, and this indicates that leaving wide riparian buffers not only sustains ecosystem functions for streams but can also prevent additional environmental disturbances in riparian zones associated with harvest operations.

5. Conclusions and Implications

This study is the first to show regional-scale discrepancies between how riparian buffers are prescribed and how they are implemented around small streams. Although many people might argue that this is already known, anecdotal evidence is not enough to change forestry practices. In the two Nordic countries, national recommendations are clear about buffer allocation to small streams, but implementation is still largely lacking, especially in Sweden. A number of ecological functions are typically expected from riparian buffers, including shading, resource subsidies, large wood inputs, filtering capacity, and biodiversity (Broadmeadow & Nisbet, 2004; Castelle et al., 1994; Sweeney & Newbold, 2014). It has been demonstrated that riparian buffers narrower than 10 m on each side of the stream are insufficient to sustain the desired ecosystem functions (Davies & Nelson, 1994; Kiffney et al., 2003; Sweeney & Newbold, 2014) and much wider buffers (>30 m) are necessary to preserve biodiversity (Marczak et al., 2010; Oldén et al., 2019; Selonen & Kotiaho, 2013). Therefore, the buffers we recorded in Sweden, BC, and southern Finland are insufficient to mitigate the negative effects associated with upland forest harvest and do not prevent local deterioration of small streams.

Further, narrow buffers were associated with higher numbers of additional impairments connected to harvest operations (e.g., machine tracks, stream crossing, and drainage ditches). Although contemporary forest management practices that include buffers have substantially improved instream conditions in places where they have been implemented (Marczak et al., 2010; Oldén et al., 2019; Olson et al., 2007), buffers are still lacking for a large portion of the stream network. Bringing awareness to this problem is the first step to attain good ecological and biochemical status of all waters, and good conservation status for water-related habitat types as required by, for example, the EU Water Framework Directive and EU Habitats Directive. It remains questionable, however, whether practices can be improved in jurisdictions where soft regulatory (voluntary) guidelines are driving buffer allocation (Sweden and Finland—Hasselquist et al., 2019). Although riparian buffers were not wider in BC, we present evidence that hard regulations (i.e., the operation-free zone) are mostly followed there. If BC laws included small streams as protection-worthy ecosystems, we might see rapid changes in buffer management practices there. On the other hand, if soft regulations without surveillance or legal consequences continue to dominate in the Nordic countries, there is no insurance that the emerging scientific evidence of the need for better riparian protection along small streams will be implemented. Based on the results of this study, it is becoming clear that there is a need to review and re-evaluate the present regulations and other tools for small, forest streams and, even more importantly, to monitor their implementation.

Data Availability Statement

The data collected in this study are currently available in repository “Svensk Nationell Datatjänst” (Kuglerová et al., 2020).

Acknowledgments
We would like to thank the forestry companies and agencies that provided us with data and access to their lands (Holmen skog, Sveaskog and SCA, Finnish Forest Centre, and Metsähallitus). We also thank all members of the field crews, namely, Mariella Becu, Matti Ermold, Liam Irwin, Iikka Jaakola, Juliana Kaufmanis, Kaisa Lehosmaa, Angie Nicolas, Joel Nyberg, Maria Rajakallio, Anwen Rees, and Teresa Silverthorn. We thank Dr. William Lidberg for providing us with stream GIS data for Sweden. Funding was provided by the Swedish Research Council Formas, Natural Sciences and Engineering Research Council of Canada, and Academy of Finland. This publication is a part of the collaborative SOSTPRO project (Source Stream Protection) that is organized through the JPI Water Works 2016 Co-funded Call.

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