Forest Ecology and Management 585 (2025) 122613

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Long-term trajectories of impacts and recovery of headwater stream temperatures after forest harvest in interior British Columbia

Douglas C. Braun[a,*], Dylan S. Cunningham[a,c], Herb E. Herunter[d,1], Sean M. Naman[a,b], Amanda M. Martens[b]

[a] Fisheries and Oceans Canada, Aquatic Research Cooperative Institute, School of Resource and Environmental Management, Simon Fraser University, Burnaby, BC, Canada
[b] Fisheries and Oceans Canada, Cultus Lake Salmon Research Laboratory, Cultus Lake, BC, Canada
[c] Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, BC, Canada
[d] Fisheries and Oceans Canada, Pacific Science Enterprise Center, West Vancouver, BC, Canada

ARTICLE INFO

Keywords:
Impact
Recovery
Riparian management
Riparian harvesting
Headwater streams
Temperature
Thermal sensitivity

ABSTRACT

This study examines the impact-recovery trajectory of stream temperatures following different riparian harvest treatments. We assessed the seasonal and annual changes in thermal sensitivity and temperatures across four different riparian management treatments in interior British Columbia using a Before-After-Control-Impact design across 6 headwater streams and 28 years. Riparian treatments included combinations of two buffer widths and two levels of retention of merchantable trees. Harvest periods included a pre-harvest period (1995–1996), short-term (1997–2009) and long-term post-harvest (2019–2024) periods. We found thermal sensitivity and stream temperatures responded rapidly to forest harvest similar to previous studies. Although stream temperatures peaked during months with the warmest air temperatures (July and August), the effect of riparian harvest on thermal sensitivity and mean daily temperatures had a strong seasonal component, whereby the largest harvest effects occurred during May and June. The largest short-term effects of forest harvest were observed in the stream with the least protective riparian management treatment and little to no effect was observed in the most protected stream. Forest harvest impacts on stream temperatures persisted through the short-term post-harvest period but recovery appeared to be underway in the long-term post-harvest period. Collectively, this work characterizes a multi-decadal impact-recovery trajectory for headwater stream temperatures across seasons and different riparian management treatments.

1. Introduction

Understanding how watersheds respond to and recover from anthropogenic stressors is critical for land use planning and management. Land use patterns in watersheds often form a complex mosaic where different patches of land are in various states of impact and recovery, making it difficult to characterize the total impact of a given land use activity on a watershed (Coble et al., 2020; Múrias et al., 2023). Further, most land use studies focus on early stages of impact, while less is known about long-term ecosystem responses (impacts) to stressors and if or when ecosystems return to pre-impact conditions (recovery) over long time scales (e.g., decades) (Bennett et al., 2006; Múrias et al., 2023). Complete impact-recovery trajectories are therefore often poorly described and uncertain (Coble et al., 2020; Downs et al., 2013; Reid, 1993). Research aimed at understanding impact-recovery relationships could help quantify, predict, and ultimately manage impacts of land use through time (Kelly and Harwell, 1990; Downs and Piégay, 2019). This requires coordination of studies that are long-term, intensive, and processes-based, which are rare for most types of land use.

A long history of research on the impacts of forest harvest activities on stream ecosystems provides a valuable platform for examining impact-recovery trajectories. Numerous intensive, processes-based studies have been conducted on the impacts of forestry on watershed processes over the past six decades (reviews: temperature response to

* Correspondence to: Fisheries and Oceans Canada, Aquatic Resource Cooperative Institute, School of Resource and Environmental Management, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada.
E-mail address: douglas.braun@dfo-mpo.gc.ca (D.C. Braun).
[1] Retired

https://doi.org/10.1016/j.foreco.2025.122613
Received 20 September 2024; Received in revised form 21 February 2025; Accepted 25 February 2025
Available online 17 March 2025

forest harvest – Moore et al., 2005; Moore and MacDonlad, 2024; peak flow response to forest harvest – Grant et al., 2008; meta-analysis of stream temperature and peak flow responses to forest harvest – Naman et al., 2024). Long-term studies of forestry impacts and stream ecosystems have provided new and unexpected insights about how these watersheds move through the impact-recovery phases of watershed change (e.g., Carnation Creek 40 + years (Tschaplinski and Pike, 2017), HJ Andrews Experimental Forest 70 + years (Andrews Experimental Forest, 2024), Upper Penticton Creek 35 + years (Winkler et al., 2021), Hubbard Brook 60 + years (Campbell et al., 2020), Alsea Watershed 60 + years (Segura et al., 2020), Caspar Creek 60 + years (Richardson et al., 2023). For example, the regeneration of forests decades after harvest can lead to decreasing summer flows and increasing stream temperatures during low flow periods (Gronsdahl et al., 2019; Segura et al., 2020). As well, forest harvest effects on recruitment of instream wood may have 50–200-year recovery times that are independent of harvest intensity (Reid and Hassan, 2020). These studies of long-term datasets provide valuable insights into the mechanism of long-term impacts and potential recovery from forest harvest. However, in most of these case studies, additional logging has continued in the study watersheds. Consequently, there are multiple overlapping impact and recovery trajectories that obscure inference into individual harvest events (i.e., a single cutblock). This combined with regional variation in climate, hydrology, forest type, and changes in forest harvest practices contribute to ongoing uncertainty about the long-term impacts from forestry and the recovery of watersheds in North America.

Water temperature is one of the most commonly measured stream responses to forest harvest (reviewed by Moore et al., 2005; Moore and MacDonlad, 2024). Increases in solar radiation from riparian vegetation removal and altered hydrology (early spring peak flows, lower summer flows) due to clear-cuts and early forest regeneration are well-documented short-term responses to forest harvest that often contribute to warmer downstream temperatures. These downstream impacts on stream temperature can have subsequent impacts on invertebrate and fish communities (Richardson and Béraud, 2014; Wilson et al., 2022). While the magnitude of forest harvest impacts on temperature varies considerably, forest harvest generally warms daytime spring and summer stream temperatures across a broad range of catchment characteristics and harvest practices (Moore et al., 2005; Naman et al., 2024). In contrast, far less is understood about long-term thermal recovery trajectories, and what modulates them, as forests regenerate and hydrological processes recover decades after harvest. A limited number of studies have documented variable recovery times from a few to 20 + years and suggest that stream size and climate zone play a strong role in the time to recovery (Summers, 1982; Moore et al., 2005; Leach et al., 2022) specifically, recovery is expected to be faster in narrower streams in warmer climates. Understanding longer term impacts and recovery of stream thermal regimes will become increasingly important given ongoing landscape change from forest harvest as well as concurrent climate change impacts on hydrology.

Here we examine the impact and recovery of water temperatures to forestry over 28 years. We revisited four experimentally logged and two control headwater streams in the Baptiste watershed in interior British Columbia. The Baptiste headwater experiment was a part of the Stuart-Takla Fisheries-Forestry Interactions Project (1995–2009) (Macdonald et al., 1992) and consisted of a series of studies that ran from 1995 to 2003. Our study builds on earlier work in this system that describes short-term impacts of forest harvest with different riparian management on stream temperature warming (Macdonald et al., 2003b) and changes in hydrology (Macdonald et al., 2003a). These studies found that there were immediate stream temperature responses but increases were gradual over 1–3 years post-harvest, due to windthrow events shading treatment streams (Macdonald et al., 2003b).

Additional unpublished stream temperature data were collected between 2004 and 2009 with data loggers that remained in the streams from the original study. We re-established a network of stream temperature monitoring sites in 2019 that replicated the original study design. Using unanalyzed stream temperature data from 2004 to 2009 and data from our re-established network of stream temperature monitoring sites, we examined the short- and long-term impacts of forest harvest and the timeline of stream temperature recovery. Specifically, we studied the impact and recovery of water temperatures to four riparian management treatments using a Before-After-Control-Impact (BACI) design. We examined the short- and long-term response and recovery of stream temperatures to forest harvest while accounting for air temperature. This approach provides insights into forest harvest impacts with respect to both absolute water temperatures and the correlation between air temperature and water temperature, also termed thermal sensitivity. Air temperature and solar radiation are correlated, therefore the correlation between air temperature and water temperature serves as a proxy for the effects of solar radiation on stream temperature (Johnson, 2003).

Our study provides new insights to both the short- and long-term responses of stream temperature to forest harvest and riparian management by examining thermal sensitivity via air temperature and water temperature relationships. We predicted: (1) stream temperatures would show the greatest response to forest harvest immediately after harvest but would decrease with time as riparian vegetation regrows and shades the stream from solar radiation; (2) stream temperature responses to and recovery from forest harvest would vary by season due to seasonal variation in solar radiation and surface water to groundwater ratios; and (3) both absolute stream temperature and thermal sensitivity would respond more strongly to forest harvest at sites with less riparian protection.

2. Methods

2.1. Study system

The Baptiste watershed is located in the Hogem Range of the Omineca Mountains in British Columbia (Fig. 1). The study portion of the watershed consisted of six headwater streams (Table 1) with watershed areas that range from 18 ha to 313 ha. The watersheds are in the Sub-Boreal Spruce biogeoclimatic zone in the Fraser River Basin. The riparian tree species present in the watershed are hybrid white x Engelmann spruce (*Picea gluaca* x *engelmanni*) and subalpine fir (*Abies lasiocarpa*), with some black cottonwood (*Populus balsamifera* spp. *trichocarpa*), alders (*Alnus* spp.), willows (*Salix* spp.), red-osier dogwood (*Cornus stolonifera*), black twinberry (*Lonicera involucrata*), devil's club (*Oplopanax horridus*), and *Rubus* spp. Fish are absent in all study sections but rainbow trout (*Onchorynchus mykiss*) have been observed in the lower reaches. The Baptiste hydrograph is dominated by snowmelt in the spring and ground water in the summer months (Story et al., 2003).

The Baptiste headwater experiment was established in July of 1995 when pre-harvest data collection began. The project consisted of intensive studies involving a wide range of ecosystem components (water and groundwater temperature, flow, nutrients, water chemistry and sediment, and macroinvertebrates) were conducted between 1995 and 2003 (Cunningham et al., 2023). Temperature data were collected between 1995 and 2009 from the original study and then from 2019 to 2023. Details about the Stuart-Takla Fish-Forestry Interaction Project can be found in Macdonald et al. (1992), Macdonald (1994), MacIsaac (2003) and Cunningham et al. (2023).

2.2. Experimental design

The original project used a multi-year BACI design to evaluate the effects of forest harvest practices on the headwater stream temperatures in the Baptiste watershed (Table 1). This included comparing sites that had been exposed to forest harvest to unharvested sites, before and after forest harvest. More specifically, the spatial design (Control-Impact) included four sites (B1, B2, B3, B5) located downstream of clear cut

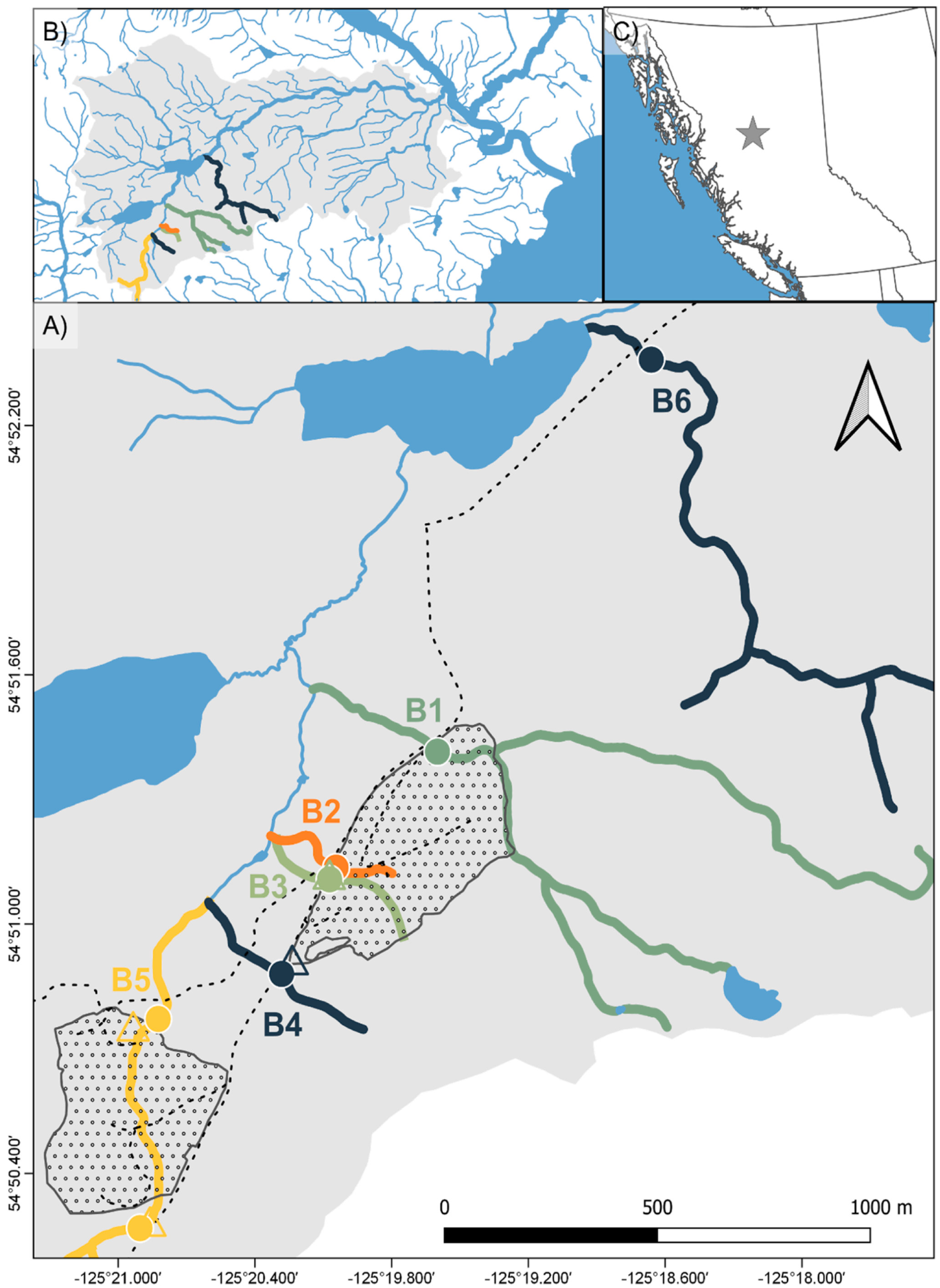

Fig. 1. Map of (A) study streams, sites, harvest cutblocks (hatched area) and roads (dashed lines). Temperature logger locations are coloured circles, and canopy density measurement locations are coloured open triangles. Insets (B) is the Baptiste watershed in grey and study streams in colour, and (C) shows the location of the Baptiste watershed in British Columbia (grey star).

logging with different riparian management treatments, each applied to a single stream (Fig. 1), upstream control sites (B3HI and B5UP) on each of the treatment steams as well as two unharvested control streams (B4 and B6). We diverged from the original study design that would have paired upstream controls sites with downstream treatment sites as some upstream control sites were often dewatered. Using the original study design would have limited the number of paired water temperatures observations in the time series. Instead, we selected control-treatment pairs based on the relationship between treatment sites and the two control streams and one upstream control site (B4, B5UP and B6) using pre-harvest data. We examined the linear relationship between control and treatment data and used three criteria to assess the most suitable control for a given treatment site: (1) intercept closest to zero; (2) slopes closest to 1; and (3) the highest R^2 value. (Figure S1, Table S1). There was generally convergence across these performance metrics. We selected the following treatment-control pairs (B1 30 m low retention – B6 control stream; B2 patch retention – B4 control stream; B3 20 m high retention – B4 control stream; B5 20 m low retention – B5UP upstream control site) (Table 1).

The temporal component of this study (Before-After) spanned 28

Table 1
Summary of Baptiste site characteristics, forest harvest, and riparian buffer treatments for spatial comparators.

Stream	Average bankfull width (m)	Watershed size (ha)	% Watershed harvested	Stream gradient (degrees)	Elevation (m)	Aspect	Riparian buffer treatment	Control site	Canopy density site
B1	2.8	313	6	11	980	W	30 m high-retention	B6	
B2	1.0	18	89	12	980	NW	Patch retention	B4	
B3	0.6	43	38	26	980	NW	20 m high-retention	B4	B3
B4	0.9	48	0	30	980	NW	Control	NA	B4
B5	1.4	150	40	7	980	N	20 m low-retention	B5UP	B5LO, B5UP
B6	3.2	210	0	5	900	NW	Control	NA	

years and included a 16 month pre-harvest period (July 1995-October 1996), followed by a 13-year short-term post-harvest period (April 1997-September 2009), and a 4 year long-term post-harvest period (August 2019-August 2023). Short and long-term post-harvest periods were defined by the break in data collection (October 2009-July 2019) between the initial project and re-initiation and provided a convenient way to refer to the different periods of data collection.

The four riparian management treatments consisted of (1) *low retention* (high riparian harvest) where all merchantable trees > 15 cm (pine) and > 20 cm (spruce) diameter at breast height (DBH) were harvested; (2) *high retention* (low riparian harvest) where all merchantable trees > 30 cm DBH were harvested; and (3) *patch retention* where the upper 40 % of the riparian vegetation was completely removed and the high retention buffer was applied to the lower 60 % of the riparian. Two buffer widths (30 m and 20 m) were evaluated with the low retention buffer. Clear cut harvesting was applied to the portions of the cut blocks outside the designated riparian buffer. Therefore, riparian treatments ranged from the most protective 30 m buffer with high retention harvest, to 30 m buffer with low retention harvest, to 20 m buffer with low retention harvest, and to patch retention, the least protective riparian management treatment. The extent of each watershed harvested ranged from 6 % to 89 %. All cut blocks were replanted 1–2 years post-harvest but there was no planting in the riparian zones. There has been no additional harvest in either of the control streams or upstream of the upstream control sites. Riparian management treatments applied in this experiment were more protective than contemporary riparian management practice in British Columbia as described in Kuglerová et al. (2020), and therefore our estimates of the effects of forest harvest are conservative.

2.3. Data collection

2.3.1. Riparian canopy closure

To examine annual changes in riparian canopy we used a convex densiometer to estimate canopy closure at four sites from 1997 to 2009 and in 2023. Measurements were taken at breast height at North, East, South, West bearings during times of the year when foliage was present. In most years riparian canopy closure was measured multiple times a year during the "leaf on" period (June to Early October), however the 2023 measurements were taken only once during August. Repeated measurements during a year were summarized into annual "leaf on" means and the associated standard deviation.

2.3.2. Water temperature

Continuous water temperature data used in this study were collected from temperature loggers installed at the seven study sites. During the original water temperature study, loggers were installed in streams and removed at different times throughout the study period (Cunningham et al., 2023). Long-term post-harvest data were not collected for B1 and B2 due to dry channels during the summer months. In the original study, loggers were secured to the bank with cable and taped to rocks that were placed logger side down without radiation shields. In the current study, loggers with radiation shields were attached to rebar installed in the streambed in deeper sections (e.g., thalweg) of the streams where water was well mixed. Loggers were installed as close as possible to the original study sites using coordinates and visual cues (e.g., presence of old infrastructure) (Cunningham et al., 2023). We estimated distances between the original and current site locations to be less than 10 m.

Water temperature (T_w) data were recorded hourly using Vemco Minilogs 1995–2009 (accuracy $\pm$ 0.2°C) and from 2019 to 2020 using HOBO pendants (accuracy $\pm$ 0.5°C) and UTB-001 2020–2023 (accuracy $\pm$ 0.2°C). Daily mean water temperatures were calculated and used in our analyses. Although using daily means removed information about the effects of forest harvest on diurnal temperature changes, it matched the available air temperature data required for thermal sensitivity analyses. Water temperature from control (control streams or upstream control sites) and treatment sites were used to calculate water temperature differences (ΔT_w = treatment - control). A positive ΔT_w indicated warmer water temperatures in the sites downstream of harvest compared to the controls (upstream control sites or control streams).

Erroneous data (e.g., when loggers were dewatered and recording air temperature, or logger errors) were identified by visualizing data and comparing stream temperature profiles to air temperature profiles. We removed data for periods when T_w resembled air temperature. In addition, we removed data where the daily variance (using hourly data) exceeded 2°C, T_w was above 15°C, and/or where the daily stream temperature range exceeded 5°C, as these values all indicate dewatered loggers in these cool, headwater streams. We also treated T_w readings below 0°C as 0°C. Removed data were not interpolated, as they indicated a lack of water and days with missing data were not used in further analyses. Loggers were checked for accuracy by comparing hourly water temperature values from the data loggers to water temperatures measured using a YSI multimeter during field visits; the mean difference was 0.1°C and did not exceed 0.2°C.

2.3.3. Air temperature

Air temperature (T_a) data for Fort St. James was downloaded from ECCC (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html). We joined data from two climate stations (historic - and recent Climate ID: 1092975) to form a continuous daily air temperature dataset from 1995 to 2023. The historic climate station reported daily mean air temperatures from 1895 to 2019 (Climate ID: 1092970; 691 m elevation, N 54.455280, W-124.285556) and the recent climate station reported hourly data from 2013 to present (Climate ID:1092975, 688 m elevation, N54.455292, W-124.285557). The relationship between the recent and historic sites was strong for the period of overlapping data (overlap years: 2013–2019; R^2=0.94, intercept = 0.048; slope = 0.995) and supported joining the two time series. These two sites were selected over multiple other meteorological stations due to their nearly continuous time series and proximity to the Baptiste watershed (~80 km Euclidean distance). Further, Mohseni et al. (1999) show that distances between air temperature and water temperature stations of 2–244 km did not significantly affect the air-water temperature relationship using weekly data. We used the daily means for air temperature data between 1995 and 2023. We also used precipitation data from the DFO Middle River camp meteorological station (1991–2009) to provide a description of the precipitation patterns near the watershed.

2.4. Data analysis

Linear regression models were used to estimate how water temperatures in headwater streams responded to forest harvest and riparian management treatments before, after, and 23 + -years post-harvest. We related regional air temperature to the difference in water temperatures between control and treatment sites. This empirical approach of relating air temperature and water has been widely used to understand and predict stream temperature (e.g., Mohseni and Stefan, 1999; Moore et al., 2013; Luce et al., 2014; Isaak et al., 2017). Relating air temperature to water temperature capitalizes on their correlated response to solar radiation, however there are other processes that can confound this relationship (reviewed in Mohseni and Stefan, 1999). For example, increase cloud cover or smoke from wildfires could alter fluxes of short and longwave radiation contributing to stream energy budgets (McKendry et al., 2019; Leach et al., 2023), at a given air temperature, thus altering the correlation between air temperature and water temperature. Given the small size and close proximity of study watersheds, we assume the impact of potential confounding effects are small relative to the strong contrast in the amount of riparian vegetation and canopy closure among treatments. In headwater streams where riparian vegetation is removed, solar radiation can increase water temperatures compared to streams with unharvested riparian zones. Our application of this approach focuses on how regional air temperature (a proxy for regional solar radiation inputs) is filtered differently through the different riparian cover conditions resulting from forest harvest.

Water temperature response, ΔT_w, was calculated by subtracting the daily mean water temperature for the control site from the treatment site. Calculating treatment minus control values has been shown to be a more statistically powerful approach in BACI studies than using the raw treatment site data as a response (Smokorowski and Randall, 2017). Daily mean regional T_a, from Fort St James was used as the explanatory variable. Air temperature-water temperature correlations decouple during cooler months (November to April in our study system) due to sub-zero air temperatures, therefore the cooler months were not considered in our analyses. Daily ΔT_w data were not independent, therefore we included a moving average parameter to address autocorrelation (Som et al., 2012). Models relating daily mean air temperature to the daily difference between control and treatment temperatures ΔT_w for each site i, month j, year k combination was as follows:

$$\Delta T_{wt} = \alpha_{ijk} + b_{ijk} T_{at} + \varepsilon_t + \Theta_{ijk}\varepsilon_{t-1} \quad (1)$$

Where, ΔT_w is the daily mean water temperature difference between the control and treatment site (treatment minus control), T_a is the daily mean regional air temperature, α is the intercept, b is the slope for the relationship between T_a and ΔT_w, θ is a moving average parameter that describes the effect of the residual error from the previous time step on ΔT_w and ε is the residual error which is assumed to follow a normal distribution. We constructed models for each control-treatment site pair, month and year combination resulting in 353 models each based on between 10 and 31 days of data.

Daily mean air temperature data were centered by subtracting the monthly mean air temperatures across all years (Schielzeth, 2010).

$$XCentered_{ijk} = X_{ijk} - \mu_j \quad (2)$$

Where; *XCentered* is the daily air temperature data for day i, month j and year k, and the mean air temperature for month j. Therefore, the intercept from Eq. (1) was interpreted as the mean ΔT_w given the mean monthly T_a across all years This allowed for the comparisons of monthly intercepts among sites and years. In other words, for each month, a positive intercept was interpreted as a warming effect of forest harvest on ΔT_w when the regional T_a was at the mean across years. More positive slopes were interpreted as an increase in the effects of forest harvest on thermal sensitivity. This means that T_w at the treatment site would increase more following a 1°C increase in T_a relative to the control site. Rather than test for differences among riparian treatments and different periods (pre-harvest, short-term post-harvest, long-term post-harvest) we plotted the intercepts and slopes to show the effects of riparian treatment and the dynamics in these response metrics through time. This provided a more comprehensive illustration of how the impact-recovery relationships vary among seasons and over the 29-year time span.

To assess the sensitivity of our results to our analytical approach we also conducted a conventional paired watershed analysis that used the pre-treatment data to predict post-treatment temperatures in both the control and treatment sites (e.g., Gomi et al., 2006; Neary, 2016). These predictions are then compared to the observed data and significant deviations between predicted and observed data suggest a treatment effect. This statistical approach assumes climate effects are consistent for the duration of the study, which may be a reasonable assumption for short-term studies, but problematic for longer-term studies. In contrast, our approach relaxed this assumption by incorporating air temperature throughout the study period. We found the conventional paired watershed analysis produced qualitatively similar results to the approach used in this study.

2.5. Seasonal response to forest harvest

We examined seasonal shifts in the effect of forest harvest on stream temperatures by calculating the mean ΔT_w and T_a for each month j and year k within each of the study periods (pre-harvest, short-term post-harvest, long-term post-harvest). We plotted the ΔT_w against the monthly mean T_a for the same time periods. For this analysis we examined all months of the year. We interpreted plots showing different ΔT_w at similar T_a as demonstrating hysteresis such that forest harvest effects vary due to season. The direction and size of the differences were used to infer seasonal patterns (Northrop and Ballif, 2021; Miralha et al., 2023). For example, clockwise loops indicated a larger effect of forestry for a given air earlier in the year compared to later in the year.

3. Results

Annual T_w for the study sites ranged from 2.3°C to 4.1°C (Table S2). Maximum daily mean T_w ranged from 11.2°C to 12.5°C (1996–2002) (Table S2) and typically occurred during the end of July or early August (Figure S2E-F); this coincided with the timing of maximum summer T_a (Figure S2 C-D). Most precipitation falls as snow during the winter and rainfall is low throughout the year peaking in April and October (Mean April=23 mm; mean October=23 mm for 1991–2009) with very few large rain events during the summer (Figure S2 A-B). The annual April to November precipitation averaged 93 mm over the years 1991–2009. Groundwater temperatures tended to peak later in the year than surface water temperatures (Figure S2 G-H). Water temperatures were zero for most days between November and April and typically began to increase in early April with the onset of snow melt and spring freshet.

The maximum differences in ΔT_w were lowest during the pre-harvest period (B1 =0.67°C, B2 =0.55°C, B3 =0.43°C, B5 =0.77°C), highest during the short-term post-harvest period (B1 =1.8°C, B2 =4.55°C, B3 =2.45°C, B5 =2.6°C), and intermediate during the long-term post-harvest period for B3 and B5 (B3 =1.41°C, B5 =1.36°C) (Fig. 2 A-D). The mean of daily T_a for July and August increased over the study period by 0.07°C per year (R^2=0.26, year coef.=0.07, S.E.=0.168, p-value<0.001) (mean of daily T_a for July and August: Pre-harvest=14.15°C; short-term post-harvest=14.9°C; long-term post-harvest=16.05°C) (Fig. 2E).

3.1. Riparian canopy closure

Riparian canopy closure was affected by forest harvest treatments. In the year following harvest (1997), forest canopy closure reflected forest harvest treatments such that it was highest in the control stream (B4)

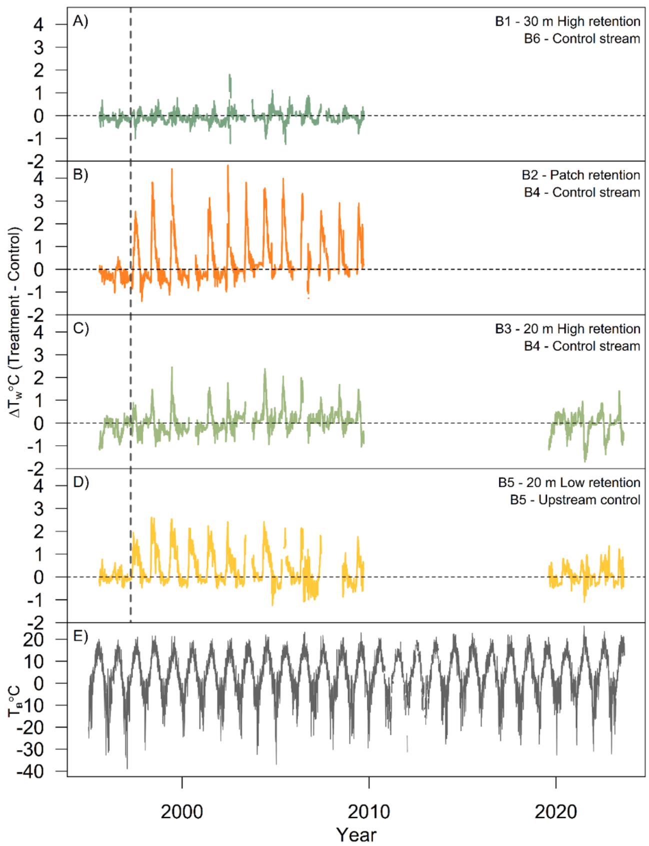

Fig. 2. Time series of the difference in water temperature between treatment and control sites (treatment minus control) for 4 treatment streams and pairs of control sites (A-D). The vertical dashed line indicates when harvest occurred. Plot E shows the daily mean air temperature at Fort St. James.

and upstream control site (B5UP), lower in the high retention site (B3) and lowest in the low retention site (B5) (Fig. 3). Windthrow events in 1997, 1998, 1999 in two treatment sites further reduced canopy closure to from 0.36 to 0.07 (1999) and 0.14–0.03 (2001) in B3 and B5LO, respectively. Site B4 also experienced a significant windthrow event in 2003. This reduction in canopy closure from windthrow reduced the differences in canopy closure between the low and high retention treatments in B3 and B5, but may have increased cover directly over sections the streams as some trees fell across the channel. By 2023, the riparian canopy closure of two treatment sites (B3 and B5LO) returned to levels similar to the unharvested site B5UP and pre-windthrow levels in B4. In all cases windthrown trees were not disturbed and left in place.

3.2. *Responses to forest harvest*

There were marked increases in ΔT_w and thermal sensitivity (i.e., the slope between T_a and ΔT_w) in the first year following harvest in all treatment sites except in the site with the most protective riparian management treatment (B1). For June, July and August, water temperatures in sites exposed to forest harvest were elevated for the duration of the short-term post-harvest period (Fig. 4; Sites B2, B3, B5). A similar trend was observed for May, but intercept values were more variable. The mean T_w for May, June, and July were between 2 and 3 degrees higher in the treatment site than in the control. These short-term post-harvest ΔT_w were substantially higher when compared to the pre-harvest period where differences in water temperature were near zero or sometimes negative.

There was a strong seasonal component to the effects of forest harvest on water temperature. Prior to harvest, ΔT_w were minimal across the seasons. However, in the more severe harvest treatments, harvest induced large seasonal increases in T_w in the treatment sites when compared to the control sites. Specifically, forest harvest had the greatest warming effect on daily mean ΔT_w in treatment sites during May, June and July (Figs. 4 and 5). During the short-term post-harvest period, estimated intercepts from the linear models were highest for

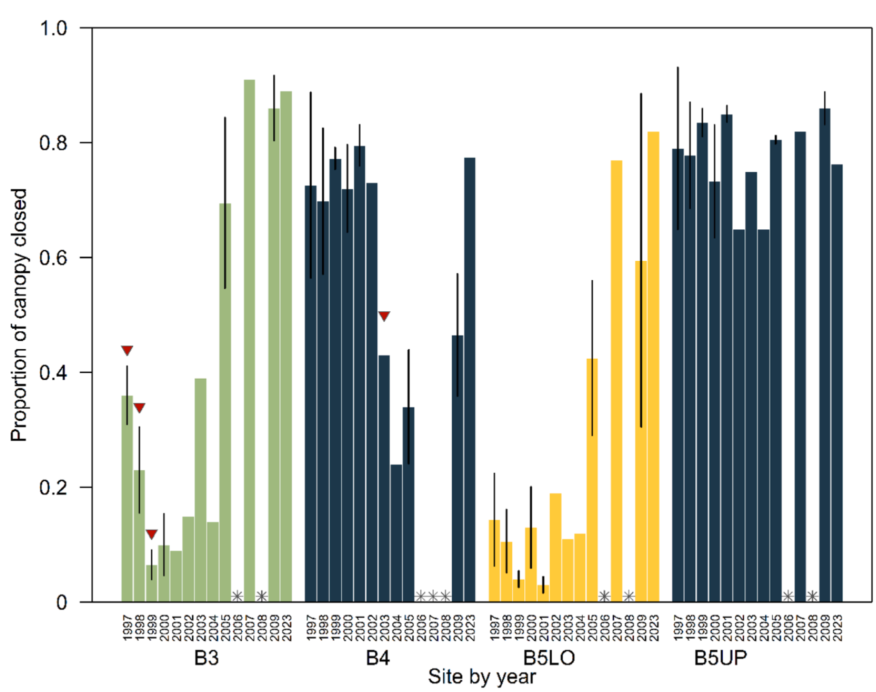

Fig. 3. Plots of the proportion of canopy closure during the "leaf on" period by site and year for 1997–2009 and 2023. Bars are the mean values for all stations within the treatment or control site and vertical lines represent ± 2 standard deviations. Missing data are indicated by no bars and bars with no vertical lines indicate canopy closure was only one measure during one sample date or there was no variation in multiple measures (i.e., standard deviation=0). Significant windthrow events (indicated by the red triangles) occurred in 1997, 1998, 1999 in B3 (20 m buffer high retention treatment) and in 2003 in B4 (unharvested control stream) that dramatically reduced the canopy cover to similar levels that were observed in B5 (20 m buffer low retention).

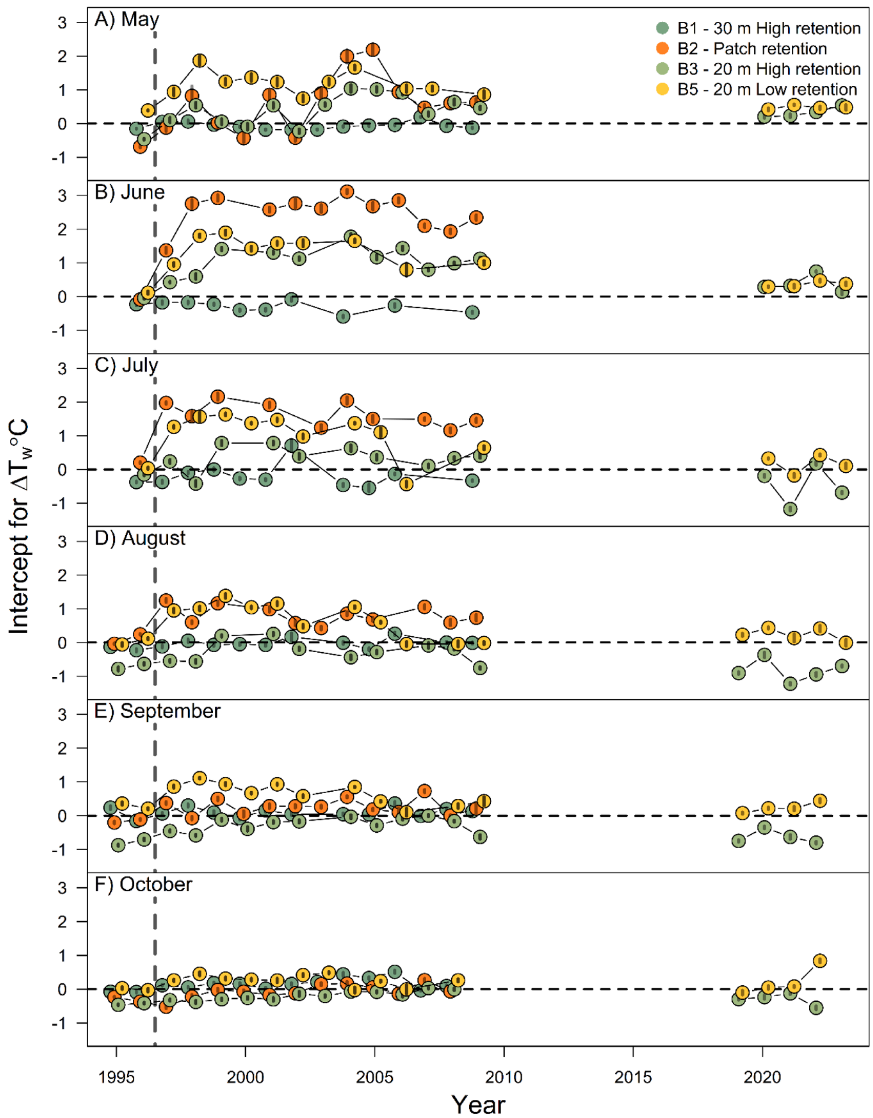

Fig. 4. Plot of intercepts from regression models by year, month, and riparian treatment between May and October and 1995 and 2023 (A-F). Intercepts represent the effect of forestry on the influence of air temperature – at its average for the month – on the mean difference in water temperature between the control and treatment. Vertical dashed line indicates when harvest occurred.

these months for 3 of the 4 riparian treatments (Fig. 4; Table S3), with the greatest warming effect estimated for June for all three sites (max intercept: B1 =0.2,°C, B2 =3.1°C, B3 =1.8°C, B5 =2.6°C). Positive intercepts indicate an increase in T_w at the treatment site relative to the control when the daily T_a is at the mean for that month over the timeseries (i.e., centered T_a is equal to zero). During the pre-harvest period the mean of May, June, July intercepts for all sites were −0.1°C and ranged from −0.8°C to 0.2°C.

Thermal sensitivities showed a similar increase immediately post-harvest and were consistently higher for the short-term post-harvest period (Fig. 6). However, thermal sensitivities were more variable among years than the intercepts. For example, there were 2 years where thermal sensitivities were consistently low among all treatment sites (2000 and 2002); each year was followed by some of the highest slopes in the timeseries (Fig. 6).

Thermal sensitivity varied by season in all treatment sites except B1; sites exposed to forest harvest warmed more for a given air temperature in the spring compared to autumn (i.e., clockwise loop shifting up the y-axis) (Fig. 5). For example, short-term post-harvest air temperatures were similar for June (13.4°C) and August (14.9°C) yet we observed ΔT_w in June to be 1.6°C higher than in August in the patch retention site B2. This seasonal hysteresis pattern (i.e., loop shifting up the y-axis) indicated that the effect of forest harvest was 3 times greater in June compared to August. The largest seasonal variation in thermal sensitivity was observed in the stream where the least protective patch retention treatment was applied (B2).

The warming effect due to forest harvest declined from mid-summer into the autumn months (Fig. 4) whereby the intercepts across all sites during the short-term harvest period for October ranged from −0.6°C to 0.5°C (Table S3). There was little to no seasonal effect of forest harvest on daily mean T_w for the most protective riparian treatment (B1 – 30 m buffer high retention) (May-July intercepts: mean=-0.16°C, range=-0.6°C – 0.7°C; August-October: mean= 0.1°C, range= −0.2°C – 0.5°C) (Table S3).

Forest harvest increased the thermal sensitivity of headwater streams, particularly during May and June (Fig. 6). For example, the mean slope between T_a and ΔT_w for the patch retention site during the short-term post-harvest period in May was 0.2°C°C^{-1} (range=0.1°C°C^{-1} - 0.3°C°C^{-1}) (Table S3). This indicated that a 1°C increase in T_a corresponded to, on average, a 0.2°C larger T_w increase in the treatment site relative to the control during the short-term post-harvest period. The effect of forest harvest on thermal sensitivity in May was intermediate

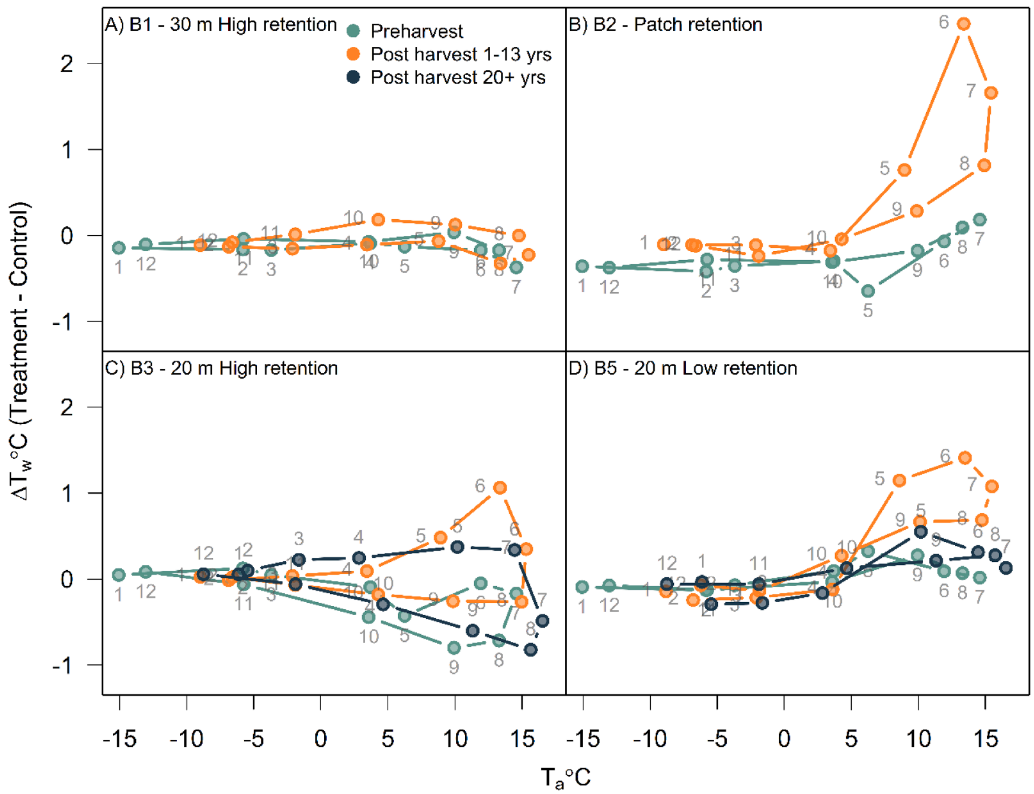

Fig. 5. Plot of monthly mean Fort St. James air temperature and monthly mean ΔT_w by harvest periods for the 4 treatment streams (A-D). Positive ΔT_w values indicate warming of treatment sites. Numbers next to points indicate month. The presence of loops indicates a seasonal hysteresis pattern in the relationship between air temperature and effect of harvest on water temperatures. Arrows show the clockwise direction of the loops which show a larger effect of harvest earlier in the year compared to later in the year.

for the low retention sites (B3: mean=0.1°C°C^{-1}, range=0.0°C°C^{-1} - 0.2°C°C^{-1}; B5: mean=0.1°C°C^{-1}, range=0.0°C°C^{-1} - 0.2°C°C^{-1}) (Table S3), and no detectable change in the high retention site (B1: mean and range =0.0°C°C^{-1}).

The effect of forest harvest on thermal sensitivities declined from May to mid-summer for all 3 sites with some negative slopes during July, August and September. Negative slopes could occur when increasing T_a (i.e., increasing solar radiation) leads to a decline in T_w and would indicate downstream cooling when comparing temperature differences between treatment and control sites. In contrast, the mean slope for the 30 m buffer high retention site during the short-term post-harvest period continued to be unaffected by forest harvest (B1: mean=0.0°C°C^{-1} for all months May to October) (Fig. 5; Table S3).

3.3. Recovery trajectories

Water temperature differences between control and treatment and thermal sensitivity appeared to be recovering two decades post-harvest. During the long-term post-harvest period, temperature differences between treatment and control sites approached pre-harvest levels for both treatment sites, B3 and B5, for most months (May to October Fig. 4; June Fig. 7; Table S3). Thermal sensitivities appear to be similar to pre-harvest levels (Fig. 6).

The trajectory of forest harvest impacts on water temperature followed a consistent pattern of impact and partial recovery over the 28 years of the study. Specifically, for sites B3 (20 m high retention) and B5 (20 m low retention), the initial impact of harvest on June temperatures was rapid. The initial impact increased the first few years to the maximum ΔT_w observed 3- and 6-years post-harvest for B3 and B5, respectively. This is followed by a general decline in the impact but at a much slower rate per year than the ascending portion of the impact curve, although a significant portion of the decline in impact is interpolated. Finally, the latter portion of the dataset suggests ΔT_w is near the pre-harvest ΔT_w.

4. Discussion

Collectively, results from this study provide rare insight into long-term impact and recovery trajectories of stream temperatures following forest harvest in different riparian management treatments. The long-term BACI experiment with varying harvest treatments revealed that stream temperatures responded rapidly to forest harvest in streams with less protective riparian management treatments and that impacts in these streams may have persisted for over 20 years. Following harvest, headwater stream temperatures warmed, thermal sensitivity increased, and the seasonality of stream temperatures shifted. This suggests that in the first decade post-harvest, streams were more sensitive to solar radiation in the spring and early summer and are warming earlier and for longer during the year. These initial impacts are broadly consistent with prior studies (e.g., Moore et al., 2005; Naman et al., 2024) and expand observations from a previous study in this watershed (Macdonald et al., 2003b). Following the initial impact period to 23-years post-harvest, impacted temperature metrics recovered toward pre-harvest levels.

Both immediate and long-term temperature impacts varied seasonally. Thermal sensitivity or the influence of solar radiation on water temperatures was highest in May – June during spring freshet and prior to “leaf on” period (June to early October), then declined into the autumn months. Increases in maximum summer temperatures can have large negative effects on fish and other organisms, thus are often the focus of stream temperature studies (Becker and Genoway, 1979; Richter and Kolmes, 2005; Bonacina et al., 2023). However, increases in stream temperatures during other times of the year may lead to substantial shifts in the timing of key life history events and ecological

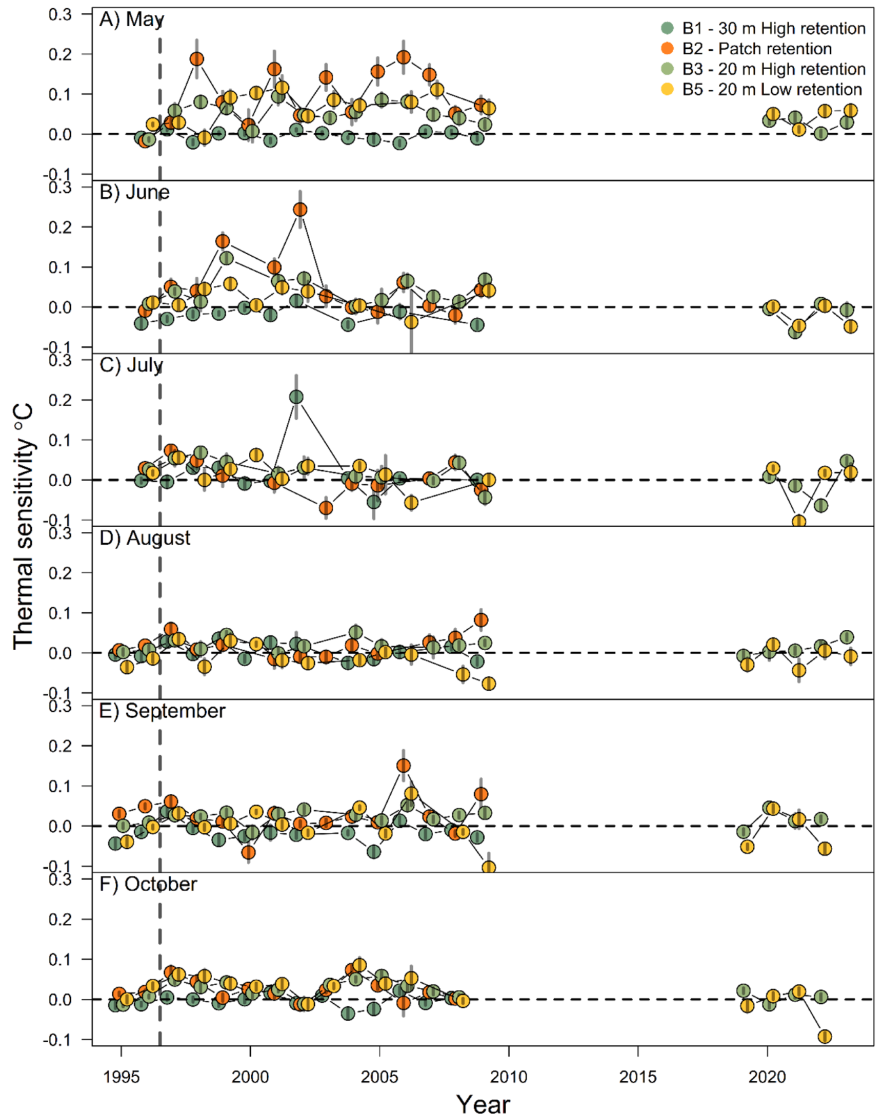

Fig. 6. Plot of slopes from regression models by year, month, and riparian treatment between May and October and 1995 and 2023 (A-F). Standardized slopes represent the effect of forestry on thermal sensitivity (i.e., the response of water temperature to a 1°C increase in air temperature). Vertical dashed line indicates when harvest occurred.

windows (Armstrong et al., 2021). Seasonal variation in the effects of forest harvest on stream temperature (Holtby, 1988) could lead to mismatch between different ecological and phenological processes such as changes in incubation rates, migration and emergence timing, and growth rates of fish.

Several mechanisms could explain the seasonal effect of forestry on stream temperatures. First, forest harvest increased solar radiation reaching the stream (Beschta, 1997; Groom et al., 2011). Harvest effects on solar radiation would be most pronounced prior to the leaf on period (May-June) and after leaves had fallen in October. Yet, while we observed similar thermal sensitivities between May and October during the pre-harvest period, thermal sensitivity values increased during May-June post-harvest while remaining low in October. Although increased solar radiation is likely the main mechanism responsible for the higher correlations between air temperature and water temperature it is insufficient to fully explain the seasonal patterns and hysteresis we observed (Janisch et al., 2012).

An additional mechanism that could help explain the lack of correlation between T_a and ΔT_w in July and August is change in the ratio of surface water to groundwater. Air temperature slopes were often near zero and sometimes negative in July and August, indicating that the effect of higher solar radiation in treatment sites compared to control sites during these months may be countered by higher ratios of groundwater (Caissie, 2006). The stabilizing effect of groundwater on stream temperatures could decouple the correlation between T_a and ΔT_w observed in other months when the contribution of surface water to stream flow is likely higher. This lack of stream temperature response to forest harvest has been observed in other systems where streams partially or full dried during the summer months (Janisch et al., 2012; Leach et al., 2022).

Previous studies have found T_w to be related to flow patterns (Janisch et al., 2012; Ulaski et al., 2023), whereby higher flows dominated by warm surface water overwhelmed the cooling effect of groundwater (Story et al., 2003). In the Baptiste watershed, Story et al. (2003) showed that stream temperatures declined when surface water was reduced and groundwater was the dominant source of stream water. A shift in the relative contribution of surface water to groundwater during the dry summer period could explain the low and sometimes negative thermal sensitivity values observed in July and August in this study (Webb et al., 2008; Moore et al., 2023). Furthermore, the variability in thermal sensitivity values were highest for these two months suggesting a strong annual effect of climate conditions that influence the ratio of surface

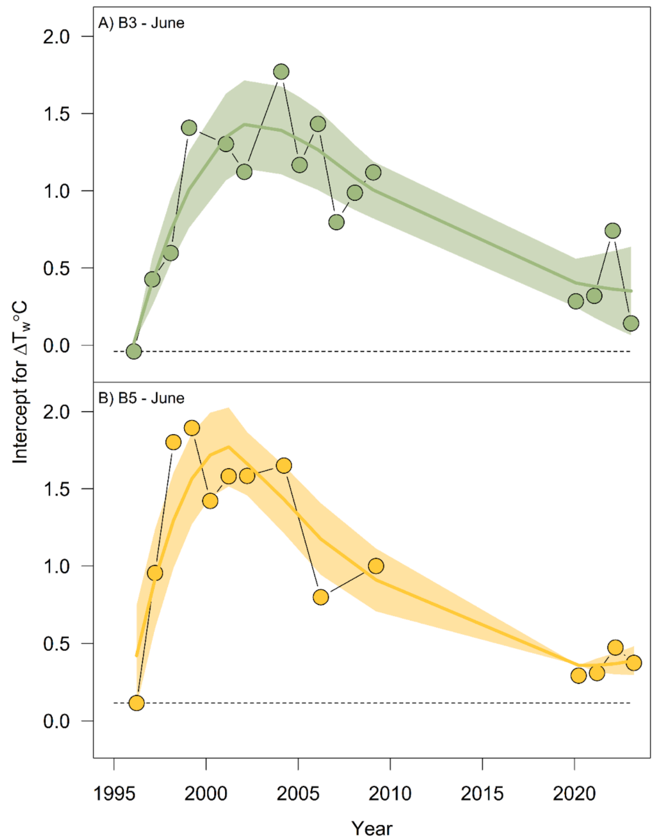

Fig. 7. Plot of intercepts from June regression models by year for (A) B3 and (B) B5 between 1996 and 2023. A LOWESS line is fit to the data to visualize the impact-recovery trajectory. The shaded area represents 1 standard deviation around the mean. Air temperature data are centered on the monthly mean for the time series so intercepts are comparable among years. The horizontal dashed line indicates the pre-harvest average ΔT_w (treatment minus control) for the average air temperature for June.

water to groundwater hydrology (e.g., snowpack and summer rainfall). We observed low flows and dry sections in streams during our site visits, suggesting a reduction in baseflow that may be related to higher water demands from forest regeneration (Gronsdahl et al., 2019). However, this interpretation is speculative given data on flow and groundwater were not available. More process-based studies are needed to better understand the role of surface-groundwater interactions in modulating forest harvest impacts and recovery trajectories.

The effects of forest harvest on stream temperatures observed in this study and in others should be considered in the larger context of climate change impacts on watershed hydrology. Climate impacts that act on stream hydrology by reducing surface water could show similarly low thermal sensitivity values, such that water temperatures appear to be insensitive to solar radiation and to a lesser degree high air temperatures. Low thermal sensitivity values during the summer months may indicate groundwater is buffering streams from the effects of solar radiation. However, if the relative contribution of surface water to stream flow continues to decrease (increasing the relative contribution of groundwater) (e.g., Moore et al., 2023), the risk of extreme low flows or dewatering would increase. In fact, we suggest that low thermal sensitivity values could be used as potential flags for low surface water inputs potentially increasing the risk of streams dewatering. The buffering potential of groundwater requires a more fulsome analysis of the interacting effects of hydrology, solar radiation, and air temperature on stream temperatures. We suggest research in this area focuses on developing a framework for assessing the risk of streams to climate change that considers thermal sensitivity across seasons in addition to absolute changes in peak water temperature metrics.

Another key result from this study was the effect of riparian management, which appeared to strongly modulate the magnitude of temperature responses. The least protective riparian management treatment (patch-retention) had the greatest increase in temperature, thermal sensitivity, and change in seasonality. In contrast, the most protective treatment (30 m buffer high-retention) showed minimal changes in all regression parameters (i.e., intercepts and slopes). This adds to a large body of evidence that adequate riparian management areas can be effective at reducing impacts of forest harvest on stream ecosystems (Richardson and Béraud, 2014; Jyväsjärvi et al., 2020) and more specifically stream thermal regimes (Moore et al., 2005; Gomi et al., 2006; Groom et al., 2011; Bladon et al., 2016). For example, Groom et al. (2011) and Bladon et al. (2016) both found that contemporary riparian management areas used in Oregon state forests led to no detectable changes in stream temperatures after forest harvest. However, it is important to note that while the direct impacts of forest harvest (i.e., increased solar radiation) may be mitigated by sufficient riparian management areas, smaller and lower retention riparian buffers are likely insufficient to minimize the impacts of forest harvest on stream temperatures. Rex et al. (2012) showed that the use of a 5 m variable retention buffer led to significant effects of forest harvest on stream temperatures. Furthermore, other forest harvest related impacts could indirectly affect stream temperatures and ecosystems through changes in hydrology (Janisch et al., 2012; Gronsdahl et al., 2019; Leach et al., 2022; Moore et al., 2023). Indeed, dry periods in the summer were observed in all streams exposed to forest harvest and in some cases prevented adequate temperature monitoring during the recovery period. The lack of long-term hydrology data prevents further evaluation of the impacts of forest harvest on flow levels in this headwater system.

Recovery of stream temperature from forest harvest is highly variable in western North America, ranging from a few years (Gomi et al., 2006) to decades (Johnson and Jones, 2000; Miller et al., 2017), reviewed in Moore et al. (2005). Variation in forest harvest practices, riparian buffers, forest type, and climate contribute to variability in the magnitude of the short-term temperature response to forest harvest and the number of years to recover to pre-harvest temperatures. For example, the use of different riparian buffers widths can result in different recovery times (Gomi et al., 2006). In a New Zealand study, stream size mediated thermal regime recovery times, whereby larger streams took longer to recover than smaller streams (Quinn and Wright-stow, 2008). Furthermore, it has been hypothesized that stream temperatures in harvested watersheds in northern and interior forests of British Columbia will take longer to recover to pre-harvest temperatures due to slower tree growth than in watersheds in more southern and coastal forest (Macdonald et al., 2003b; Rex et al., 2012). The recovery trajectory indicated by our analysis is consistent with this hypothesis. Recovery of water temperature in the Baptiste system appears to be substantially longer than the 10 years reported for many of the studies included in Moore et al. (2005), despite the return to near baseline riparian canopy cover levels observed earlier in the study.

There have been substantial efforts to mitigate the impacts of forest harvest, such as the development and study of riparian buffers around streams (Richardson et al., 2012); however, their efficacy and application often falls short of meeting their objective (Harding et al., 1998; Kuglerova et al., 2023). For example, in British Columbia there are no riparian reserves (i.e., no harvest zones) for small headwater streams (Kuglerova et al., 2020; Tschaplinski and Pike, 2017; BC Ministry of Forests, 1995) leaving larger downstream reaches vulnerable to increased warming as water travels through reaches with cleared riparian zones (Roon et al., 2021). Furthermore, riparian buffers can experience windthrow, reducing their effectiveness (Grizzel and Wolff, 1998). Windthrow events occurred at two of our study streams, one of which was a control site. Recognizing the limitations of our study, our results suggest that riparian buffers that are wider, longer, and retain a greater proportion of trees provide greater protection of stream temperatures from forest harvest relative to buffers that are narrower, shorter, and selectively harvested. Thermal sensitivity was also greater in harvested reaches with weaker riparian protections, meaning that stream reaches exposed to insufficient riparian protections may be disproportionately impacted by solar radiation and in part warming air temperatures associated with climate change. Thus, adequately sized and properly functioning riparian zones may act to buffer from the cumulative impacts of forestry and climate change.

Most studies of impacts of forest harvest on stream temperature tend to focus on summer temperatures that typically peak during July and August in western North America (Moore et al., 2005; Moore and MacDonlad, 2024; Naman et al., 2024). For example, in British Columbia, provincial water quality guidelines focus on maintaining mean weekly maximum temperatures below 18°C to protect fish (British Columbia Ministry of Environment and Climate Change Strategy, 2006). This however, ignores other potentially thermally sensitive times of year that may be important to fish and other organisms. To address this peak temperature bias, we assessed the effects of forest harvest on stream temperature across the growing season (i.e., when stream temperatures >1°C). We observed seasonal changes in the effects of forest harvest suggesting that the largest impacts on thermal sensitivity and the mean temperature were during May and June, which tend to be on the shoulder of the summer high temperatures. Miralha et al. (2024) also found strong seasonal variation in temperature responses to forest harvest in 18 headwater catchments in northern California. Although the largest responses were observed at different times of the year compared to our study, seasonal variation appears to be an important component to consider when assessing forestry impacts on stream temperature (Moore and MacDonlad, 2024). Our results suggest that focusing on peak summer temperatures would ignore the larger temperature effects from forest harvest in the Baptiste system, potentially underrepresenting the full scale of impacts from forest harvest on headwater stream thermal regimes. We suggest managers should consider how changes in land use can affect stream thermal regimes during the most thermally sensitive times of year, in addition to the timing and magnitude of peak temperatures

5. Conclusions

To understand the total impact of a given land use activity, the current state of each altered patch as it moves through the impact-recovery trajectory needs to be estimated. This study directly quantifies the impact-recovery of water temperatures through seasons and across a 23-year period post-harvest and is a first step in better quantifying the cumulative effects. Our results suggested a rapid response of stream temperature to forest harvest that was greatest with the least protective riparian management. We also found strong seasonal effects of harvest on stream temperature where the correlation between stream temperature and air temperature were strongest during the late spring. Stream temperatures from a single harvest event appear to be recovering 23-years post-harvest. By characterizing this impact-recovery trajectory one could estimate the cumulative effects of a mosaic of land use activity on a watershed (Coble et al., 2020; Reid, 1993). For example, the results from this study (Fig. 7) could be applied to a mosaic of riparian zone age or time since harvest to better quantify the cumulative impacts of forest harvest on stream temperatures within a catchment (see Coble et al., 2020 for example). However, similar to equivalent clear cut area (ECA) methods that incorporate recovery and are primarily applied at the stand-level (Reid, 1993), there is uncertainty in how these inferences scale up to whole watersheds (Zhang and Wei, 2012; Winkler and Boon, 2017) and apply across regions. An alternative approach could be to combine conceptual and empirical characterizations of downstream changes in stream temperatures from natural (e.g., Fullerton et al., 2015) and anthropogenic processes (e.g., Moore et al., 2005) to better estimate how temperatures in impacted reaches propagate downstream. Future studies should aim to combine the impact-recovery trajectory and variation in longitudinal stream temperatures to better characterize the cumulative effects of forestry at a watershed scale. This approach would link the results from small-scale process-based experimental studies to large-scale observational studies of stream temperature and forest harvest patterns that can inform regional scale management.

CRediT authorship contribution statement

Douglas C. Braun: Conceptualization, Data curation, Analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Dylan S. Cunningham:** Conceptualization, Data curation, Writing – review & editing. **Herb Herunter:** Data curation, Project administration, Writing – review & editing. **Sean M. Naman:** Methodology, Analysis, Writing – review & editing. **Amanda M. Martens:** Analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Steve Macdonald for his leadership in developing the Stuart-Takla Fish Forestry Program and oversight of the Baptiste headwater project as well as everyone that contributed to the Baptiste Watershed Project between 1995 and 2009. We are grateful for field assistance from Brittany Milner, David Patterson, and Kendra Robinson. We also thank DFO stock assessment staff for accommodations during field work. We thank Jonathan Moore and Daniel Moore for thoughtful reviews on previous drafts of this manuscript. This research was funded by DFO's SPERA and the Fisheries Act Renewal Programs. Earlier components of the research were funded by Forest Renewal BC.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122613.

Data availability

Data will be made available on request.

References

H.J. Andrews Experimental Forest, 2024. Long-term ecological research. Anon, https://andrewsforest.oregonstate.edu/ (accessed 21 August 2024).

Armstrong, J.B., Fullerton, A.H., Jordan, C.E., Ebersole, J.L., Bellmore, J.R., Arismendi, I., Penaluna, B.E., Reeves, G.H., 2021. The importance of warm habitat to the growth regime of cold-water fishes. Nat. Clim. Chang. 11, 354–361. https://doi.org/10.1038/s41558-021-00994-y.

BC Ministry of Forests. 1995. Riparian management area guidebook. Province of British Columbia, Victoria, BC. Available from 〈https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/silviculture/silvicultural-systems/silviculture-guidebooks/riparian-management-area-guidebook〉.

Becker, C.D., Genoway, R.G., 1979. Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. Env. Biol. Fish. 4, 245–256.

Bennett, A.F., Radford, J.Q., Haslem, A., 2006. Properties of land mosaics: implications for nature conservation in agricultural environments. Biol. Conserv. 133, 250–264.

Beschta, R.L., 1997. Riparian shade and stream temperature: an alternative perspective. Rangel 19, 25–28.

Bladon, K.D., Cook, N.A., Light, J.T., Segura, C., 2016. Forest ecology and management A catchment-scale assessment of stream temperature response to contemporary forest harvesting in the Oregon Coast Range. For. Ecol. Manag. 379, 153–164. https://doi.org/10.1016/j.foreco.2016.08.021.

Bonacina, L., Fasano, F., Mezzanotte, V., Fornaroli, R., 2023. Effects of water temperature on freshwater macroinvertebrates: as systematic review. Biol. Rev. 98, 191–221.

British Columbia Ministry of Environment and Climate Change Strategy. 2006. British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture -

Guideline Summary. Water Quality Guideline Series, WQG-20. Prov. B.C., Victoria B. C.
Caissie, D., 2006. The thermal regime of rivers: a review. Freshw. Biol. 51, 1389–1406. https://doi.org/10.1111/j.1365-2427.2006.01597.x.
Campbell, J.L., Rustad, L.E., Bailey, S.W., Bernhardt, E.S., Driscoll, C.T., Green, M.B., Groffman, P.M., Lovett, G.M., McDowell, W.H., McGuire, K.J., Rosi, E.J., 2020. Watershed studies at the Hubbard Brook Experimental Forest: Building on a long legacy of research with new approaches and sources of data. Hydrol. Process. e14016. https://doi.org/10.1002/hyp.14016.
Coble, A.A., Barnard, H., Du, E., Johnson, S., Jones, J., Keppeler, E., Kwon, H., Link, T.E., Penaluna, B.E., Reiter, M., River, M., Puettmann, K., Wagenbrenner, J., 2020. Long-term hydrological response to forest harvest during seasonal low flow: Potential implications for current forest practices. Sci. Total Environ. 730, 138926.
Cunningham, D.S., Braun, D.C., Herunter, H., Macdonald, J.S., 2023. Environmental datasets from the stuart- takla fish-forestry interaction project: baptiste watershed from 1995 to 2009. Can. Tech. Rep. Fish. Aquat. Sci. 3585 v + 52p.
Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. Geomorphol 338, 88–104.
Downs, P.W., Dusterhoff, S.R., Sears, W.A., 2013. Geomorphology reach-scale channel sensitivity to multiple human activities and natural events: Lower Santa Clara River, California, USA. Geomorphol 189, 121–134. https://doi.org/10.1016/j.geomorph.2013.01.023.
Fullerton, A.H., Torgersen, C.E., Lawler, J.J., Faux, R.N., Steel, E.A., Beechie, T.J., Ebersole, J.L., Leibowitz, S.G., 2015. Rethinking the longitudinal stream temperature paradigm: region-wide comparison of thermal infrared imagery reveals unexpected complexity of river temperatures. Hydrol. Process. 29, 4719–4737. https://doi.org/10.1002/hyp.10506.
Gomi, T., Moore, R.D., Dhakal, A.S., 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada. W08437 Water Resour. Res. 42. https://doi.org/10.1029/2005WR004162.
Grant, G.E., Lewis, S.L., Swanson, F.J., Cissel, J.H., McDonnell, J.J., 2008. Effects of forest practices on peak flows and consequent channel response: a state-of-science report for western Oregon and Washington. USDA For. Serv. Gen. Tech. Rep. PNW-GTR 760, 1–82. https://doi.org/10.2737/PNW-GTR-760.
Grizzel, J.D., Wolff, N., 1998. Occurrence of windthrow in forest buffer strips and its effect on small streams in northwest Washington. Northwest Sci. 72, 214–223.
Gronsdahl, S., Moore, R.D., Rosenfeld, J., McCleary, R., Winkler, R., 2019. Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific Northwest. Hydrol. Process. 33, 3152–3168. https://doi.org/10.1002/hyp.13580.
Groom, J.D., Dent, L., Madsen, L.J., Fleuret, J., 2011. Response of western Oregon (USA) stream temperatures to contemporary forest management. For. Ecol. Manag. 262, 1618–1629. https://doi.org/10.1016/j.foreco.2011.07.012.
Harding, J.S.H., Benfield, E.F.B., Bolstad, P.V.B., Helfman, G.S.H., Jones, E.B.D., 1998. Stream biodiversity: the ghost of land use past. Proc. Natl. Acad. Sci. USA 95, 14843–14847. https://doi.org/10.1073/pnas.95.25.14843.qq.
Holtby, B.L., 1988. Effects of logging on stream temperature in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Onchorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 45, 502–515.
Isaak, D.J., Wenger, S.J., Peterson, E.E., Ver Hoef, J.M., Nagel, D.E., Luce, C.H., Hostetler, S.W., Dunham, J.B., Roper, B.B., Wollrab, S.P., Chandler, G.L., Horan, D. L., Parkes-Payne, S., 2017. The NorWeST summer stream temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resour. Res. 53, 9181–9205. https://doi.org/10.1002/2017WR020969.
Janisch, J.E., Wondzell, S.M., Ehinger, W.J., 2012. Headwater stream temperature: interpreting response after logging, with and without riparian buffers, Washington, USA. For. Ecol. Manag. 270, 302–313. https://doi.org/10.1016/j.foreco.2011.12.035.
Johnson, S.L., 2003. Stream temperature: scaling of observations and issues for modelling. Hydrol. Process. 17, 497–499.
Johnson, S.L., Jones, J.A., 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. Sci. 57 (. 2), 30–39. https://doi.org/10.1139/f00-109.
Jyväsjärvi, J., Koivunen, I., Muotka, T., 2020. Does the buffer width matter: testing the effectiveness of forest certificates in the protection of headwater stream ecosystems. For. Ecol. Manag. 478, 118532. https://doi.org/10.1016/j.foreco.2020.118532.
Kelly, J.R., Harwell, M.A., 1990. Indicators of ecosystem recovery. Environ. Manag. 14, 527–545.
Kuglerová, L., Jyväsjärvi, J., Ruf, C., Muotka, T., Jonsson, A., 2020. Cutting edge: a comparison of contemporary practices of riparian buffer retention around small streams in Canada, Finland, and Sweden. Water Resour. Res. 56, e2019WR026381. https://doi.org/10.1029/2019WR026381.
Kuglerová, L., Muotka, T., Chellaiah, D., Jyväsjärvi, J., Richardson, J.S., 2023. Protecting our streams by defining measurable targets for riparian management in a forestry context. J. Anim. Ecol. 00, 1–9. https://doi.org/10.1111/1365-2664.14549.
Leach, J.A., Hudson, D.T., Moore, R.D., 2022. Assessing stream temperature response and recovery for different harvesting systems in northern hardwood forests using 40 years of spot measurements. Hydrol. Proc. 36, e14753. https://doi.org/10.1002/hyp.14753.
Leach, J.A., Kelleher, C., Kurylyk, B.L., Moore, R.D., Neilson, B.T., 2023. A primer on stream temperature processes. WIREs Water 10, e1643. https://doi.org/10.1002/wat2.1643.
Luce, C., Staab, B., Kramer, M., Wenger, S., Isaak, D., McConnell, C., 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. Water Resour. Res. 50, 3428–3443. https://doi.org/10.1002/2013WR014329.
Macdonald, J.S. 1994. Proceedings of the Takla Fishery/Forestry Workshop: A Two Year Review April 1, 1993, Prince George, B.C. Can. Tech. Rep. Fish. Aquat. Sci. 2007, 104 p.
Macdonald, J.S., Scrivener, J.C., Smith, G., 1992. The Stuart-Takla fisheries/forestry interaction project: study description and design. Can. Tech. Rept. Fish. Aquat. Sci. 1899, 39.
Macdonald, J.S., MacIsaac, E.A., Herunter, H.E., 2003b. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. Can. J. For. Res. 33, 1371–1382. https://doi.org/10.1139/x03-015.
Macdonald, J.S., Beaudry, P.G., MacIsaac, E.A., Herunter, H.E., 2003a. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. Can. J. For. Res. 33, 1397–1407. https://doi.org/10.1139/X03-110.
MacIsaac, E.A., 2003. Forestry impacts on fish habitat in the northern interior of British Columbia: a compendium of research from the Stuart-Takla Fish-Forestry Interaction Study. Can. Tech. Rep. Fish. Aquat. Sci. 2509 v + 266p.
McKendry, I.G., Christen, A., Lee, S.C., Ferrara, M., Strawbridge, K.B., O'Neill, N., Black, A., 2019. Impacts of an intense wildfire smoke episode on surface radiation, energy and carbon fluxes in southwestern British Columbia, Canada. Atmos. Chem. Phys. 19, 835–846. https://doi.org/10.5194/acp-19-835-2019.
Miller, S.A., Gordon, S.N., Eldred, P., Beloin, R.M., Wilcox, S., Raggon, M., Andersen, H., and Muldoon, A. 2017. Northwest Forest Plan The First 20 Years (1994-2013): Watershed Condition Status and Trend. Portland, Oregon.
Miralha, L., Wissler, A.D., Bladon, K.D., 2023. Characterizing stream temperature hysteresis in forested headwater streams. Hydrol. Process. 37, e14795. https://doi.org/10.1002/hyp.14795.
Miralha, L., Segura, C., Bladon, K.D., 2024. Stream temperature responses to forest harvesting with different riparian buffer prescriptions in northern California, USA. For. Ecol. Manag. 552, 121581. https://doi.org/10.1016/j.foreco.2023.121581.
Mohseni, O., Stefan, H.G., 1999. Stream temperature/air temperature relationship: a physical interpretation. J. Hydrol. 2019, 128–144.
Mohseni, O., Erickson, T.R., Stefan, H.G., 1999. Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resour. Res. 35, 3723–3733.
Moore, R.D., MacDonlad, R.J., 2024. JAMES BUTTLE REVIEW quantifying the influence of forestry and forest disturbance on stream temperature: methodologies and challenges. Hydrol. Process. 38, e15223. https://doi.org/10.1002/hyp.15223.
Moore, R.D., Spittlehouse, D.L., Story, A., 2005. Riparian microclimate and stream temperature response to forest harvesting: a review. J. Am. Water Resour. Assoc. 41, 813–834.
Moore, R.D., Nelitz, M., Parkinson, E., 2013. Empirical modelling of maximum weekly average stream temperature in British Columbia, Canada, to support assessment of fish habitat suitability. Can. Water Resour. J. 38, 135–147. https://doi.org/10.1080/07011784.2013.794992.
Moore, R.D., Guenther, S.M., Gomi, T., Leach, J.A., 2023. Headwater stream temperature response to forest harvesting: do lower flows cause greater warming? Hydrol. Process. 37, e15025. https://doi.org/10.1002/hyp.15025.
Múrias, T., Ribeiro, S.B., Lomba, A., Ferrand De Almeida, F., 2023. Mind the gap: exploring the usefulness of historical data to assess the impacts of land-use change on bird diversity in a farmland mosaic of Northeastern Portugal (1980-2000, 11.10.566211;doi: bioRxiv https://doi.org/10.1101/2023.11.10.566211.
Naman, S.M., Pitman, K.J., Cunningham, D.S., Potapova, A., Chartrand, S.M., Sloat, M. R., Moore, J.W., 2024. Forestry impacts on stream flows and temperatures: a quantitative synthesis of paired catchment studies across the Pacific salmon range. Ecol. Solut. Evid. 5, e12328. https://doi.org/10.1002/2688-8319.12328.
Neary, D.G., 2016. Long-term forest paired catchment studies: what do they tell us that landscape-level monitoring does not? Forests 7, 1–15. https://doi.org/10.3390/f7080164.
Northrop, A.C., Ballif, B.A., 2021. Clockwise and counterclockwise hysteresis characterize state changes in the same aquatic ecosystem. Ecol. Lett. 24, 94–101. https://doi.org/10.1111/ele.13625.
Quinn, J.M., Wright-stow, A.E., 2008. Stream size influences stream temperature impacts and recovery rates after clearfell logging. For. Ecol. Manag. 256, 2101–2109. https://doi.org/10.1016/j.foreco.2008.07.041.
Reid, L.M. 1993. Research and cumulative watershed effects. U.S. Dep. watershed effects. U.S. Dep. watershed effects. U.S. Dep. watershed effects. U.S. Dep. Agric. For. Serv., Albany, Calif. Gen. Tech. Rep. PSW-GTR-141.
Reid, D.A., Hassan, M.A., 2020. Response of in-stream wood to riparian timber harvesting: Field observations and long-term projections. Water Resour. Res. 56 e2020WR027077. https:// doi.org/10.1029/2020WR027077.
Rex, J.F., Maloney, D.A., Krauskopf, P.N., Beaudry, P.G., Beaudry, L.J., 2012. Variable-retention riparian harvesting effects on riparian air and water temperature of sub-boreal headwater streams in British Columbia. For. Ecol. Manag. 269, 259–270. https://doi.org/10.1016/j.foreco.2011.12.023.
Richardson, J.S., Béraud, S., 2014. Effects of riparian forest harvest on streams: a meta-analysis. J. Appl. Ecol. 51, 1712–1721. https://doi.org/10.1111/1365-2664.12332.
Richardson, J.S., Naiman, R.J., Bisson, P.A., 2012. How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices? Freshw. Sci. 31, 232–238. https://doi.org/10.1899/11-031.1.
Richardson, P.W., Cafferata, P.H., Dymond, S.F., Keppeler, E.T., Wagenbrenner, J.W., Whiting, J.A., 2023. Past and future roles of paired watersheds: a North American

inventory and anecdotes from the Caspar Creek Experimental Watersheds. Front. For. Glob. Change 6, 1275392. https://doi.org/10.3389/ffgc.2023.1275392.
Richter, A., Kolmes, S.A., 2005. Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. Rev. Fish. Sci. 13, 23–49. https://doi.org/10.1080/10641260590885861.
Roon, D.A., Dunham, J.B., Torgersen, C.E., 2021. A riverscape approach reveals downstream propagation of stream thermal responses to riparian thinning at multiple scales. Ecosphere 12, e03775. https://doi.org/10.1002/ecs2.3775.
Schielzeth, H., 2010. Simple means to improve the interpretability of regression coefficients. Methods Ecol. Evol. 1, 103–113. https://doi.org/10.1111/j.2041-210X.2010.00012.x.
Segura, C., Bladon, K.D., Hatten, J.A., Jones, J.A., Hale, V.C., Ice, G.G., 2020. Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. J. Hydrol. 585, 124749. https://doi.org/10.1016/j.jhydrol.2020.124749.
Smokorowski, K.E., Randall, R.G., 2017. Cautions on using the before-after-control-impact design in environmental effects monitoring programs. Facet 2, 212–232. https://doi.org/10.1139/facets-2016-0058.
Som, N.A., Zégre, N.P., Ganio, L.M., Skaugset, A.E., 2012. Corrected prediction intervals for change detection in paired watershed studies. Hydrol. Sci. J. 57, 134–143. https://doi.org/10.1080/02626667.2011.637494.
Story, A., Moore, R.D., Macdonald, J.S., 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. Can. J. For. Res. 33, 1383–1396. https://doi.org/10.1139/X03-087.
Summers R.P. 1982. Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds. Master's thesis. Oregon State University. ⟨https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/4j03d2047?locale=en⟩.
Tschaplinski, P.J., Pike, R.G., 2017. Carnation Creek watershed experiment—long-term responses of coho salmon populations to historic forest practices. Ecohydrol 10, e1812. https://doi.org/10.1002/eco.1812.
Ulaski, M.E., Warkentin, L., Naman, S.M., Moore, J.W., 2023. Spatially variable effects of streamflow on water temperature and thermal sensitivity within a salmon-bearing watershed in interior British Columbia, Canada. River Res. Appl. 1–12. https://doi.org/10.1002/rra.4200.
Webb, B.W., Hannah, D.M., Moore, R.D., Brown, L.E., Nobilis, F., 2008. Recent advances in stream and river temperature research. Hydrol. Process. 22, 902–918. https://doi.org/10.1002/hyp.6994.
Wilson, K.L., Bailey, C.J., Davies, T.D., Moore, J.W., 2022. Marine and freshwater regime changes impact a community of migratory Pacific salmonids in decline. Glob. Chang. Biol. 28, 72–85. https://doi.org/10.1111/gcb.15895.
Winkler, R., and Boon, S. 2017. Equivalent clearcut area as a n indicator of hydrologic change in snow-dominated watersheds of southern British Columbia. Prov. B.C., Victoria, B.C. Exten. Note 118. ⟨www.for.gov.bc.ca/hfd/pubs/Docs/En/En118.htm⟩.
Winkler, R.D., Allen, D.M., Giles, T.R., Heise, B.A., Moore, R.D., Redding, T.E., Spittlehouse, D.L., Wei, X., 2021. Hydrol. Process. 35, e14123. https://doi.org/10.1002/hyp.141237.
Zhang, M., Wei, X., 2012. The effects of cumulative forest disturbance on streamflow in a large watershed in the central interior of British Columbia, Canada. Hydrol. Earth Syst. Sci. 16, 2021–2034. https://doi.org/10.5194/hess-16-2021-2012.