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Downstream Temperature Effects of Boreal Forest Clearcutting Vary With Riparian Buffer Width

M. Myrstener[1,2], C. Greiser[3], and L. Kuglerová[1]

[1]Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, Sweden, [2]Now at Department of Fish, Wildlife and Environmental Studies, Swedish University of Agricultural Sciences, Umeå, Sweden, [3]Department of Physical Geography, Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden

M. Myrstener and C. Greiser shared 1st authorship.

Key Points:

- Clearcutting of boreal forests can warm streams, and these temperature effects can be propagated at least 150 m downstream
- Temperature effects are not only isolated to summer, but instead patterns can also sustain into autumn and resemble those in summer
- Riparian buffers wider than 15 m protected against water temperature increases

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

M. Myrstener and C. Greiser,
maria.myrstener@slu.se;
caroline.greiser@su.se

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Author Contributions:

Conceptualization: M. Myrstener, C. Greiser, L. Kuglerová
Data curation: C. Greiser
Formal analysis: C. Greiser
Funding acquisition: L. Kuglerová
Investigation: M. Myrstener
Methodology: M. Myrstener, L. Kuglerová
Project administration: M. Myrstener
Resources: L. Kuglerová
Visualization: C. Greiser
Writing – original draft: M. Myrstener, C. Greiser

Abstract Clearcutting increases temperatures of forest streams, and, in temperate zones, the effects can extend far downstream of the clearcut itself. Here, we studied whether similar patterns are found in colder, boreal zones, and if riparian buffers can prevent stream water from heating up. We recorded temperature at 45 locations across nine streams with varying buffer widths. In these streams, we compared upstream (control) reaches with reaches at clearcuts and up to 150 m immediately downstream of the clearcut. In summer, we found daily maximum water temperature increases at clearcuts up to 4.1°C, with the warmest week ranging from 12.0°C to 18.6°C. We further found that warming was sustained 150 m downstream of clearcuts in three out of six streams with buffers <10 m. Surprisingly, temperature patterns in autumn resembled those in summer, yet, with lower absolute temperatures (maximum warming was 1.9°C in autumn). Clearcuts in boreal forests can indeed warm streams, and, because these temperature effects are propagated downstream, we risk catchment-scale effects and cumulative warming when streams pass through several clearcuts. In this study, riparian buffers wider than 15 m protected against water temperature increases; hence, we call for a general increase of riparian buffer width along small streams in boreal forests.

1. Introduction

Organisms inhabiting northern waters have evolved over millennia to withstand the challenges posed by cold temperatures and pronounced seasonality. However, joint climatic shifts and human land-use practices are subjecting these northern waters to rising temperatures (Sarkkola et al., 2009; Van Vliet et al., 2011). Increases in water temperature triggers heightened metabolic rates in aquatic organisms, leading to faster decomposition, nutrient cycling, and CO_2 outgassing (Demars et al., 2011), and increased energy demands as well as alterations in critical life-history transitions, such as egg hatching in fish (Réalis-Doyelle et al., 2016). Moreover, the consequences of changes in thermal fluctuations, including diel variation, can significantly impact the development of taxa like salmonids (Steel et al., 2012), trigger community responses of macroinvertebrates (Bonacina et al., 2023), and, determine the growth and survival of endangered species such as the freshwater pearl mussel (Wagner et al., 2024).

Boreal stream temperature is a result of incoming solar radiation (modified by canopy cover and bank morphology), air temperature, groundwater input, surface water input, and upstream catchment features (Figure 1, Brown, 1969; Oswood et al., 2006). This creates temporal, spatial, and longitudinal variability in stream temperature (Jackson et al., 2020). For instance, headwater streams situated in the top branches of river networks are typically cold-water systems, due to the large contribution of (cold) groundwater (Ploum et al., 2018), and limited radiation reaching the water surface. Such streams can harbor unique biological communities that cannot be found in downstream, warmer water bodies (Richardson, 2019). Exceptions are headwater streams at lake outlets, which typically experience warmer waters (Winterdahl et al., 2016), and these streams normally have longitudinal decreases in temperature (Leach et al., 2017). As streams increase in size, the relative influences of canopy shading and groundwater inflow decrease, leading to gradual longitudinal warming.

Due to the tight link between stream temperature and the surrounding forest (Warren et al., 2016), forest management in headwater catchments can affect water temperatures to a large degree. The primary influence of forestry on stream temperature is through the removal of riparian canopy cover, and the consequent increase in solar radiation to the water surface (Kiffney et al., 2003). However, at a clearcut, stream temperatures can also be affected by increased groundwater flow due to decreased transpiration. If this groundwater is heated at the clearcut due to the loss of canopy cover, it can exacerbate the stream warming; yet, if this excess groundwater is

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M. Myrstener, C. Greiser, L. Kuglerová

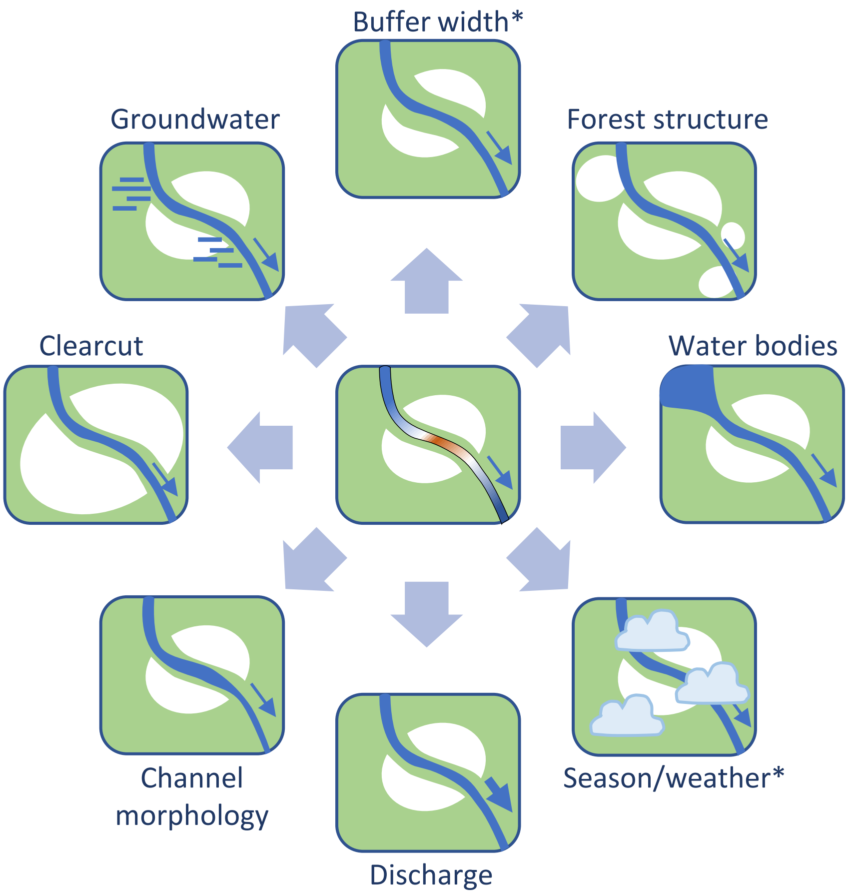

Figure 1. Various factors influencing the direction and magnitude of water temperature changes at clearcuts and in downstream forests. The central panel visualizes the hypothesized temperature changes, with warming at a clearcut and cooling downstream, with some downstream propagation of the clearcut-induced warming. However, this pattern can be attenuated or entirely obscured by other catchment properties (surrounding panels). We focused on quantifying the effects of riparian buffer width and season (marked with an asterisk), but study streams included variability in all factors above.

not heated, it might instead cool the stream (Moore et al., 2005). Riparian buffers have been developed as a strategy to protect streams from the negative effects of forestry, and studies from temperate regions do support their effectiveness in regulating temperature (Gomi et al., 2006; Kiffney et al., 2003; Martin et al., 2021). Studies in boreal regions are, however, sparse (but see Jyväsjärvi et al., 2020; Chellaiah & Kuglerová, 2021) even though intensive forest harvesting schemes (e.g., Scandinavia and Canada) together with extensive daylight hours during summer might well contribute to temperature changes in the streams. Understanding how land-use, in terms of forest management, may contribute to changes in aquatic ecosystems is important, considering that accelerating climate change already puts boreal freshwaters under enormous pressure due to for example, increased occurrence of extreme hydrological events (Aminjafari et al., 2024; Laudon et al., 2021; Moore et al., 2023).

In many boreal countries, including Sweden, Finland, Norway, and Canada, most forests are managed via rotational forestry, involving regular clearcutting, replanting, and thinning. Consequently, one fifth of forest stands in Sweden are 0–21 years old, resulting in limited canopy cover (Nilsson et al., 2023). Moreover, riparian buffer management regulation either does not prescribe a minimum buffer width (Sweden), or it does not require buffers along small,non-fish bearing streams (Canada, parts of the US), or modified streams (Finland) at all (Kampf et al., 2021; Kuglerová et al., 2024). The outcomes of such management guidelines are narrow (<10 m) or no buffers along a majority of streams situated in boreal production forests, especially along sensitive headwaters (Kuglerová et al., 2020; Ring et al., 2023). Further, narrow buffers are usually subjected to severe wind-felling (Kuglerová et al., 2023), leaving essentially no buffers post-disturbance. Since small streams (catchments <15 km^2) constitute about 90% of the stream length in Sweden (Bishop et al., 2008), most of the stream networks are directly affected by insufficient buffer management. Given the intensity of forestry in boreal forests and the contemporary buffer management, it is likely that headwaters are subject to temperature increases, potentially propagating these effects to downstream waters. In temperate regions, studies have shown catchment-scale effects of intense forest management with elevated temperatures extending to downstream reaches (Roon et al., 2021; Swartz et al., 2020), but equivalent studies are lacking in boreal regions. Catchment-scale increases in stream temperatures could have profound implications for both the structure and function of ecosystems, particularly affecting species and communities adapted to cold water conditions, and in need of cold refugia (Guzzo et al., 2017).

In this study, we quantified the effect of clearcuts with either no, thin (<10 m) or wide (≥15 m) buffers on stream temperature, and, in particular, the propagation of temperature changes to forested stream reaches downstream of the clearcuts ("downstream propagation", Figure 1). We used high frequency temperature sensors at 45 locations across nine streams situated in boreal forest in Sweden. We compared stream temperature in control stream reaches upstream of clearcuts, in impacted reaches (at clearcuts), and in forested streams downstream of clearcuts during both summer and autumn. We hypothesized that water temperatures increase when the stream crosses a clearcut, and that elevated stream temperatures propagate downstream to the forested reaches. We expected these patterns to be most pronounced in streams with no or thin riparian buffers (<10 m width), and least pronounced or absent in streams with wide buffers (≥15 m), or streams that do not have fully forested upstream control reach (e.g., lake outlets). Finally, we expected clearcut effects to be most pronounced during the warmer and drier summer, compared to autumn.

2. Methods

2.1. Stream Selection

We conducted this study in summer and autumn 2020 in nine streams located in the county of Västerbotten, all within ~1 hr driving distance from the city of Umeå, northern Sweden (Figure 2a). This area is classified as boreal, with soil frost and persistent seasonal snow cover during winter, and an annual mean temperature of 1.8°C (1981–2010). The annual precipitation averages 640 mm, of which 40%–60% falls as snow, and the spring snow melt typically accounts for about half of the total annual runoff (Teutschbein et al., 2015). Our study period (July to Oct 2020) was, on average, 1.1°C warmer and 26 mm wetter than long-term average (SMHI, 2024). All streams are first and second order, with an average discharge around 10–20 L s^{-1}, and run through areas that were clearcut between 2014 and 2020 (Table 1, Figure S1a in Supporting Information S1). We selected streams in the following way. First, we aimed at streams situated in clearcuts younger than 6 years and used open-access Geographic Information System data on clearcuts from the Swedish Forest Agency and a stream layer generated from a digital elevation model (2 m resolution and 6 ha stream initiation threshold) with catchment area range between 10 ha and 3 km^2 (Lidberg et al., 2017). We then overlaid streams that passed through clearcuts with forest data to locate streams that have forest both upstream and downstream of the clearcut for at least 200 m stream length. Because lakes and wetlands are a frequent part of boreal landscape, and may determine thermal regimes of an outlet stream in a different way compared to forest (Leach et al., 2017; Rayne et al., 2008), we included two lake-outlet streams and one wetland-outlet stream. After visiting approximately 25 potential streams, we excluded streams that were not accessible (gates on the roads) or were recently ditched. The final selection was based on achieving a gradient in buffer widths that could be separated into three categories: no buffer (sparse trees occur), thin buffer (<10 m on both sides) and wide buffer (≥15 m on both sides). The buffers are present on both sides of the steams (Figure 2). Given the mosaic forest landscape in the region, it was difficult to achieve all the criteria, so the final nine streams differ in stream slope and elevation (Table 1). All the streams are small (typically ≤1 m in wetted width), non-fish bearing headwaters with similar post-glacial geomorphology typical of the region (Laudon et al., 2021). Ultimately, the final nine streams also vary in the forest age in the upstream and downstream locations (30–80 years). The riparian buffers were typical of the production forest in northern Sweden; that is, dominated by mature spruce (>25 cm in breast diameter), with a few birches, and with sparsely developed understory tree and shrub layer (Chellaiah & Kuglerová, 2021; Hasselquist et al., 2021).

2.2. Logger Placement

At each selected stream, we placed loggers at six longitudinal locations: upstream of the clearcut ("up"), in the center of the clearcut ("mid"), at the downstream end of the clearcut ("end"), as well as "20", "70", and "150 m" downstream of the clearcut, that is, when the stream had entered forest again (Figure 2b). Two streams have an

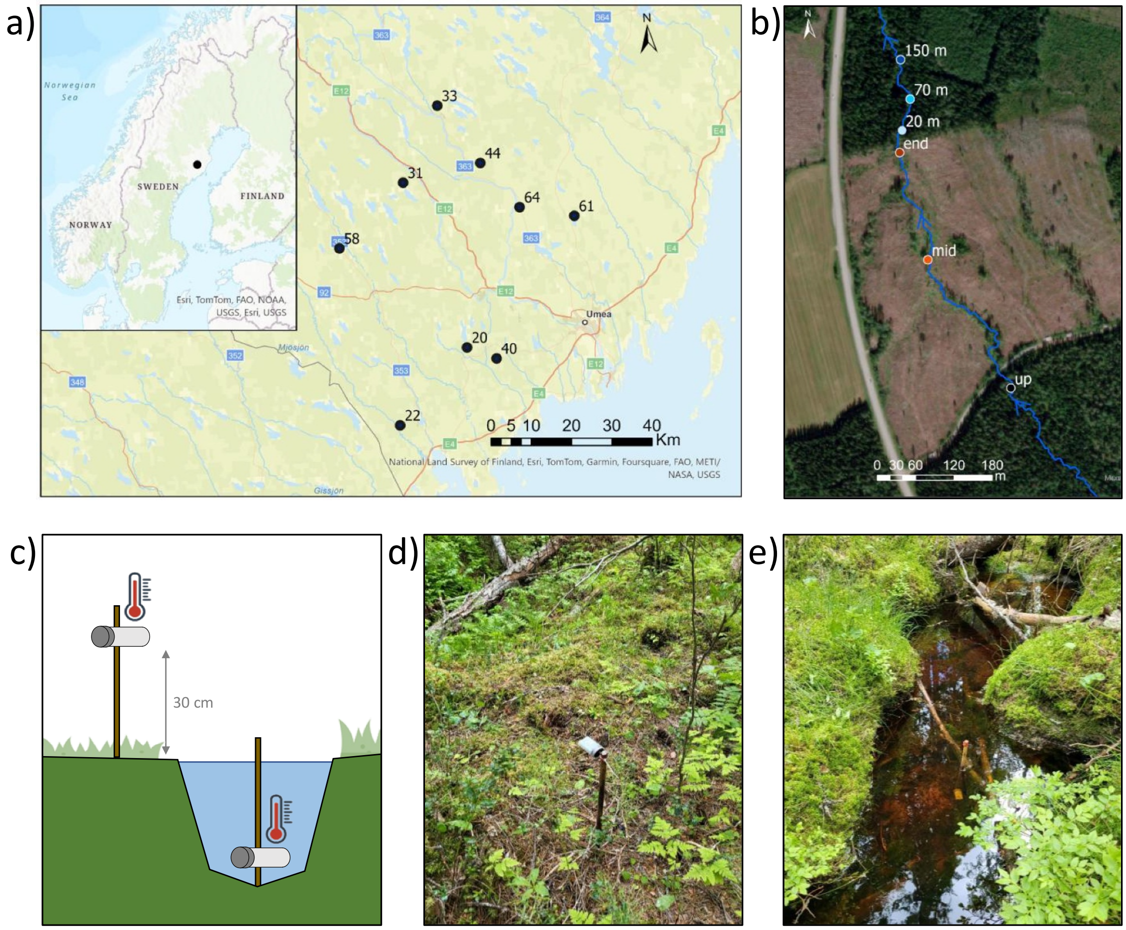

Figure 2. Left: (a) Location of the study region in Northern Sweden (inset map), and the nine study streams, (b) A detailed map of one of the streams (64), with points indicating the six locations where loggers were placed in relation to the clearcut (flow direction is north in this case, see blue arrows). A thin buffer can be seen on the aerial photograph, (c) Schematic overview of how loggers were installed to measure water and air temperature, (d) A temperature logger installed in the riparian zone, and (e) a temperature logger installed in the stream.

Table 1
Stream Coordinates and Characteristics

Buffer width	Stream	Longitude (WGS 84)	Latitude (WGS 84)	Elevation (m.a.s.l)	Stream gradient (unitless)	Clearcut size (ha)	Stream length within clearcut (m)	Clearcut age (years)	Upstream habitat	Lux air on mid CC	Lux air 150 m downstream
No	44	19.7909	64.20111	185	0.033	2.1	528	3	Forest	13,736	917
	22	19.29214	63.63104	96	0.084	8.9	151	5	Forest	11,840	858
	58	19.04416	64.03307	241	0.052	5.4	237	5	Lake	21,451	5,478
Thin	61	20.24726	64.06752	146	0.007	10.3	318	2	Wetland	11,469	1,371
	64	19.97382	64.09644	114	0.026	12.7	430	1	Forest	27,475	2,640
	31	19.38988	64.16963	235	0.014	4.4	81	7	Forest	9,128	2,403
Wide	20	19.65496	63.79371	122	0.017	1.9	198	4	Forest	8,106	1,516
	40	19.79956	63.76440	160	0.032	4.3	285	4	Forest	7,586	1,361
	33	19.59200	64.33538	211	0.034	17.1	444	5	Lake	2,612	1,291

Note. The "no" buffer category has a few dispersed trees, "thin" buffer widths are 1–10 m with multiple gaps and "wide" buffers are ≥15 m wide.

upstream lake, and one stream has an upstream wetland, but the upstream control stream reaches, where the loggers were located, were always forested. At each location, we placed a temperature logger (HOBO pendant temperature logger UA-002-64, Onset) attached to a metal rod fixed in the thalweg of the stream channel, ca 10 cm below the water surface (summer baseflow), and thus close to the stream bottom (Figures 2c and e). The temperature loggers have an accuracy of ±0.53°C. At each stream, we placed two air temperature loggers beside the stream in the riparian zone (ca 30 cm above the ground), one in the center of the clearcut, and one 150 m downstream of the clearcut (Figure 2c). These loggers in the riparian zone were also used to record light as lux. Average values for light (lux) from the riparian zone are presented as "lux air" in Table 1. Lux from the water was not used. All loggers were set to measure temperature every hour, and were deployed simultaneously from 26 June until 17 October 2020.

2.3. Data Cleaning

Data compiling, cleaning, analysis, and visualization were done in *R* version 4.2.3 (R Core Team, 2023). Data at stream 31 was unreliable before 3 July, which is why data from all streams were cropped to start on 3 July. At stream 31, the logger in the middle of the clearcut failed. For the analysis, we focused on data from the core warm season in summer, that is, 3 July–31 August. However, we calculated all temperature metrics also for the autumn data, that is, 1 September–17 October, to check for seasonal differences in temperature patterns along streams (Figure S1 in Supporting Information S1).

2.4. Temperature Metrics

For each logger and day, we calculated the absolute daily maximum ("T_{max}") from the hourly records. As an additional metric, we used the maximum 7 day moving average of daily maximum temperature ("T7DayMax"), which is the temperature of the warmest week, and has been repeatedly used as an ecologically relevant temperature variable (Miralha et al., 2024). For statistical analysis and further calculation of warming/cooling rates, we focused on Tmax, which was calculated for loggers measuring water temperature and loggers measuring air temperature. We compared seasonal averages for daily maximum air temperatures inside and outside the forest to evaluate the warming/cooling potential at each stream, caused by open clearcuts or closed forests, respectively. Finally, we used the average of daily maximum water temperatures in summer (July and August), to calculate the mean temperature change rates, expressed as change in temperature over distance (°C 100 m^{-1}). The rates account for differences in clearcut size, and create comparable numbers to those found in the literature (e.g., Zaidel et al., 2021).

2.5. Statistical Testing

We present maximum temperatures (T_{max}) in three different ways: absolute temperatures (°C), temperature deviations relative to the upstream temperature (°C), and temperature change rates relative to distance (°C 100 m^{-1}). Absolute temperatures were chosen because they can be linked to physiological thresholds of organisms or processes. Relative temperature deviations are used to enable comparison of downstream changes across streams with different upstream reference temperatures. Temperature change rates account for the thermal inertia of water to warm up or cool down, and allow comparisons across streams with different clearcut sizes.

We tested differences in air and water temperatures (T_{max}) with linear mixed effect models using the lme4 package in *R* (Bates & Maechler, 2009). The models included stream and day as serial random effects to account for repeated measurements. Model assumptions, such as normality and constant variance of residuals, were confirmed with the diagnostic plots from sjPlot package in R. We removed temporal autocorrelation in our datasets by selecting every third day for further analysis of daily temperatures. This thinning strategy was chosen after checking for temporal autocorrelation in the data using the functions acf () and pacf () in R. The significance of the fixed effects and their interaction was assessed using analysis of variance with Type III sums of squares from the basic stats package. Post-hoc pairwise comparisons with *t*-tests on the estimated marginal means (least-squares means) were conducted using the emmeans package (Lenth, 2023), with adjustments for multiple comparisons made using the Bonferroni correction. We ran the post-hoc tests with Bonferroni correction only on the pairs of interest. For air temperature, the pair of interest was mid clearcut (= outside forest) versus 150 m downstream (= inside forest). For water temperature, the pairs of interest were the ones that described the changes at the clearcut (upstream vs. mid clearcut; upstream vs. end clearcut), the changes downstream of the clearcut (end clearcut vs. all downstream loggers), and the overall downstream propagation (upstream vs. 150 m downstream logger). We focus our results on the temperature changes and differences in Tmax that were significant in the statistical tests ($p < 0.05$).

2.6. Air Temperature

We tested the difference in daily maximum air temperature (Tmax.air) between the open clearcut (mid clearcut) and the forest interior (150 m downstream), and if this difference differed across streams with varying buffer width using the following model structure:

Model 1: T_{max}.air ~ location × buffer + (1|stream) + (1|day).

Concretely, we tested for the effect of location (two levels: inside, outside), in interaction with buffer (three levels: wide, thin, no buffer), to examine if wider buffers could mitigate the warming effect of open clearcuts.

2.7. Water Temperature

We tested the difference in daily maximum water temperature (Tmax.water) between locations along each stream (i.e., to test the effect of clearcut and subsequent forest on water temperatures), in two different models: (a) across all streams in each buffer category (day and stream as random effect), and (b) in each stream separately (only day as a random effect), because we found a large variability in longitudinal stream temperature differences among streams. The model structures were:

Model 2: T_{max}.water ~ location × buffer + (1|stream) + (1|day).

Model 3: T_{max}.water ~ location × buffer + (1|day).

3. Results

3.1. Air Temperature

The average daily maximum air temperature (at 30 cm above ground in the riparian zone) during July and August across all nine streams was 24.7°C at clearcuts (range: 20.0–28.3°C), and 18.7°C in downstream forested locations (range: 17.1–22.5°C; Figure 3a, Table S4 in Supporting Information S1). Air temperatures were generally warmer at clearcuts than in forested locations (F (1,329) = 414.09, $p < 0.0001$), especially when buffers were thin or missing (significant interaction between location and buffer: F (2,329) = 5.57, $p = 0.004$; Figure 3a). Clearcut locations with no buffer were, on average, 6.71°C warmer than forested locations (t (329) = 14.26, $p < 0.0001$), whereas temperatures on sites with thin buffer they were 5.4°C warmer (t (329) = 11.51, $p < 0.0001$), and on sites with wide buffers, they were still 4.5°C warmer (t (329) = 9.48, $p < 0.0001$) than forested locations.

3.2. Water Temperature

Water temperature patterns among streams, and within each stream, were heterogeneous. In summer, temperatures of the warmest week (T7dayMax) ranged from 11.7 to 18.7°C across streams and locations (Figure 3b). Summer average daily maximum stream temperature (T_{max}) ranged from 9.8 to 16.2°C (Figure 3c). Generally, we observed the hypothesized patterns of increasing temperatures in stream water at clearcuts with no and thin buffers, and that elevated temperatures were propagated to downstream locations. This effect was not present in the wide buffer streams. Yet, the magnitude of warming, cooling, and downstream propagation varied among streams.

3.2.1. Effect of Riparian Buffer Width

Daily maximum summer temperatures changed longitudinally in the streams, and this change depended on the buffer width (significant interaction between location and buffer: F (10,1017) = 20.85, $p < 0.001$). Both in the category with no and with thin buffers, water temperatures increased at the clearcut and decreased downstream of the clearcut (Figures 3b–3d). The average temperature increase at the clearcut was 1.3 and 2.5°C, in the no and thin-buffer streams, respectively (Figure 4; Table S1 in Supporting Information S1). Individual streams had a twofold higher increase (see next paragraph). The warmed-up streams cooled down after having entered the forest again, but some still remained warmer than the upstream reference at 150 m downstream of the clearcut. This

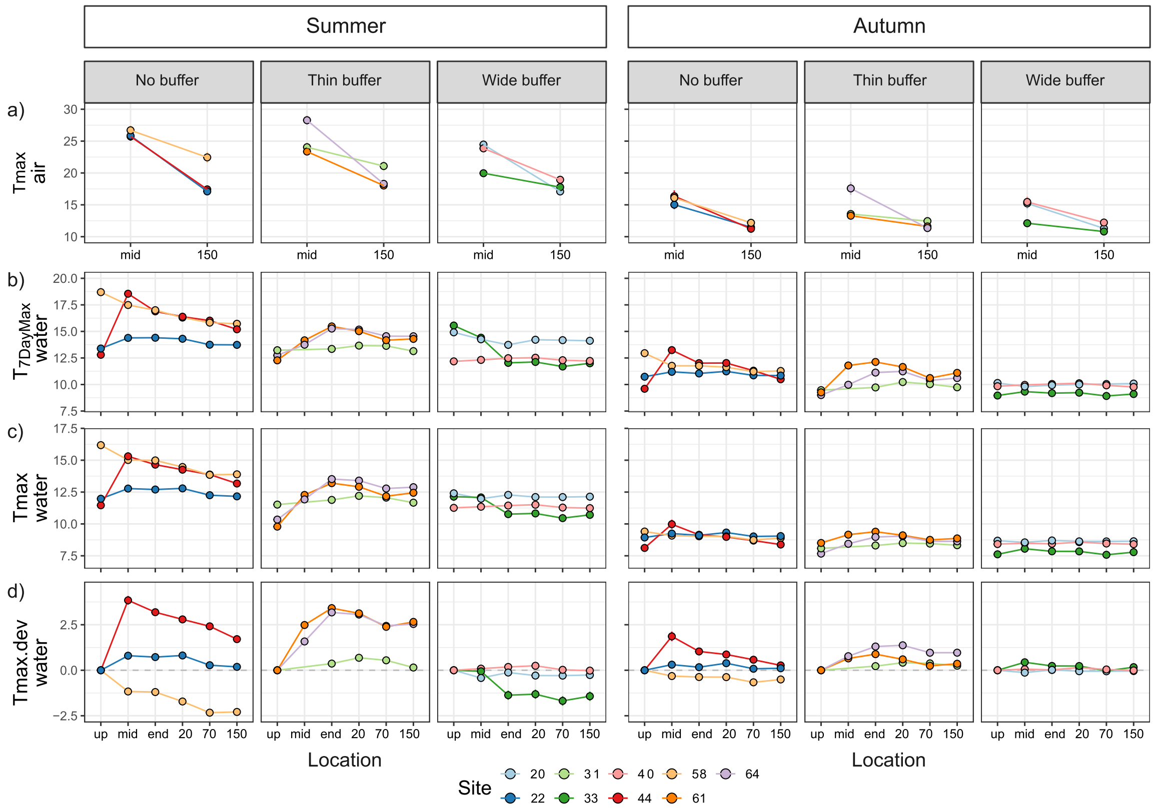

Figure 3. Summary of air and water temperatures at six locations in each of nine streams along a longitudinal gradient, starting from the upstream reference (Up), continuing through a clearcut (mid clearcut and end clearcut), and then into the forest again with 20, 70, and 150 m downstream from the edge of the clearcut. The streams were either protected by a wide forest buffer (≥15 m), a thin buffer (<10 m with gaps), or no buffer (individual trees). We used daily data from July and August in 2020. (a) Daily maximum air temperature (mean ± SE) measured at 30 cm height at the clearcut (mid) and in the forest of the most downstream location (150 m downstream), (b) T7DayMax: Maximum of 7 Day moving average of daily maximum temperature, (c) Mean ± SE of daily maximum temperature (see also Figure 5), and (d) Difference of mean daily maximum temperature compared to upstream location: positive values indicate warmer temperatures than upstream, and negative values indicate cooler temperatures.

downstream propagation was significant in the thin-buffer streams, with downstream temperatures being, on average, 1.9°C higher than upstream references ($p < 0.0001$). The no buffer group was highly affected by stream 58 (lake outlet) and therefore did not show a significant temperature difference between 150 m downstream and the upstream reference. The wide buffer streams did not show any significant longitudinal temperature change.

3.2.2. Longitudinal Temperature Changes Within Streams

Stream temperatures were significantly higher at the clearcut as compared to upstream locations in five out of six no or thin buffer streams (Figures 3c and 5, Tables S2, S3 in Supporting Information S1). The highest relative warming on a clearcut was measured in stream 44, with 4.1°C and 5.8°C increase (Tmax and T7dayMax, respectively). Generally, streams increased in water temperatures ($T_{\max}$) at the clearcut, with rates ranging from 0.1 to 1.2°C 100 m^{-1} (Table 2, Figures 3 and 5). Most streams either cooled down or did not change significantly in temperature from the end of the clearcut to 150 m downstream, with Tmax cooling rates ranging from −0.2 to −1.0°C 100 m^{-1} (Table 2). Of the five streams that warmed up at the clearcut, three streams were still warmer 150 m downstream of the clearcut (inside forest), compared to the upstream locations (also inside forest). This downstream propagation of temperature ranged from 1.8 to 2.8°C (Figures 3b–3d, and 5, Table 2, Tables S2, S3 in Supporting Information S1). Stream 58 and 33 (lake outlets) showed different patterns as compared to the other streams, with longitudinal cooling along the whole stream reach, that is, all locations were relatively cooler compared to the upstream reference. Wide buffer streams did not significantly warm up at the clearcut, except for one stream (0.2°C, Figure 5, Table S3 in Supporting Information S1).

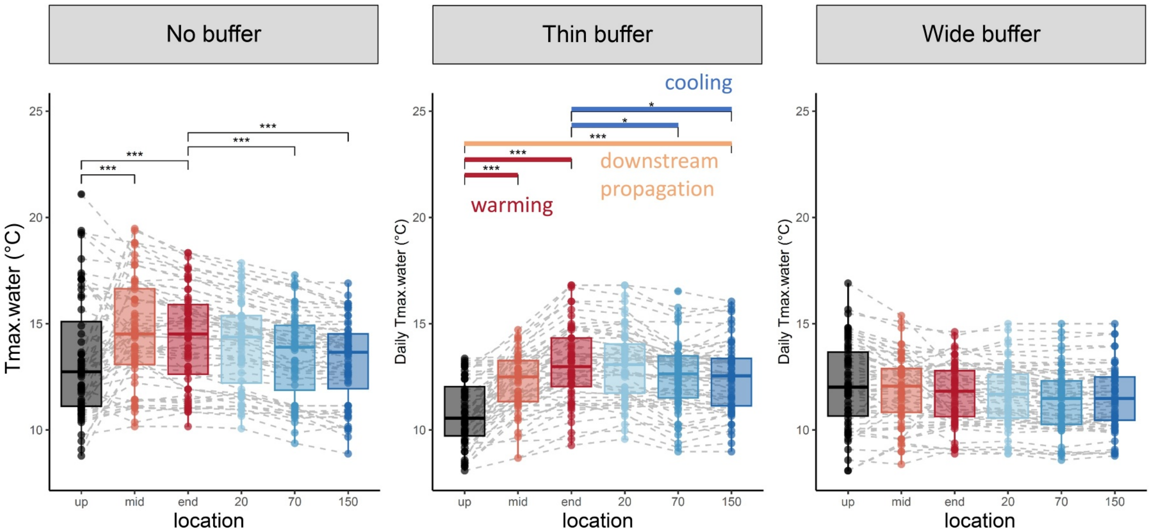

Figure 4. Comparison of daily maximum water temperatures at six locations in each of nine streams along a latitudinal gradient, starting from the upstream reference (Up), continuing through a clearcut (mid clearcut and end clearcut), and then into the forest again with 20, 70, and 150 m downstream from the edge of the clearcut. The streams were either protected by a wide forest buffer (≥15 m), a thin buffer (<10 m with gaps), or no buffer (individual trees). We used data from every third day in July and August in 2020. Gray dashed lines connect measurement from single days. Differences between groups (i.e., locations along each stream) were tested with a linear mixed model ($T_{max} \sim$ buffer × location + (1|day) + (1|stream)), a posthoc Type III analysis of variance and posthoc-pairwise comparisons using a Bonferroni-correction. Significant pairwise comparisons are marked with "*" on top of each panel.

3.2.3. Autumn Temperatures

The described temperature variations along and across streams were still visible in autumn, but with generally lower temperatures and smaller contrasts than in the summer (Figure 3, Figure S1b in Supporting Information S1). Maximum air temperatures were still consistently warmer at clearcuts compared to air temperatures inside the forest, with an average difference of 4.4, 3.2 and 3.2°C in the no-buffer, thin-buffer, and wide-buffer categories, respectively (T_{max}, Figure 3a, Table S4 in Supporting Information S1). The no and thin buffer streams warmed, on average, 0.6 and 0.8°C at the clearcuts compared to upstream water temperatures (T_{max}, Figure 3b, Figures S2, S3 in Supporting Information S1, Table S6 in Supporting Information S1). Single streams did, however, warm up to 1.9°C at the clearcut as compared to their upstream location (Figure S3 in Supporting Information S1, Table S5, S7, S8 in Supporting Information S1). During the warmest week (T7DayMax), the largest observed water temperature increase was 3.6°C (stream 44 with no buffer). The wide-buffer streams experienced no significant temperature changes at the clearcut, whereas all but one stream with missing or thin buffers significantly warmed at the clearcut. The exception was, again, stream 58 with an upstream lake. Notably, the pattern of downstream propagation sustained in autumn, and four streams were still significantly warmer in the 150 m downstream location compared to the upstream temperatures (Figure 3b, Figure S3 in Supporting Information S1, Table S5, S7, S8 in Supporting Information S1). These four streams belong to the no or thin buffer category.

4. Discussion

Boreal forests are under combined pressure from land-use and climate change, both of which risk increasing water temperatures and air temperatures in the riparian zone (Kreutzweiser et al., 2009), with effects on ecosystem functions (Myrstener et al., 2016), and species (Bonacina et al., 2023; Murdoch et al., 2020). Removal of riparian forest can dramatically increase water temperatures, both in reaches within clearcuts (Brown & Krygier, 1970; Janisch et al., 2012; Miralha et al., 2024), but also further downstream (Mcintyre et al., 2018), yet, to our knowledge, this has not been previously studied in boreal or subarctic forests. In this study, we found that within riparian buffers thinner than 10 m, summer stream temperatures increased up to 5.8°C, and autumn stream temperatures up to 3.6°C during the warmest weeks, compared to their upstream control locations. Summer maximum temperatures (T_{max}) in the thin buffer group warmed, on average, 2.5°C. Strikingly, in half of the streams with thin or no buffers, the heating effect propagated at least 150 m downstream of the clearcut. Importantly, we did not see those trends occurring in streams with wide (≥15 m) forested buffers. Yet, as the

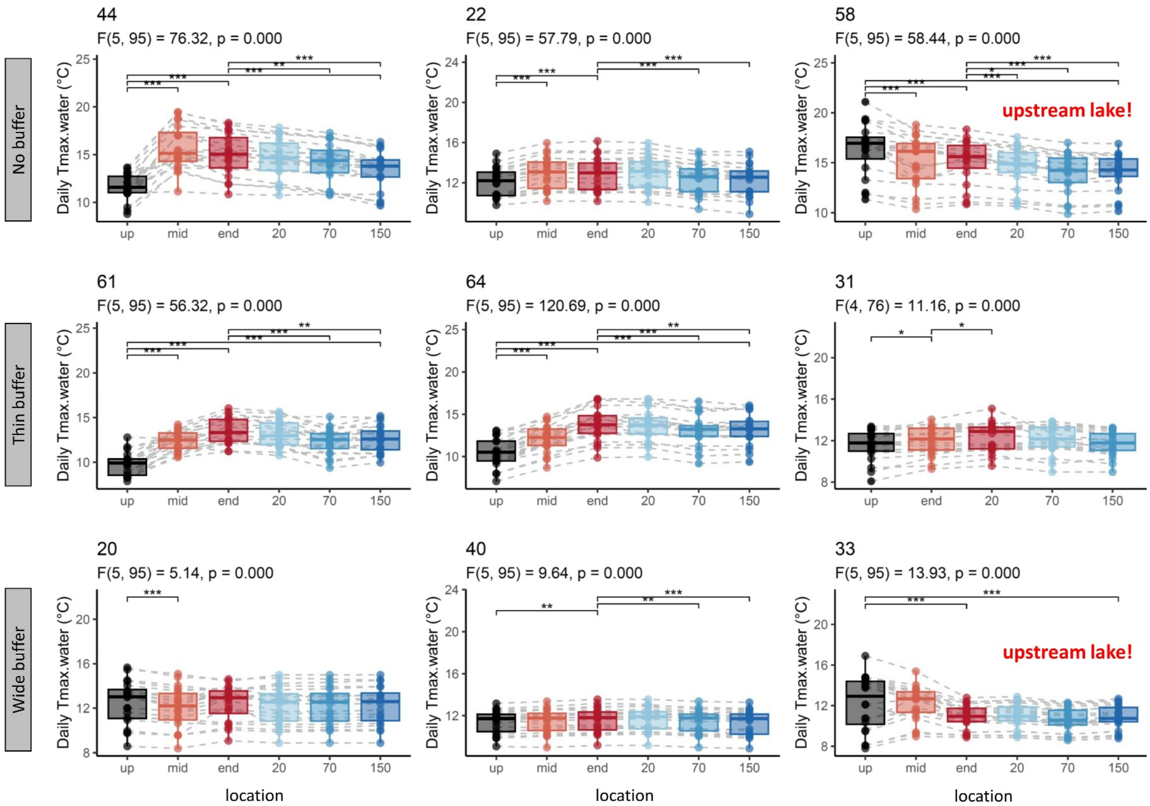

Figure 5. Statistical comparison of daily maximum water temperatures at six locations in each of nine streams along a latitudinal gradient, starting from the upstream reference (Up), continuing through a clearcut (mid clearcut and end clearcut), and then into the forest again with 20, 70, and 150 m downstream from the edge of the clearcut. The streams were either protected by a wide forest buffer (≥15 m), a thin buffer (<10 m with gaps), or no buffer (individual trees). We used data from every third day in July and August in 2020. Gray dashed lines connect measurement from single days. Note that *Y*-axes cover different ranges. Differences between groups (i.e., locations along each stream) were tested with a linear mixed model ($T_{max} \sim$ buffer × location + (1|day)), a posthoc Type III analysis of variance and posthoc-pairwise comparisons using a Bonferroni-correction. Test results are shown on top of each panel in this order: (F (Dfn, Dfd) = F, p), where F = F-statistics, Dfn = Degrees of freedom of the numerator (between groups), Dfd = Degrees of freedom of the denominator (within groups), and p = P-value. Note that streams 58 and 33 are at the outlet of an upstream lake, which impacts their thermal regime.

average riparian buffer zone along streams in Sweden is only 5–7 m (Ring et al., 2023), and 20% of the production forest has a stand age of 0–21 years (Nilsson et al., 2023), with clearcut-like temperature regimes, our results raise concern for widespread heating of boreal waters. Clearcutting of riparian, boreal forests ultimately risk causing warming of stream water that extends beyond the clearcut itself in terms of space (downstream propagation), time (beyond the initial years of clearcutting), and across seasons.

The impact that forest harvesting may have on water temperatures has been recognized for decades (Martin et al., 2021; Moore et al., 2005). As a response, retaining buffer strips along streams were developed as a potentially mitigating strategy (Richardson et al., 2012). However, some argued that changes in the stream temperature in harvested catchments could not be completely prevented by riparian buffers, because of warming of shallow groundwater on the harvested upland (Bourque & Pomeroy, 2001). On the contrary, elevated baseflow due to loss of tree-transpiration has shown to be able to prevent stream warming (Kibler et al., 2013). As an outcome, studies that assessed stream water warming as a response to clearcutting show large variation in the absolute numbers (see review by Martin et al., 2021). Nevertheless, stream warming by several degrees has been found repeatedly in clearcuts where riparian buffers were not retained. Brown and Krygier (1970) reported warming up to 10°C during summer temperature maxima in Oregon's coast range. In Washington state (US), Jackson et al. (2001) found warming of small streams in clearcuts without buffers to be between 1.2°C and 16.8°C, and a similar range (2–8°C) in harvested streams in British Columbia was reported by Gomi et al. (2006). Compared to no-buffer streams, evaluating the effectiveness of riparian forest retention has showed varied responses, yet, buffers that are narrower than 10 m has generally failed to prevent water from heating, and buffers over 20 m has shown to mitigate water temperature changes (Martin et al., 2021). Nevertheless, no such

Table 2
Temperature Changes and Change Rates in Each of the Nine Streams Along a Longitudinal Gradient, Starting From the Upstream Reference (up), Continuing Through a Clearcut (mid Clearcut and End Clearcut), and Then Into the Forest Again With 20, 70, and 150 m Downstream From the Edge of the Clearcut

		Relative temperature changes at clearcut			Relative temperature changes downstream of clearcut				Downstream propagation
Stream	Buffer	Up_mid (°C)	Up_end (°C)	Up_end.rate (°C 100 m^{-1})	End_20 (°C)	End_70 (°C)	End_150 (°C)	End_150.rate (°C 100 m^{-1})	Up_150 (°C)
44	No	**4.1**	**3.4**	**0.6**	−0.4	**−0.8**	**−1.6**	**−1.0**	**1.8**
22	No	**0.9**	**0.8**	**0.5**	0.1	**−0.5**	**−0.6**	**−0.3**	0.2
58	No	**−1.2**	**−1.2**	**−0.5**	**−0.6**	**−1.2**	**−1.1**	**−0.7**	**−2.3**
61	Thin	**2.6**	**3.7**	**1.2**	−0.3	**−1.1**	**−0.9**	**−0.5**	**2.8**
64	Thin	**1.7**	**3.4**	**0.9**	−0.1	**−0.7**	**−0.7**	**−0.5**	**2.7**
31	Thin	NA	**0.4**	**0.5**	**0.4**	0.2	−0.3	−0.1	0.1
20	Wide	**−0.4**	0.0	0.0	−0.2	−0.2	−0.2	−0.1	−0.2
40	Wide	0.1	**0.2**	**0.1**	0.0	**−0.2**	**−0.3**	**−0.2**	−0.1
33	Wide	−0.1	**−1.3**	**−0.3**	0.1	−0.3	−0.1	0.0	**−1.4**

Note. Presented is the mean of daily maximum temperature (T_{max}) across July and August 2020. Positive values (red) indicate a warming effect between two locations along the stream, and negative values (blue) indicate a cooling effect. Gray, non-bold numbers indicate non-significant temperature differences (based on posthoc pairwise comparison test, Figure 5, Table S2 in Supporting Information S1). Downstream propagation is the relative temperature change between each upstream and 150 m downstream location. For absolute temperatures at each stream and location, see Table S1 in Supporting Information S1.

assessments have been conducted at latitudes above 50° north (but see Jyväsjärvi et al., 2020), making our results from 64° north highly timely. We found heating of clearcut stream water in all streams with thin (<10 m) or missing buffers, while none of the wide buffer streams (≥15 m) showed this pattern. The wide buffer category actually had only a third of the solar radiation within the clearcuts compared to no or thin buffers, likely explaining why wide buffer streams did not warm up (Brown & Krygier, 1970; Moore et al., 2005). The only exceptions to clearcut heating of thin/missing buffers where lake outlets (stream 33 and 58) and/or streams that had only short reaches situated at the clearcut (stream 31 with only 81 m of the stream at the clearcut). In these streams, the water in the upstream control locations was already as warm as some of the clearcut locations, and thus, we observed no longitudinal warming (Leach et al., 2022). Given that high-latitude boreal forest ecosystems are generally energy-limited, with relatively cool summers, we may expect saturation of warming in streams, so that temperatures do not exceed certain air temperature thresholds. Beyond those maximum temperature thresholds, clearcuts will not cause additional warming, yet, based on our results, keep stream temperatures elevated. All in all, we conclude that buffer width significantly affected stream temperatures, both at clearcuts and in the downstream reaches.

While many studies evaluated the changes in stream temperatures within clearcuts or directly downstream of them (Martin et al., 2021), only a handful has followed the longitudinal patterns for hundreds of meters downstream of clearcuts. The general temperature trend in a forested stream, without the influence of upstream lakes or clearcuts, is gradual warming (Bladon et al., 2018). Indeed, in a forested stream within our study area, we estimated a longitudinal warming of 0.18°C 100 m^{-1} (Krycklan Catchment Study, 2023). Our clearcut streams with thin or missing buffers warmed up 3–6 times more, by 0.5–1.1°C 100 m^{-1}. Further, the warmed-up streams displayed downstream cooling by up to −0.9°C 100 m^{-1} downstream of the clearcuts. This rate of cooling corresponds to trends of streams with upstream lakes (Leach et al., 2017). Similarly, Roon et al. (2021) showed that, in Oregon coastal streams, temperatures can remain elevated 150–200 m downstream of harvested reaches. In parallel with our results, they did not detect downstream effects in stream reaches that did not experience warming at the clearcuts. Also in Oregon, Groom et al. (2011) has reported elevated water temperatures (by nearly 1°C compared to upstream control), up to 288 m downstream of clearcuts. Surprisingly, these studies from temperate regions showed less warming than what we observed in our most extreme cases in the boreal region. One explanation for our relatively large temperature increases, when compared to some temperate studies, could be the extended day length. At our latitude (64°N), we experience 20 hr daylight during the month of July. Another important factor is the large clearcut sizes (up to 17.1 ha) in our study area, and finally, the fact that cold water has a higher potential to be warmed up when exposed to increased solar radiation at clearcuts (Zaidel et al., 2021). Indeed, clearcut warming effects persisted into autumn for multiple streams in spite of colder weather and higher discharge (Figure S1a in Supporting Information S1). The spatial extent of warming of boreal streams due to harvesting of riparian forests is still unknown, yet, here we show that we can expect downstream propagation to at least 150 m during both summer and autumn.

In this study, we focused on testing how riparian buffer management influenced thermal regimes of streams at and downstream of clearcuts. While we have observed strong trends that are undoubtedly linked to buffer management, we have also seen variation in temperature patterns that relate to other controls of water temperature (Figure 1). For example, we have not quantified the effects of groundwater, but together with buffer width, it has been shown to be an important factor in controlling temperature regimes (Moore et al., 2005). Following harvest, groundwater levels increase, leading to increased baseflow, and, given that soils warm up more on open clearcuts (Oni et al., 2017), it is likely that the groundwater is also heated. Yet, even if this was an unquantified mechanism in our study, we show that wide buffers were able to mitigate it. Channel geomorphology also plays a vital role in thermal regimes of streams, especially if streams are incised, and thus shaded (Moore et al., 2005), despite reduced canopy cover in riparian zones. Our most incised channel was stream 31, a thin buffer stream that experienced the least clearcut warming. Stream 31 had, however, also the shortest stream segment (81 m) situated at the clearcut, which possibly contributed to the lack of temperature increase, similar to results reported for buffers that are cut in patches (Newton & Cole, 2013). Finally, common catchment features, like lakes, wetlands, or more open forests, affect the input of groundwater versus surface water, which is important for the thermal status of headwater networks (Moore et al., 2005; Oswood et al., 2006), and need to be considered by forest management.

Even though our study is based on a relatively small data set (nine streams), we showed that only buffers that equal or exceed 15 m in width can mitigate warming of stream water by preventing incoming solar radiation and/or inflow of heated groundwater. As of now, less than 10% of small streams in Sweden have buffer widths ≥15 m (Kuglerová et al., 2020; Lind et al., 2020; Ring et al., 2023), and the buffer situation is not much different in other boreal countries with intense, rotational forestry (Kuglerová et al., 2024). Further, in Sweden and Finland, most small streams have been modified in the past by deepening and straightening channels to promote forest growth (Hasselquist et al., 2018), and an estimated 1 million km of forest ditches have been dug (Lidberg et al., 2023). Ditches rarely receive riparian buffers (Ring et al., 2023), and thus, they provide warm water to receiving, natural, water bodies. Wider riparian buffer strips would not only prevent higher water temperatures but also air temperatures in the riparian understory from heating because of clearcutting. In our study, we measured elevated daytime temperatures at all clearcuts (compared to forest interiors), regardless of buffer width. Although the absolute air temperature values must be interpreted with care due to potential overheating of unshielded loggers (Maclean et al., 2021), we demonstrate that not even wide buffers (≥15 m) were enough to overcome microclimatic edge effects. In fact, microclimatic edge effects easily extend 40 m or further into the forest interior (Hofmeister et al., 2019; Vanneste et al., 2024). Altogether, our results call for management systems that move away from strict rotation forestry and instead adopt, for example, wider buffers (30 m), managed by alternative management principles to better balance protection and production needs on the long term and protect both surface waters and riparian understory.

5. Conclusion and Outlook

Stream temperatures in heavily managed boreal forests require more attention than they are currently given. Despite experiencing a generally cooler climate than well-studied temperate forest streams, boreal streams risk thermal regime shifts, with potential consequences for aquatic and riparian ecosystems. Climate change is causing boreal forests to warm at a faster rate than the global average (Gauthier et al., 2015), and we show that current rotational forest management practices in Scandinavia cause additional local and downstream warming of streams and understory microclimates. Given the diversity of factors that influence the magnitude and direction of clearcut effects on stream temperature (Figure 1), these factors need to be studied in combination. Ultimately, we need to establish critical temperature thresholds of species, populations, communities, and ecosystem functions, which accommodates target ecosystem biodiversity and services (Heino et al., 2009). Thermal thresholds have been experimentally identified or referred from geographical distributions for several aquatic species (Bennett et al., 2018; Steel et al., 2012), but, are to our knowledge largely missing for relevant species in the boreal forest in Scandinavia, such as arctic charr, burbot, and brown trout (but see Baroudy & Elliott, 1994; Réalis-Doyelle et al., 2016). Carrying our research further and studying both drivers and impacts of boreal stream temperature will eventually enable evidence-based recommendations on how to transform current forestry practices to a sustainable use of natural resources.

Data Availability Statement

The data and code underlying this manuscript are available at the Figshare database under the DOI https://doi.org/10.17045/sthlmuni.27188004.

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