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A riverscape approach reveals downstream propagation of stream thermal responses to riparian thinning at multiple scales

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Abstract. Hydrological connectivity in river networks influences their response to environmental changes as local effects may extend downstream via flowing water. For example, localized changes in riparian forest conditions can affect stream temperatures, and these effects may propagate downstream. However, studies evaluating stream temperature responses to riparian forest management have not considered cumulative effects across entire watersheds. Improved understanding at these scales is needed because land managers are increasingly required to consider broad-scale consequences of their actions. To address this question, we deployed a high-density network of sensors across watersheds to examine stream temperature responses to experimental thinning of riparian forests. A riverscape approach that combined high-resolution data throughout the study watersheds made it possible to examine local and downstream patterns of stream temperature at multiple spatial and temporal scales. We found that local responses of temperature to thinning varied widely depending on the intensity of thinning treatments. Downstream propagation of local responses extended from 100 m to over 1000 m and depended on the magnitude of the local response. We characterized these responses as a series of waveforms. In the watersheds with more intensive thinning, thermal responses occurred most often as an extended pulse where downstream increases in temperature attenuated gradually at variable distances. Although we observed no evidence of cumulative effects associated with thinning at the downstream extent of stream networks, effects emerged where thinning treatments were closely spaced (<400 m apart) and local warming did not dissipate with downstream distance. In a watershed with less intensive thinning, there was either no response or a localized pulse with no downstream propagation. Collectively, these patterns suggest that riparian forest thinning influenced downstream thermal conditions to varying extents depending on the intensity, scale, and spatial proximity of treatments. We found that a multiscale riverscape approach and conceptual framework based on contrasting waveforms provided a foundation for understanding the cumulative watershed effects of riparian thinning. The approach developed here can be adapted more broadly when evaluating downstream propagation of local changes in river networks and has direct implications for guiding restoration in riparian ecosystems.

Key words: coast redwood forests; cumulative effects; downstream propagation; forest restoration; northern California; riparian thinning; riverscape; spatiotemporal variability; stream temperature; watershed; waveform analysis.

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Introduction

Cumulative effects in watersheds emerge from the interaction of multiple land uses that affect upslope, riparian, and in-stream processes (Reid 1998, Seitz et al. 2011, Erdozain et al. 2021). Such effects differ from other systems (e.g., terrestrial, marine) because they can propagate downstream via flowing water. To better understand and effectively manage cumulative watershed effects, it is important to extend the scales of analysis beyond potentially affected locations and consider broader spatial extents (Reid 1998, Allan 2004).

Advances in the landscape ecology of stream networks, or riverscape ecology (sensu Fausch et al. 2002, Wiens 2002), offer insights for improving understanding of cumulative watershed effects across broader scales. Stream ecosystems have traditionally been viewed as continua that gradually change in a downstream direction (Vannote et al. 1980, Fullerton et al. 2015). However, streams often display extensive spatial variability that is better described as a mosaic of patches rather than continuous longitudinal gradients (Pringle et al. 1988, Townsend 1989, Poole 2002). A riverscape perspective characterizes this variability continuously in space and time across multiple scales (Fausch et al. 2002, Lowe et al. 2006). As a result, the concept of riverscapes builds on earlier models of stream ecosystems to incorporate additional complexity that emerges from considering multiple scales, hydrological connectivity, and heterogeneity in processes among locations that collectively control stream function and response to human activities (Fausch et al. 2002, Allan 2004, Humphries et al. 2014). Although riverscape ecology has provided key conceptual and theoretical advances, application of these ideas in practice has proven more challenging (Carbonneau et al. 2012).

Thermal regimes of riverscapes drive ecological processes and are a primary factor influencing the decline of threatened cold-water-adapted species (Magnuson et al. 1979, Poole and Berman 2001, Poole et al. 2004, McCullough et al. 2009). Advances in understanding stream temperature across riverscapes stem from improved methods for quantifying spatial and temporal variability with remote sensing (Torgersen et al. 1999, Dugdale et al. 2016) and digital temperature data loggers (Dunham et al. 2005). Process-based heat budget models elucidate the energetic drivers of thermal regimes (Johnson 2004, Dugdale et al. 2017) but are data-intensive and, therefore, difficult to employ over broad spatial scales (Wondzell et al. 2019). Spatial stream network models account for network structure and spatial autocorrelation over broad scales and have greatly improved understanding of thermal regimes in riverscapes (Isaak et al. 2014, Fullerton et al. 2018, Gendaszek et al. 2020). However, the cumulative watershed effects of land use on stream thermal conditions remain difficult to quantify and predict (Steel et al. 2017, Ouellet et al. 2020, Erdozain et al. 2021).

Cumulative watershed effects of land use on thermal regimes in streams are well recognized (Poole and Berman 2001). For example, forest harvest can increase stream temperatures locally and downstream (Moore et al. 2005). Although downstream effects of forest harvest are of interest to managers (Beschta et al. 1987, Zwieniecki and Newton 1999, Johnson 2004, Moore et al. 2005), the spatial extent of downstream effects is highly context-dependent and logistically challenging to quantify. Previous research has focused on local responses conducted at small spatial extents (e.g., Groom et al. 2011). When downstream effects have been considered, they were either limited to conditions immediately downstream from treatment locations (e.g., Arismendi and Groom 2019), or much farther downstream (e.g., >1 km) likely beyond the spatial extent of the treatment effect (e.g., Bladon et al. 2018). New approaches are needed to continuously track longitudinal thermal patterns over broader spatial extents at the scale of entire watersheds to describe cumulative watershed effects in relation to forest harvest. Applying a riverscape approach over large spatial extents at high resolutions may more effectively capture such variability.

Here, we address the question of how thinning second-growth riparian forests influences local and downstream stream temperatures at watershed extents. Thinning riparian forests has been proposed in the temperate forests in the Pacific coastal ecoregion of western North America as a restoration strategy for second-growth forests (Berg 1995, Russell 2009, Keyes and Teraoka 2014). Resource managers in the coastal redwood

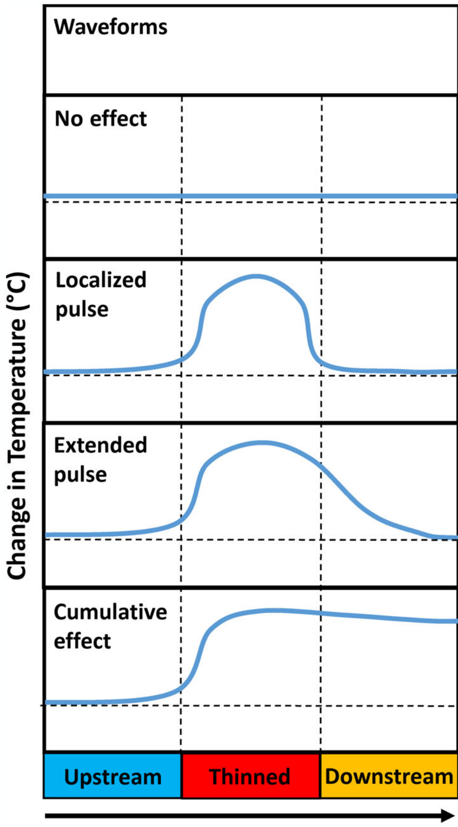
(*Sequoia sempervirens*) forests of northern California are currently evaluating thinning of second-growth riparian forests to (1) accelerate the recovery of late-successional forest structure and composition; (2) increase stand heterogeneity; (3) provide a future source of large wood for structuring instream habitats; and (4) increase aquatic biodiversity and productivity (O'Hara et al. 2010, Teraoka and Keyes 2011, Pollock et al. 2014, Benda et al. 2016, Reeves et al. 2016, Wohl et al. 2019). However, forest harvest can affect stream temperatures (Moore et al. 2005), so it is important to understand the local and downstream thermal effects associated with proposed riparian thinning actions.

In this study, we applied a riverscape approach to evaluate the cumulative watershed effects of riparian forest thinning on stream thermal regimes at multiple spatiotemporal scales. We used a large-scale manipulative field experiment, in which patches of riparian forest were experimentally thinned along 10 stream reaches distributed across three watersheds located in coastal northern California. We combined this approach with a dense network of temperature sensors positioned upstream and downstream of each experimental thinning treatment reach as well as systematically every ~200 m through each watershed. Then, by collecting data before and after experimental thinning treatments, we addressed four objectives: (1) quantify pretreatment spatial and temporal variability in stream temperature conditions; (2) evaluate local responses in stream temperature to riparian thinning; (3) assess the spatial extent and temporal duration of downstream effects to local responses in temperature; and (4) characterize local and downstream responses to thinning with a conceptual framework based on waveforms (sensu Humphries et al. 2014).

Conceptual Framework

Stream thermal regimes are a product of multiple energetic processes that influence the gain or loss of heat (Johnson 2004, Caissie 2006). While there are many energetic processes that influence stream thermal regimes, here we focused on two primary drivers of local and downstream temperature conditions in smaller streams: radiative and advective processes. Systematic reviews by Johnson (2004), Moore et al. (2005), Caissie (2006), and Dugdale et al. (2017) provided the context on which we based our understanding of radiative and advective processes and the potential interacting factors (Appendix S1: Table S1). In small, low-order streams, solar radiation is typically the primary input of heat and is regulated by riparian vegetation and topography (Johnson 2004, Moore et al. 2005, Caissie 2006). Variation in riparian forest conditions can result in local increases in stream temperature via radiative processes (Moore et al. 2005, Dugdale et al. 2017). In lotic systems, these local increases in temperature can propagate longitudinally farther downstream via advective processes (i.e., surface or subsurface streamflow; Moore et al. 2005). To quantify how thinning in riparian zones may affect local and downstream thermal conditions, we used a conceptual framework that illustrates alternative scenarios of local radiative and longitudinal advective energetic processes. We applied this framework to evaluate cumulative watershed effects and test hypotheses about how local changes in stream temperature associated with thinning propagate downstream through stream networks.

We hypothesized that local and downstream thermal responses occur as a series of waveforms (Humphries et al. 2014) that vary in shape depending on the relative strength of local radiative and longitudinal advective processes (Fig. 1). We generalized these as four categories of response. Local responses depend on sufficient increases in radiative energy to increase stream temperatures; therefore, minor local reductions in shade may result in no effect. More intensive changes in radiative energy may result in a localized pulse but not extend downstream if advective processes are truncated, for example, during periods of low flow (Gendaszek et al. 2020). However, if advective processes are present, local responses may propagate downstream following different trajectories. Moore et al. (2005) and others have suggested that downstream effects eventually dissipate as an extended pulse due to reduced inputs of radiative energy or mediation by cold-water tributaries or upwelling groundwater (Story et al. 2003, Moore et al. 2005, Garner et al. 2014, Davis et al. 2016). However, if increases in temperature remain elevated or do not have sufficient time or space to dissipate



Waveforms	Local Response (Radiative)	Downstream Response (Advective)	Possible Mechanisms
No effect	**No**	**No**	If a local increase in radiative energy is minor, the local or downstream response may not be apparent.
Localized pulse	**Yes**	**No**	Local response occurs via radiative processes, but there may be no downstream response because advective processes are truncated, possibly due to low flow or upwelling groundwater.
Extended pulse	**Yes**	**Yes**, but eventually dissipates	Advective processes (i.e., discharge) transport heat pulse downstream, but heat dissipates due to reduced rate of solar heating, groundwater, or tributary inputs.
Cumulative effect	**Yes**	**Yes**, but remains elevated	Water temperature remains elevated downstream due to insufficient time or space for radiative and advective processes to dissipate heat (e.g., stream flows through another patch of riparian thinning).

Fig. 1. Four conceptual models for how local changes in temperature associated with riparian thinning propagate downstream. Potential waveforms (far left panels) illustrate different local and downstream thermal responses associated with a patch of riparian thinning and mechanisms via local radiative and longitudinal advective energetic processes.

before the water flows through another patch of thinning, then downstream thermal increases may accumulate as a cumulative effect (Reid 1998).

Methods

Study area

The study area encompassed three watersheds in the redwood forests of coastal northern California (USA) (Fig. 2). Two watersheds (west and east forks of Tectah Creek) occurred on private timberland owned by Green Diamond Resource Company, and the third watershed (Lost Man Creek) occurred in Redwood National Park. The three study systems consisted of small watersheds (5.8–8.4 km^2) drained by steep, low-order perennial streams (bankfull widths: 3.2–6.6 m) that are located within 15 km of the Pacific Ocean and experience a cool, maritime climate (Welsh et al. 2000, Lorimer et al. 2009). Riparian forests within these watersheds consist of second-growth forests regenerated from timber harvest 40–60 yr ago and include a mix of coast redwood, red alder (*Alnus rubra*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), tanoak (*Notholithocarpus densiflorus*), western red cedar (*Thuja plicata*), and vine maple (*Acer circinatum*). Stream channels in these systems are heavily shaded by riparian forests with little longitudinal variation (mean canopy closure: 94.3 ± 1.3% standard deviation). These watersheds support resident populations of coastal cutthroat trout (*Oncorhynchus clarkii clarkii*), coastal giant salamander (*Dicamptodon tenebrosus*), and coastal tailed frog (*Ascaphus truei*), all of which are cold-water-adapted and sensitive to changes in temperature (Huff et al. 2005).

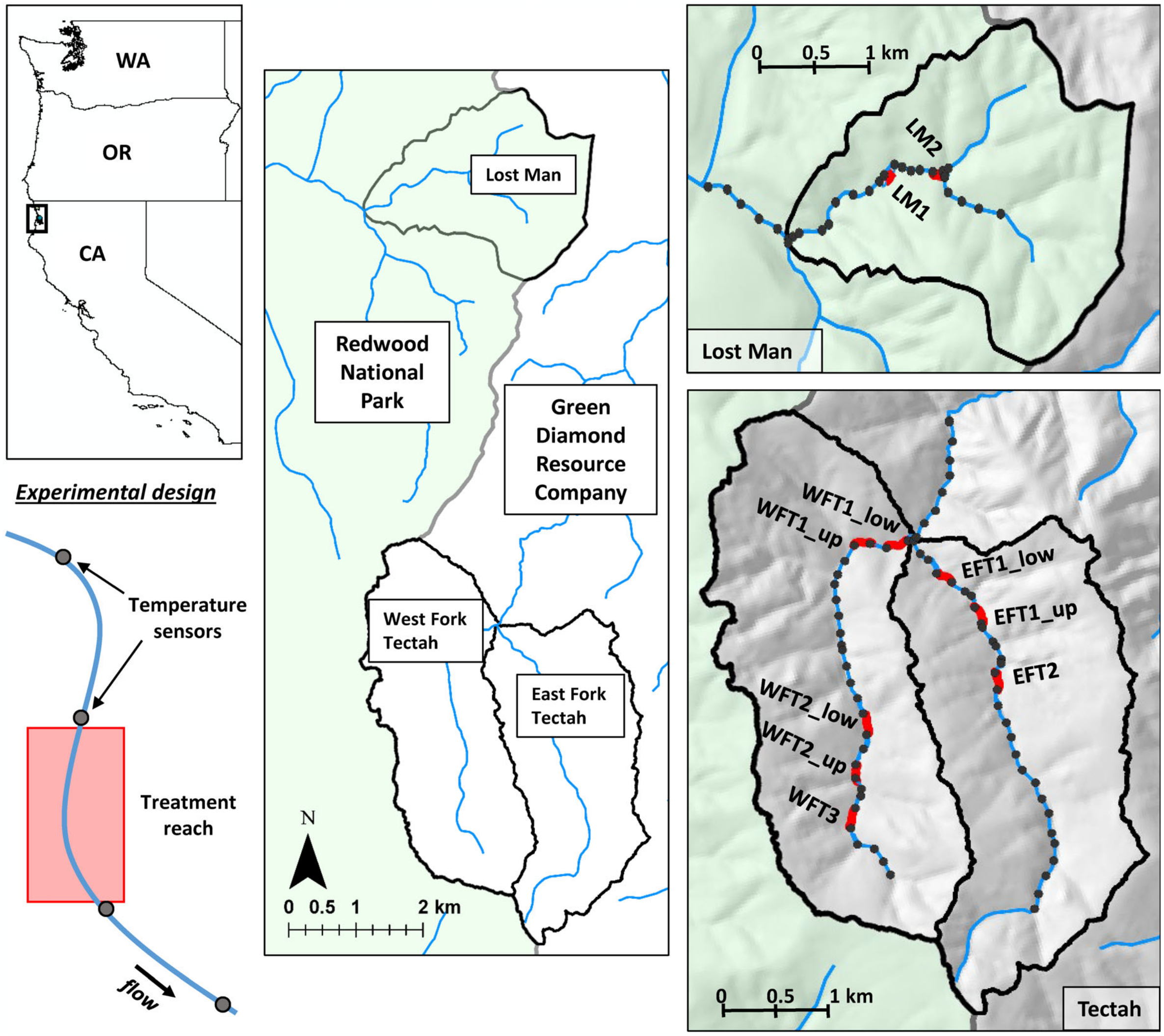


Fig. 2. Study watersheds, treatment reaches, and experimental design in northern California (USA). Experimental riparian thinning treatments occurred along 100–200-m reaches of stream in 10 locations distributed across three watersheds. Abbreviated names and red lines on maps indicate the position of treatment reaches in study watersheds. See Table 1 for physical characteristics of treatment reaches and *Methods: Experimental design* for description of treatment reach abbreviations. Points indicate the positions of temperature sensors (n = 100) deployed at upstream and downstream extents of treatment reaches as well as systematically every ~200 m through each study watershed. The high-density sampling design was used to quantify spatial variability, local temperature responses associated with thinning, and downstream propagation of local responses. Data were collected before and after experimental thinning treatments during pre-treatment (2016) and post-treatment years (2018).

Experimental design

Experimental thinning of riparian forests and monitoring of water temperature were implemented across the three study watersheds following a before–after–control–impact (BACI) design (Fig. 2). We collected pre-treatment data in 2016, experimental thinning treatments occurred in 2017, and then, we collected post-treatment data in 2018. Riparian forests were experimentally thinned in 10 treatment reaches across the three watersheds (Table 1). Treatment reach identifiers corresponded to their watershed (West Fork Tectah = WFT, East Fork Tectah = EFT, Lost Man = LM) and the number of thinning treatments in each watershed (e.g., LM1). In the Tectah watersheds, multiple thinning treatments sometimes occurred adjacent to a single harvest unit and were assigned a lower or upper designation (e.g., WFT1_low, WFT1_up). Although this study consisted of three watersheds and 10 treatment reaches, we considered the reaches individually and collectively to better understand how site and treatment heterogeneity may affect thermal responses at local and watershed extents.

Thinning treatment prescriptions varied between landowners to meet their respective management objectives. Thinning treatments in the Tectah watersheds on Green Diamond Resource Company property took place as part of a larger riparian canopy experiment approved by Green Diamond's Aquatic Habitat Conservation Plan that allows for experimental harvests for research purposes (Green Diamond Resource Company 2016). Thinning treatment prescriptions in the Tectah watersheds were intended to reduce canopy closure within the riparian zone by 50% on both sides of the active stream channel along a 200-m reach. Thinning treatments bordered upslope timber harvest units and targeted red alder and some conifer depending on the density and composition of the stand. In all treatment reaches, larger conifers were left intact as they are anticipated to contribute large wood in riparian zones and in streams. Trees were removed from the riparian zone via cable yarding. Non-thinned reaches adjacent to the harvest units were protected by Green Diamond's standard riparian buffer prescription that consisted of a single-sided 45-m wide buffer with a 22.5-m wide inner zone of 85% canopy retention and 22.5-m wide outer zone of 70% canopy retention (Green Diamond Resource Company 2006). An analysis of buffered reaches relative to intact forest reference reaches documented no difference in riparian shade, light, and stream temperature conditions between buffer types (Roon et al. 2021).

Thinning treatments in the Lost Man watershed in Redwood National Park coincided with a larger restoration thinning effort intended to promote late-successional coastal redwood forests and increase stand heterogeneity in the middle fork of the Lost Man Creek watershed (Teraoka and Keyes 2011, Redwood National Park 2014). Restoration thinning previously targeted upland forests, but now National Park managers are interested in thinning second-growth forests within the riparian zone (Redwood National Park 2014). Riparian thinning treatment prescriptions reduced basal area by up to 40% on both sides of the active stream channel along a 100–

Table 1. Physical characteristics for experimental thinning treatment reaches nested within study watersheds.

Watershed	Watershed area (km^2)	Treatment reach	Watershed position (m)	Treatment reach length (m)	Mean bankfull width (m)	Change in riparian shade (%)	Change in light (%)	Local change in summer MWMT (°C)
West Fork Tectah (GD)	8.4	WFT1_low	140	225	6.6	−25.5	34.8	3.6
		WFT1_up	535	175	6.0	−24.0	32.8	2.1
		WFT2_low	2750	205	4.7	−26.2	26.4	3.5
		WFT2_up	3320	195	3.7	−27.2	32.6	4.2
		WFT3	3840	220	3.2	−23.6	18.2	2.7
East Fork Tectah (GD)	7.8	EFT1_low	450	195	5.3	−19.8	21.8	2.8
		EFT1_up	990	170	6.1	−19.2	18.7	1.8
		EFT2	1850	225	4.6	−30.5	31.2	3.8
Lost Man (RNP)	5.8	LM1	1450	135	4.5	−4.1	2.7	0.3
		LM2	2300	140	4.1	−4.7	5.3	0.4

Notes: See experimental design section for explanation for treatment reach abbreviations. Watershed position indicates how far upstream treatment reach occurred from the confluence. Changes in riparian shade, light, and summer MWMT are estimated as the differences between post-treatment and pre-treatment years. See Roon et al. (2021) for more details on methods for shade, light, and stream temperature responses. Abbreviations: EFT, East Fork Tectah; GD, Green Diamond; LM, Lost Man; MWMT, Maximum of the weekly average of the maximum temperature; RNP, Redwood National Park; WFT, West Fork Tectah.

150-m reach on slopes <20%. Thinning treatments targeted commercially planted Douglas-fir and red alder. Harvests followed a lop-and-scatter protocol leaving felled trees in the riparian zone but out of the stream channel (Redwood National Park 2014).

The intensity of thinning treatments varied between landowners due to differences in treatment prescriptions (Table 1). Reductions in shade over the stream channel as measured by hemispherical photography indicated that thinning treatments in the Tectah watersheds (Green Diamond property) were more intensive (reductions in effective shade over the stream channel: 19–30%) than the treatments in the Lost Man watershed (Redwood National Park) (reductions in effective shade over the stream channel: 4–5%) (Table 1).

Stream temperature data

We measured stream temperatures using digital temperature sensors (Onset Hobo Water Temperature Pro v2 and TidbiT Water Temperature Data Loggers, Onset Computer Corporation, Bourne, Massachusetts, USA) deployed approximately every 200 m through each watershed as well as downstream of the confluence in the Tectah watersheds (n = 100). Before deployment, we checked that all sensors were calibrated following the protocol described in Heck et al. (2018). We used solar shields constructed from 5-cm diameter polyvinyl chloride (PVC) pipe ~13 cm in length. We anchored sensors to the streambed using Duckbill Earth Anchors (MacLean Civil Products, Fort Mill, South Carolina, USA) modified with 5-mm diameter vinyl-coated galvanized steel cables in gravel and cobble dominant habitats or with waterproof epoxy (Pettit Splash Zone Marine Epoxy, Pettit Paint, Rockaway, New Jersey, USA) in habitats where bedrock or large boulders predominated (Heck et al. 2018). Temperature sensors recorded data hourly, and we summarized the data hourly, daily, and monthly during both pre-treatment and post-treatment water years (October 1 – September 30).

To measure finer-scale longitudinal patterns in stream temperature, we used an AquaTuff 35100-K Waterproof Thermocouple Instrument (Cooper-Atkins, Middlefield, Connecticut, USA) attached to a 2-m PVC pole. We measured stream temperature every 10 m through upstream reference, thinned, and downstream reaches during the afternoon in late summer (August 13–24, 2018) at low flow when thermal variability was highest. We recorded fine-scale temperature measurements in the thalweg of the stream channel ~5 cm above the streambed. To detect potential thermal stratification in low-flow pools >0.3 m in depth (Nielsen et al. 1994), we took measurements near the surface and the streambed.

Data analysis

A riverscape approach to understanding lotic ecosystems involves visualizing and quantifying biotic or physical responses in ways that address spatial and temporal variability throughout stream networks (Fausch et al. 2002). In keeping with the concept of a riverscape approach, we used a series of analyses that characterized conditions across multiple resolutions and extents (Reid 1998, Lowe et al. 2006). As recommended by Reid (1998), these analyses emphasized quantifying spatial patterns (Turner 1989). This approach allowed us to explore how local changes in temperature associated with riparian forest thinning propagated in space and time, thus allowing us to evaluate patterns within our framework for assessing responses (Fig. 1). First, we used semivariograms to evaluate how spatial autocorrelation varied before and after thinning. Second, we documented local and downstream thermal responses to thinning at a watershed extent across different temporal resolutions, including seasonal, daily, and diel (hourly) fluctuations. Last, we used Lagrangian analyses to track how changes in temperature traveled through space and time (Doyle and Ensign 2009, Vatland et al. 2015). For each analysis, to detect changes in thermal conditions associated with thinning, we compared conditions during pre-treatment (2016) and post-treatment years (2018). We examined how thinning influenced local and downstream temperatures between years and then related these patterns to the waveforms described in Fig. 1. We conducted all analyses in R version 4.0.2 (R Core Team 2020) and plotted all graphics in the ggplot2 package (Wickham 2016) unless otherwise noted.

*Spatial autocorrelation.—*Spatial dependence is pervasive in ecological data (Levin 1992, Legendre 1993) and especially in riverscapes, which are connected longitudinally via flowing water (Ward 1989). Geostatistical tools quantify spatial autocorrelation and structure in watersheds (Ganio et al. 2005). We used semivariograms of summer degree days to determine the presence of spatial autocorrelation and how that spatial structure was related to thinning treatments (Torgersen et al. 2004, Ganio et al. 2005). We selected summer degree days as a cumulative measure of thermal exposure that has implications for wide range of ecological processes (Steel et al. 2012, Benjamin et al. 2016, Campbell et al. 2020). We constructed semivariograms for each watershed using summer cumulative degree days for all locations distributed in the sensor network, and we compared how spatial dependence changed before and after thinning. We generated semivariograms in the gstat package in R (Pebesma 2004).

Temporal variation of local and downstream responses.—To evaluate baseline spatial variability and how thinning influenced longitudinal patterns, we examined watershed-scale longitudinal profiles at different time steps. We plotted summer cumulative degree days for each of the temperature sensors during pre- and post-treatment years to explore longitudinal patterns in stream temperature over the entire summer season (July 1–September 30). To track the spatial extent of downstream propagation of local increases in temperature associated with thinning, we applied a modified distance-to-edge approach following the methods described in Harper and Macdonald (2001) and Arismendi and Groom (2019). Using summer degree days, we set the before–after difference in temperature at the upstream end of each thinning reach (n = 10) to 0 and quantified temperature increases locally by comparing the difference at the downstream end of the thinned reach. Then, to track propagation of local increases in temperature downstream, we determined the distance that temperatures remained elevated.

To evaluate the spatial extent and temporal duration of local and downstream effects of thinning at a daily time step, we examined daily maximum temperatures over the entire water year (October 1–September 30) using spatiotemporal heatmaps constructed in the geom_raster function in the ggplot2 package in R. We compared pre- and post-treatment water years for each watershed to see how spatiotemporal patterns of temperature changed after thinning.

To explore the response of diel temperature fluctuations to thinning, we plotted watershed-scale longitudinal profiles of hourly data for each watershed on the warmest day of the year during our pre-treatment (30 July 2016) and post-treatment (25 July 2018) years. We selected the warmest day of the year to maximize the potential signals revealed in diel temperature fluctuations, which are expected when fluctuations are greatest. Diel fluctuations were evaluated to characterize how thinning influenced thermal variability, which can have implications for biota and ecological processes (Fraterrigo and Rusak 2008, Steel et al. 2012).

Lagrangian analyses.—In addition to measuring stream temperature responses at fixed locations (i.e., an Eulerian approach), we tracked changes in temperature through space and time using a Lagrangian framework (Doyle and Ensign 2009, Vatland et al. 2015). First, to determine how temperature responses associated with thinning moved through these watersheds over time, we tracked the timing of maximum temperatures on the warmest day of the year as an indication of spatiotemporal thermal variability (Fullerton et al. 2018). We noted the hour of the day when temperature peaked for all locations in the temperature sensor network, and we plotted the distribution of those times using kernel density functions. We compared differences using non-parametric Kolmogorov-Smirnov tests, which examine if the distribution of observations (in this case timing of maximum temperatures) varied between years (α = 0.05).

Second, to quantify how temperature responses moved through the watersheds over space, we mapped fine-scale longitudinal temperature patterns through upstream reference, thinned, and downstream reaches. This approach was inspired by Moore et al. (2005) and allowed us to observe the magnitude of temperature increases, where they peaked within thinning reaches, and how these increases dissipated downstream under intact forest cover. To standardize comparisons among treatment reaches, we set the temperature above the upstream reference reach to 0 and quantified longitudinal variation in upstream, thinned, and downstream reaches. We then compared fine-scale empirical measurements with locally estimated scatterplot smoothing (LOESS) regression lines.

Results

Spatial autocorrelation

Semivariograms revealed spatial autocorrelation that varied among watersheds and after thinning treatments (Fig. 3). Pre-treatment semivariograms indicated stronger spatial dependence in West Fork Tectah than in East Fork Tectah and Lost Man. In contrast, post-treatment semivariograms showed increased spatial heterogeneity in East Fork Tectah and West Fork Tectah that corresponded to the spacing of the thinning treatments, but Lost Man remained unchanged (Fig. 3). Post-treatment spatial heterogeneity increased the most in West Fork Tectah, with an elevated sill, shorter range, and steeper ascending limb with stepped sills indicating increased patchiness at multiple scales. Spatial heterogeneity also increased in East Fork Tectah but to a lesser extent.

Temporal variation of local and downstream responses

Longitudinal profiles of summer degree days in the pre-treatment year (2016) showed inherent spatial variation, with maximum longitudinal differences in degree day accumulation ranging from 66° to 112°C within each watershed (Fig. 4). Thermal heterogeneity increased during the post-treatment year (2018) within each watershed by 20° to 139°C degree days over the summer season, but the magnitude of responses varied between watersheds (Fig. 4). In the Tectah watersheds, post-treatment temperatures increased locally in thinned reaches and frequently remained elevated farther downstream (Fig. 4). In parts of the Tectah watersheds where thinning reaches occurred farther apart (>400 m), temperature increases dissipated downstream (Fig. 4). However, in other parts of the Tectah watersheds where thinning treatments occurred closer together (<400 m), temperature increases did not dissipate completely before encountering next thinning reach. In contrast, in the Lost Man watershed, post-treatment temperature responses were minimal in thinned reaches and showed no evidence of downstream propagation (Fig. 4).

Distance-to-edge analyses indicated consistent local increases in summer degree days associated with thinning treatments, but the magnitude of responses varied widely among watersheds (Fig. 5). Local temperature increases associated with riparian thinning were most evident in treatment reaches in the Tectah watersheds, accumulating 45° to 115°C additional degree days over the summer compared to the treatment reaches in the Lost Man watershed, which only accumulated 10° to 15°C degree days (Fig. 5). Propagation of local temperature increases downstream of treatment reaches showed a consistent cooling pattern, but the spatial extent of downstream propagation varied and depended on the magnitude of local increase (Fig. 5). Treatment reaches where temperature increases associated with riparian thinning were smaller, such as in the Lost Man watershed, had shorter travel distances, ranging from 75 to 150 m downstream, but treatment reaches with larger temperature increases such as in the Tectah watersheds had longer travel distances downstream, ranging from 300 to nearly 1000 m (Fig. 5).

Spatiotemporal heatmaps of daily maximum stream temperatures during the pre-treatment water year showed minimal longitudinal variation within each watershed along the x-axis but greater seasonal variation along the y-axis (Fig. 6). Pre-treatment seasonal patterns indicated that thermal conditions stayed relatively cool in fall through spring, with stream temperatures peaking as expected during summer months especially in July and August (longitudinal maximums: 13.2–17.4°C) (Fig. 6). Post-treatment heatmaps indicated increased spatial and temporal variability, but responses differed among watersheds. Increased spatiotemporal variability occurred exclusively in the Tectah watersheds, with no responses visible in the Lost Man watershed. Post-treatment temperatures increased the most in the thinned reaches in the Tectah watersheds (maximum temperatures in thinned reach: 16.8–21.8°C), but also extended downstream of each thinning reach (Fig. 6). The temporal duration of these temperature responses lasted the longest within thinning treatments and often persisted from May through September and decreased downstream from each thinning reach (Fig. 6). The spatial

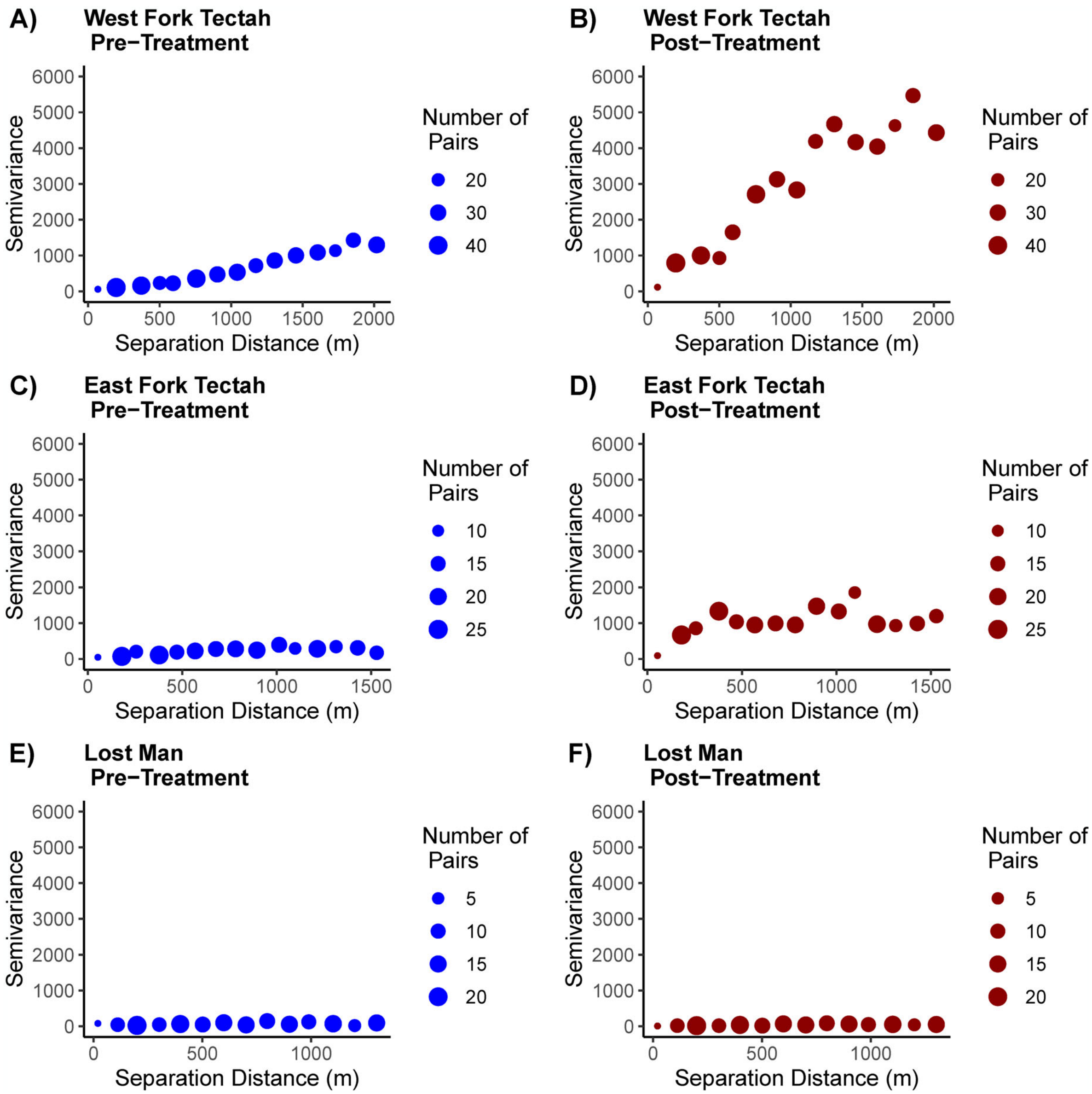


Fig. 3. Semivariograms depicting spatial autocorrelation in stream temperature (cumulative summer degree days) for each watershed before and after thinning. Size of points indicates the number of pairs at that separation distance.

extent of downstream effects varied seasonally, peaking during summer months (especially in July and August) and ranging from 200 to over 1200 m (Fig. 6). No local or downstream responses in space or time were evident in the Lost Man watershed (Fig. 6).

Longitudinal profiles of diel fluctuations on the warmest day of the year indicated inherent spatial variability, with pre-treatment diel fluctuations ranging from 0.3° to 2.4°C (Fig. 7). Post-treatment diel fluctuations displayed increased thermal heterogeneity, causing diel fluctuations to range from 0.3° to 8.7°C (Fig. 7). Post-treatment diel fluctuations increased the most within thinning reaches but also remained elevated downstream. Local and downstream

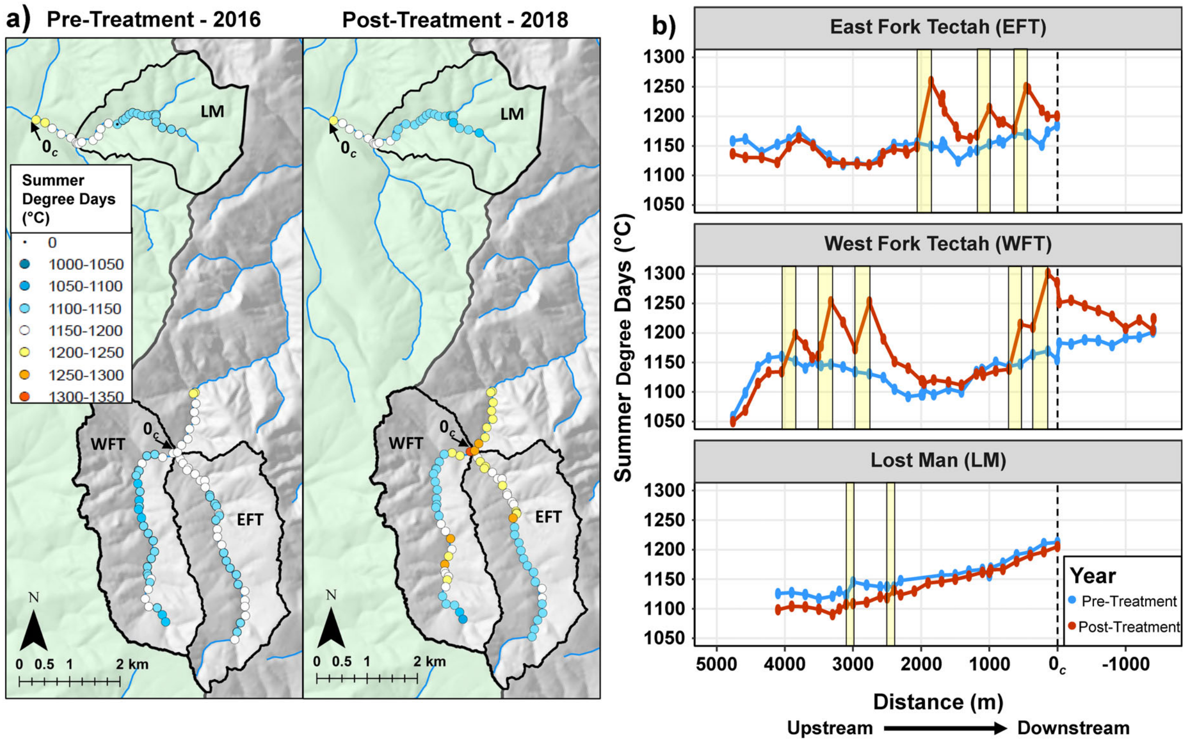


Fig. 4. Watershed-scale spatial patterns of stream temperature as indicated by summer cumulative degree days during pre-treatment and post-treatment water years. (a) Spatial patterns of cumulative degree days between July through September during pre-treatment and post-treatment years. (b) Longitudinal profiles of cumulative degree days between July through September for each watershed during pre-treatment and post-treatment years. Points (a) indicate temperature sensors, spatial position in watershed, and conditions during pre- and post-treatment years. Yellow polygons (b) indicate the positions of experimental thinning treatment reaches. The *x*-axis (b) shows the distance upstream from the major confluence (distance = 0_c) in each watershed indicated by a dashed vertical line; the direction of flow (left to right) is shown by the horizontal arrow (b).

post-treatment responses increased the most in the Tectah watersheds, whereas no responses were evident in the Lost Man watershed (Fig. 7). In the Tectah watersheds, when thinning reaches occurred farther apart (>400 m), local increases in diel fluctuations dissipated as they continued downstream. However, when thinning reaches occurred closer together (<400 m), local increases remained elevated, sometimes resulting in larger subsequent increases in temperature (Fig. 7).

Lagrangian analyses

Lagrangian analyses indicated that thinning shifted the timing of maximum temperatures on the warmest day of the year (Fig. 8). Pre-treatment kernel density distributions showed that maximum temperatures peaked over a shorter window of time in the late afternoon at 14:00–19:00 in the Tectah watersheds and at 12:00–19:00 in the Lost Man watershed (Fig. 8). In the post-treatment year, kernel density distributions indicated that the timing of maximum temperatures peaked over a broader temporal window, especially in the Tectah watersheds. Locally within thinning reaches, the timing of maximum temperatures occurred earlier in the afternoon, most frequently peaking at 12:00–13:00 (Fig. 8). As this pulse of warmed water traveled downstream, it delayed the timing of maximum temperatures, most frequently peaking in downstream locations at 18:00–21:00 (Fig. 8). These shifts in timing differed between years (Kolmogorov-Smirnov test: $P < 0.05$). No

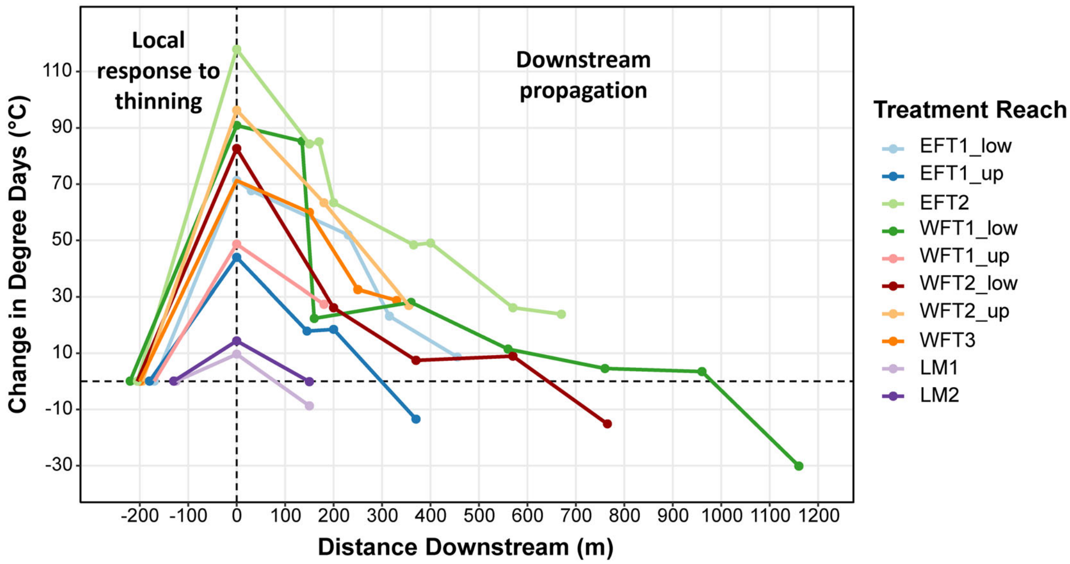


Fig. 5. Longitudinal profiles of changes in summer cumulative degree days depicting local temperature responses to riparian thinning, downstream propagation of local responses, and variation among treatment reaches. Changes in summer cumulative degree days were calculated as before–after differences in temperature where conditions at the upstream end of each thinning reach is set to 0 to standardize across treatment reaches. Each line indicates the local response and downstream dissipation of temperature changes associated with treatment reaches (n = 10). The magnitude of temperature increase associated with thinning is plotted on the y-axis. Distance downstream from the thinned reach is plotted on x-axis where positions to the left of 0 are within the thinned reach (negative numbers) and positions to the right of 0 are downstream of the treatment (positive numbers). See Table 1 and *Methods: Experimental design* for descriptions of treatment reach abbreviations.

shifts in timing occurred between years in the Lost Man watershed (Kolmogorov-Smirnov test: $P > 0.05$) (Fig. 8).

Fine-scale longitudinal profiles during the post-treatment year showed distinct patterns in upstream reference, thinned, and downstream reaches, but responses varied between watersheds (Fig. 9). In all watersheds, fine-scale temperature patterns in upstream reference reaches remained constant or cooled downstream. In the Tectah watersheds, stream temperatures in thinned reach continuously warmed with distance downstream, increasing from 2.0° to 4.7°C (Fig. 9). Local increases in temperature extended into downstream reaches but exhibited distinct cooling trajectories. In some treatment locations, temperatures returned to initial conditions by the end of the downstream reach (e.g., EFT1_low, EFT1_up, WFT1_low, WFT2_low), whereas in other locations, temperatures dissipated partially (e.g., EFT2, and WFT1_up, WFT2_up, WFT3) (Fig. 9). In some downstream reaches, abrupt drops in temperature in the downstream reach coincided with low-flow pools (e.g., WFT1_low, WFT2_low, EFT2, EFT1_up) followed by cooler temperatures farther downstream (Fig. 9). In contrast, treatment reaches in the Lost Man watershed showed no change longitudinally in thinned or downstream reaches (Fig. 9).

Discussion

We found that the combination of a riverscape approach (Fausch et al. 2002), guided by interpretations from our conceptual framework of management responses (Reid 1998, Humphries et al. 2014), proved effective in evaluating the influences of riparian thinning on stream thermal regimes across watersheds. This study design was particularly effective for quantifying and envisioning patterns of heterogeneity in stream temperatures (Steel et al. 2017). Although we observed inherent spatial variation in thermal conditions in our study watersheds (Fullerton

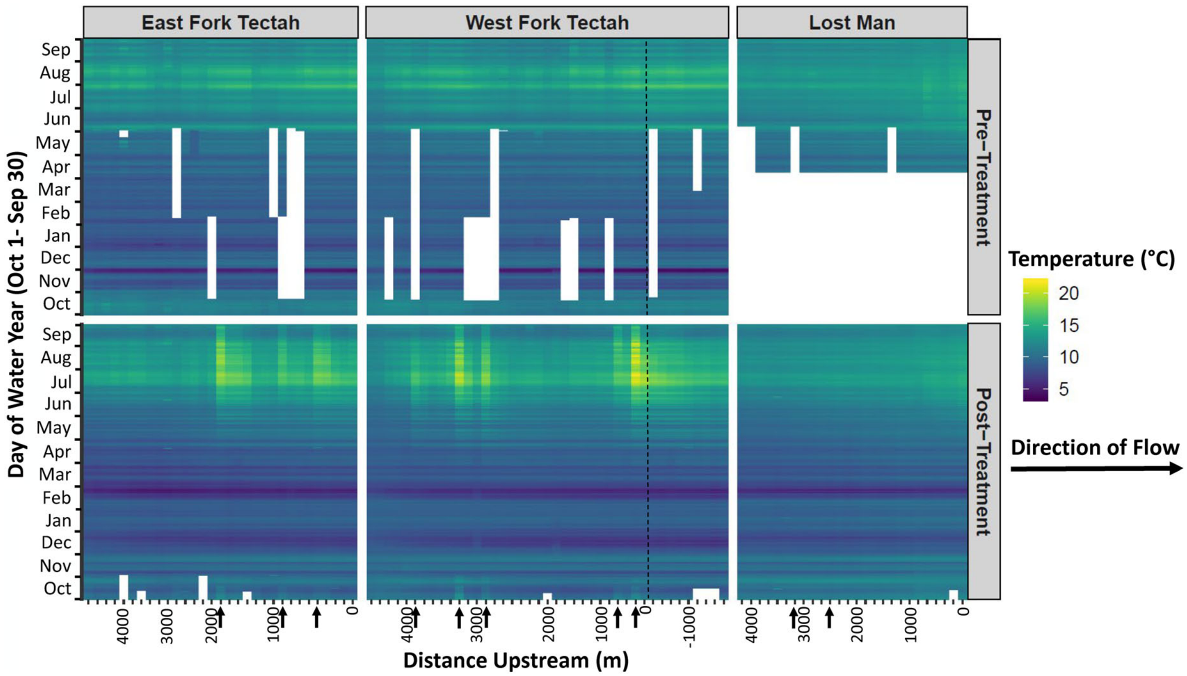


Fig. 6. Spatiotemporal patterns of daily maximum stream temperature in the study watersheds for pre- (first row) and post-treatment (second row) water years. For each watershed, time is a daily time step in the water year (October 1–September 30) on the y-axis, and the spatial position in the watershed (distance upstream from the confluence) is on the x-axis. Direction of flow (left to right) is shown with a horizontal arrow. Vertical arrows on the x-axis show the positions of experimental thinning treatments in each watershed. White spaces indicate no data. Dashed vertical line marks stream confluences.

et al. 2015, Leach et al. 2017), we observed that riparian thinning increased thermal heterogeneity beyond the natural range of variation in pretreatment conditions, a finding consistent with previous studies (Fraterrigo and Rusak 2008, Steel et al. 2017, Fullerton et al. 2018). Increases in thermal heterogeneity occurred across multiple spatiotemporal scales and varied among watersheds with different intensities of riparian thinning. Elucidating these responses required several lines of analyses informed by our conceptual framework for describing cumulative watershed effects (Fig. 1, Table 2).

Riparian thinning altered longitudinal patterns in spatial autocorrelation

Spatial autocorrelation of stream temperature cumulative degree days indicated distinct post-treatment responses among watersheds. In the Tectah watersheds, where more intensive thinning treatments occurred, riparian thinning resulted in increased heterogeneity (i.e., higher variance and patchiness) at multiple spatial scales. Heterogeneity increased the most in the West Fork Tectah watershed where the most thinning treatments occurred (n = 5). The East Fork Tectah watershed displayed similar patterns of increased heterogeneity at multiple scales, but to a lesser extent than in the West Fork watershed, which coincided with fewer thinning treatments (n = 3). In contrast, semivariograms for the Lost Man watershed exhibited a pure nugget effect (i.e., no increase in semivariance with separation distance) during both pre- and post-treatment years. Other studies have shown semivariograms with shapes similar to the ones we observed (i.e., pure nugget effect, spherical, and nested) for fish counts (Torgersen et al. 2004, Ganio et al. 2005), water chemistry (McGuire et al. 2014), and stream temperature (Gendaszek et al. 2020). However, few studies have applied semivariograms for change-detection purposes

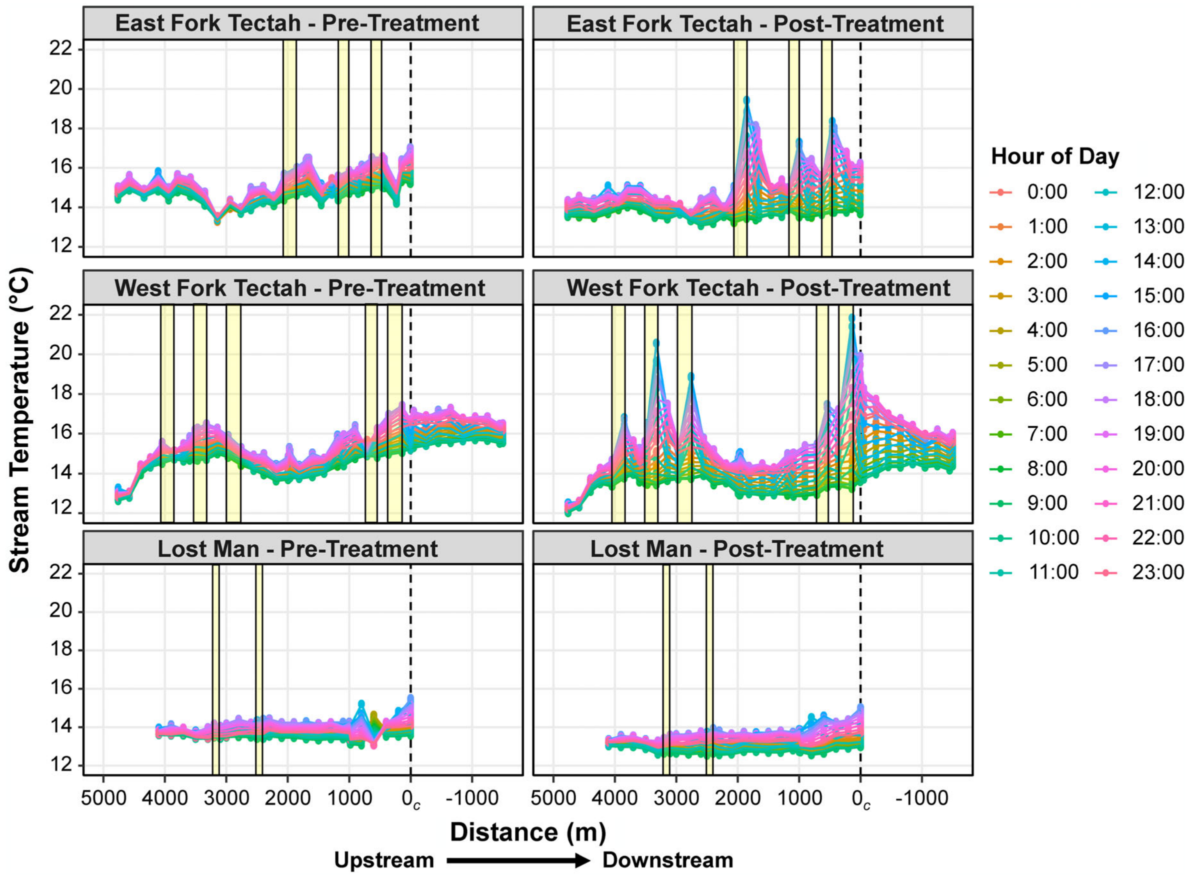


Fig. 7. Watershed-scale longitudinal profiles of diel fluctuations in hourly temperatures on the warmest day of the year during pre- (July 30, 2016) and post-treatment years (July 25, 2018). Yellow polygons indicate the positions of experimental thinning treatments. The *x*-axis shows distance upstream from major confluence (distance = 0_c) in each watershed indicated by a dashed vertical line; the direction of flow (left to right) is shown by the horizontal arrow.

(but see Dent and Grimm 1999, Johnson et al. 2010). Our study results highlight that semivariograms are effective tools for detecting land-use impacts, in this case documenting increased thermal heterogeneity associated with experimental riparian thinning treatments.

Riparian thinning increased local and downstream temperatures across multiple scales

Watershed responses to riparian thinning indicated that stream temperatures increased the most within thinned reaches, but the magnitude of thermal responses varied with treatment intensity. In the Tectah watersheds, which experienced more intensive thinning treatments, we observed larger thermal responses across each temporal scale considered. We observed this pattern as abrupt peaks in seasonal and daily longitudinal profiles as well as distinct hotspots in spatiotemporal heatmaps. Not only did thinning increase the magnitude of stream temperatures, but it also altered the thermal regime in other ways, as evidenced by increased thermal variability in diel fluctuations and as prolonged temporal durations in spatiotemporal heatmaps during summer low flows (Steel et al. 2017, Roon et al. 2021). In contrast, we observed minimal or no thermal responses in the Lost Man watershed, which experienced less intensive thinning treatments. These patterns corroborate other studies documenting that the magnitude of stream temperature responses to forest harvest corresponds

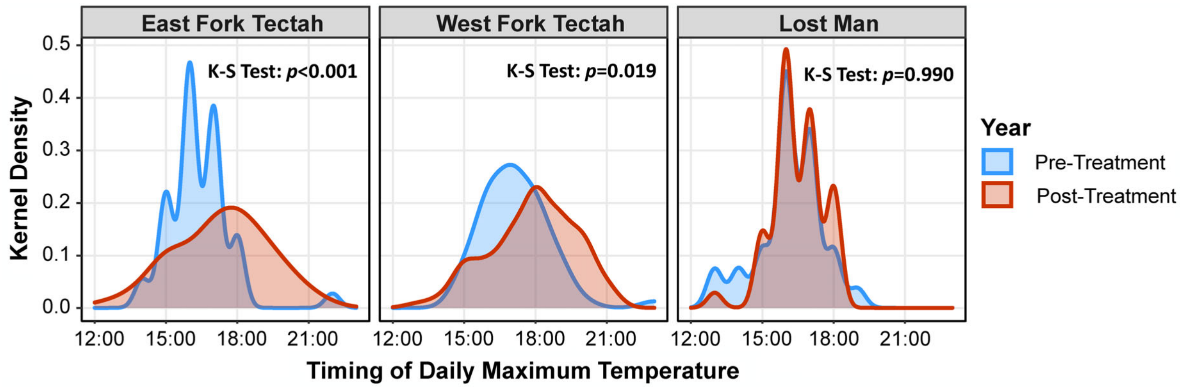


Fig. 8. Kernel density distributions of the timing of daily maximum temperatures for study watersheds on the warmest day of the year during pre- (July 30, 2016) and post-treatment years (July 25, 2018). Non-parametric Kolmogorov-Smirnov (K-S) tests indicate whether the kernel density distributions differed between years ($\alpha = 0.05$).

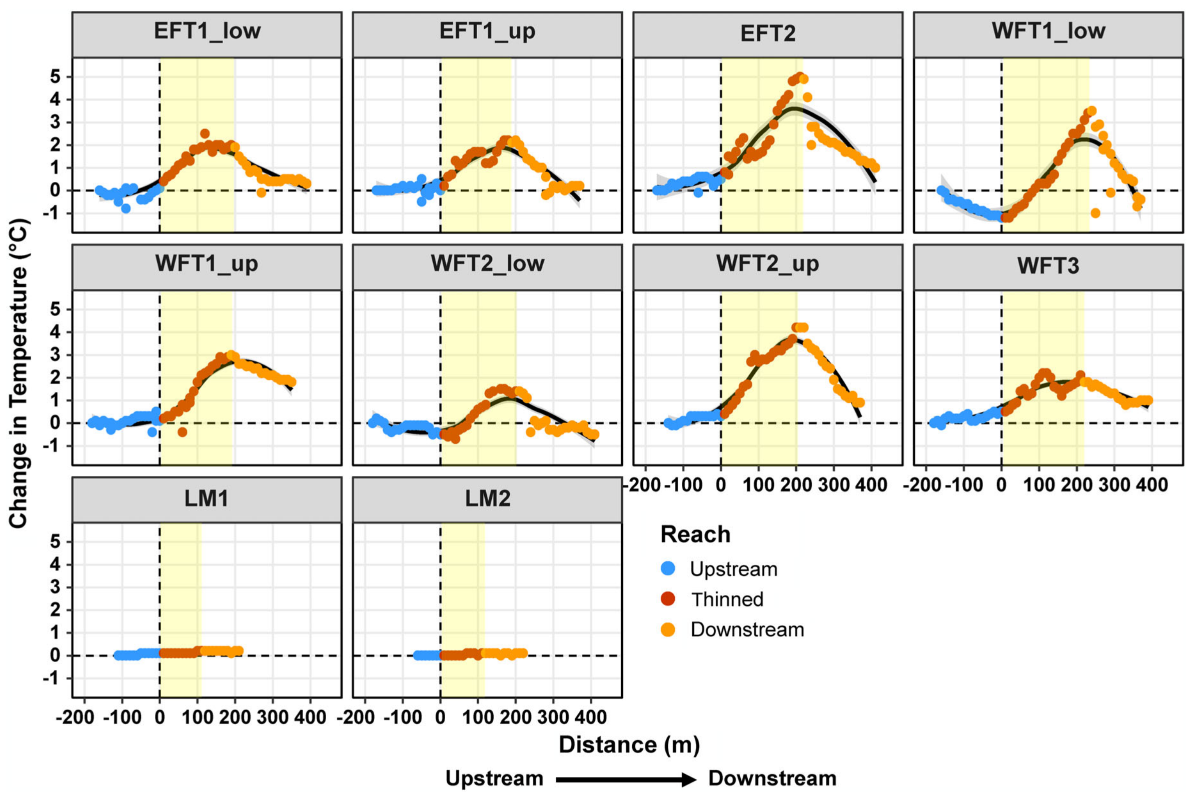


Fig. 9. Fine-scale Lagrangian longitudinal profiles at 10-m resolution in upstream reference, thinned, and downstream reaches at low-flow during the post-treatment year on August 13–24, 2018. Change in temperature on y-axis is determined relative to conditions at upstream extent of upstream reference reach. Distance on *x*-axis is set to 0 at upstream extent of thinned reach indicated by dashed vertical line. The boundaries of the thinned reach are highlighted by yellow polygons. Direction of flow (left to right) is indicated by horizontal arrow. Smoothed regression line (LOESS) is shown with standard error (grey envelope).

Table 2. Local and downstream thermal responses associated with thinning at multiple spatiotemporal scales.

Perspective	Spatial scale	Temporal scale	Response variable	Magnitude of local response	Spatial extent of downstream propagation	Temporal duration	Waveforms
Eulerian	Watershed	Seasonal	Cumulative summer degree days	Tectah: +45–115°C Lost Man: +10–15°C	Tectah: 300–1000 m Lost Man: 75–150 m	Summer season	Tectah: Extended pulse, Cumulative effect between treatments ≤400 m apart Lost Man: Localized pulse
Eulerian	Watershed	Daily	Daily maximum	Tectah: +0.0–8.5°C Lost Man: no change	Tectah: 200–1200 m Lost Man: no change	Tectah: May – September Lost Man: no change	Tectah: Extended pulse, Cumulative effect between treatments ≤400 m apart Lost Man: No effect
Eulerian	Watershed	Hourly	Diel fluctuation	Tectah: +2.2–6.5°C Lost Man: no change	Tectah: 200–1200 m Lost Man: no change	Tectah: +0–10 h on warmest day of year Lost Man: no change	Tectah: Extended pulse, Cumulative effect between treatments ≤400 m apart Lost Man: No effect
Lagrangian	Watershed	Hourly	Timing of maximum temperature	Tectah: occurred earlier (12:00–13:00) Lost Man: no change	Tectah: occurred later (18:00–21:00) Lost Man: no change	Tectah: +0 – 4 h on warmest day of year Lost Man: no change	Tectah: Extended pulse, Cumulative effect between treatments ≤400 m apart Lost Man: No effect
Lagrangian	High resolution (every 10 m)	Seconds	Instantaneous temperature	Tectah: +2.0–4.7°C Lost Man: no change	Tectah: 150–200 + m Lost Man: no change	Tectah: Warm afternoons at low flow Lost Man: no change	Tectah: Extended pulse, Cumulative effect between treatments ≤400 m apart Lost Man: No effect

Note: Descriptions of waveforms are provided in Fig. 1.

with the extent of changes in riparian shade and solar radiation (Johnson 2004, Moore et al. 2005).

Downstream propagation of local responses was evident at every temporal scale we considered, but the spatial extents of downstream effects ranged widely and often depended on the magnitude (i.e., increase in temperatures) of local responses to thinning. Distance-to-edge analyses of summer degree days showed that treatment reaches in the Tectah watersheds (where local increases in temperature were larger) extended farther downstream (300–1000 m), while treatment reaches in the Lost Man watershed (where local increases were much smaller) did not extend downstream very far (≤100 m). Spatiotemporal heatmaps of year-round daily maximum temperatures revealed that the spatial extent of downstream effects fluctuated seasonally and peaked during July and August, reflecting the timing of local responses associated with thinning treatments. Tracking downstream effects year-round and across multiple temporal scales provided valuable insights not possible from a single scale (Fausch et al. 2002, Lowe et al. 2006).

Although downstream effects of forest management have been a focus in research and management (Moore et al. 2005), knowledge gaps still remain. Multiple studies describe responses immediately downstream of treatment locations (e.g., Shrimpton et al. 2000, Story et al. 2003, Arismendi and Groom 2019), often documenting downstream propagation, but there are relatively few attempts to track the spatial extent of those effects. Wilzbach et al. (2005) detected downstream effects in the Tectah watershed extending up to 430 m downstream of treatments that completely removed the riparian canopy along a 100-m reach. Davis et al. (2016) applied Newton's law of cooling to model the downstream effects associated with a range of riparian buffer widths (6–50 m wide) in the Oregon Coast Range and found that ~50% of local increases persisted at 300 m downstream, similar to our observations in the Tectah watersheds. In contrast, Zwieniecki and Newton (1999) estimated that downstream temperatures cooled to initial conditions within 150 m of harvests that included a ~20-m wide riparian buffer along a 350–1600-m reach. However, they derived these estimates relative to an averaged longitudinal trend line that did not account for the effects of inherent longitudinal thermal variability (Johnson 2004, Fullerton et al. 2015). Bladon et al. (2018) also observed minimal downstream effects from upstream harvests that consisted of a 10–15-m wide riparian buffer in watersheds located in western Oregon, but positions of downstream monitoring stations varied in spacing from treatments and did not allow for detailed analysis of spatial patterns. The spatial extents of downstream effects that we measured in this study occurred at intermediate scales (100–1200 m), which are often most relevant to management and biota (Fausch et al. 2002, Bladon et al. 2018, Arismendi and Groom 2019). These results highlight the value of a riverscape approach that combines high-resolution data across a broad spatial extent to provide a more spatially and temporally continuous view of downstream changes.

Riparian thinning altered stream temperatures through space and time

Our Lagrangian analyses complemented patterns observed in watershed-scale analyses that relied on *Eulerian* data (Doyle and Ensign 2009). By applying a Lagrangian perspective, we tracked how temperature changes associated with riparian thinning treatments moved through time and space, documenting increased spatiotemporal heterogeneity (Vatland et al. 2015). We found that thinning increased thermal asynchronies in space and time (Malcolm et al. 2004, Vatland et al. 2015, Fullerton et al. 2018) where maximum temperatures peaked earlier in thinned reaches but peaked later in downstream locations; these findings are consistent with the advective transfer of heat downstream (Moore et al. 2005). The emergence of these thermal asynchronies varied with treatment intensity, where shifts in timing were more dramatic in the Tectah watersheds (which had greater treatment intensity) than in the Lost Man watershed. Added thermal complexity in space and time as documented by Lagrangian analyses has implications for ecological processes and biota in these watersheds (Fraterrigo and Rusak 2008, Steel et al. 2017, Fullerton et al. 2018).

Fine-scale longitudinal profiles at a spatial resolution of 10 m revealed how quickly stream temperature increased downstream through a patch of thinning and how these increases dissipated farther downstream. As predicted by Moore et al. (2005), stream temperature continued to increase through the thinning reach, peaking at the downstream end. However, in some downstream reaches, we observed abrupt decreases in temperature that corresponded with low-flow pools, which were often thermally stratified (Nielsen et al. 1994, Ouellet et al. 2017). The mechanisms driving this pattern are complex and difficult to quantify directly (e.g., mediation by upwelling groundwater or small amounts of warmed water interacting with a larger volume of cooler water), but the end result was a buffering effect on upstream increases in temperature that limited propagation farther downstream. These results illustrate the value of high-resolution approaches that can reveal fine-scale patterns of thermal heterogeneity, such as remote sensing (Torgersen et al. 1999, Fullerton et al. 2015, Vatland et al. 2015, Dugdale 2016) or distributed temperature sensing (DTS) (Roth et al. 2010, Hall et al. 2020).

Application of conceptual framework

A key objective of this study was to provide insights afforded by a riverscape approach and apply them within a conceptual framework based on waveforms that allows for interpretations that are directly relevant for managers (Fig. 1). When we compare our results to the waveforms in Fig. 1 (Humphries et al. 2014), they reveal a series of distinct waveforms that varied in shape depending on the intensity, scale, and proximity of thinning treatments. Waveforms in the Tectah watersheds were most frequently characterized as an extended pulse in which localized increases in temperature extended downstream of the riparian treatments but eventually dissipated at variable distances. Extended pulses appeared in the thermal responses to thinning in watershed-scale longitudinal profiles, distance to edge analyses, spatial–temporal heatmaps, and fine-scale longitudinal profiles, especially when thinning reaches were spaced farther apart (>400 m). Extended pulses have been described in other studies, but the mechanisms responsible for driving this eventual downstream cooling and the rates at which they cool vary among systems (Shrimpton et al. 2000, Rutherford et al. 2004, Moore et al. 2005, Garner et al. 2014, Davis et al. 2016, Erdozain et al. 2021). For example, Story et al. (2003) and Moore et al. (2005) suggested that downstream cooling in extended pulses may be due to mediation by cooler inputs such as conduction with the streambed, upwelling groundwater, hyporheic flow, or junctions with cold-water tributaries. However, by using a process-based energy budget model, Garner et al. (2014) determined that patterns of downstream cooling were not necessarily due to mediation by cooler inputs, but instead were more likely caused by reductions in solar energy under closed canopies that reduced the rate of heating as water flowed downstream.

Overall, we observed no evidence of cumulative watershed effects at the downstream extent of each of our study watersheds. However, responses in the Tectah watersheds showed cumulative effects (Reid 1998) between thinning treatments where thinning treatments occurred close together (<400 m apart), and local increases in temperature did not dissipate completely before entering another patch of thinning. Alternatively, apparent cumulative effects observed between thinning treatments may represent superimposition of two or more extended pulses from upstream thinning treatments. The subsequent increase in temperature was sometimes greater in magnitude, suggesting a compounding effect. Although Beschta et al. (1987) suggested that increases in temperature associated with timber harvest may continue to increase in a downstream direction, little empirical evidence has supported this hypothesis (Shrimpton et al. 2000, Johnson 2004, Moore et al. 2005, Fullerton et al. 2015, Erdozain et al. 2021). Our data suggest that cumulative effects were limited to locations that occurred between patches of thinning. However, given sufficient space, or if no additional thinning treatments were encountered, downstream cooling then followed as an eventual extended pulse.

In contrast to the waveforms observed in the Tectah watersheds, waveforms in the Lost Man watershed were generally characterized as "no effect." This is most likely explained by minimal changes in solar radiation associated with the less-intensive thinning treatments. Alternatively, the coastal climate, pervasive hyporheic flow, and upwelling groundwater characteristic of the Lost Man watershed may have offset the small increase in solar radiation (Welsh et al. 2000). Distance-to-edge analyses of cumulative summer degree days did, however, show a localized pulse with a highly truncated extended pulse ~100 m downstream. We did not observe this pattern at shorter temporal scales (e.g., daily, diurnal), suggesting that this waveform only occurred across broader seasonal windows.

Waveforms depicting local radiative and longitudinal advective processes were useful for evaluating and characterizing local and downstream changes in thermal conditions. Although we applied this conceptual framework to specifically evaluate the local and downstream thermal effects associated with riparian thinning treatments, the framework could be used to examine cumulative effects of other disturbances that alter riparian forest conditions in lotic systems and have the potential to propagate downstream. While this approach may be applied most directly to parameters that propagate easily with flow, such as temperature or water chemistry (McGuire et al. 2014, Abbott et al. 2018), it could also be applied to biological responses (e.g., Feijo-Lima et al. 2018).

Biological implications

Stream thermal conditions drive ecological processes in aquatic ecosystems (Magnuson et al. 1979, Cassie 2006, McCullough et al. 2009), so it is crucial to consider the biological implications of the thermal responses we observed to riparian thinning. These watersheds support resident populations of coastal cutthroat trout, coastal giant salamander, and coastal tailed frog, all of which are sensitive to changes in temperature (Huff et al. 2005, Bury 2008). While temperature increases exceeded common cold-water thresholds of 15° and 20°C (Fullerton et al. 2018) for prolonged durations during summer months and the realized thermal niche for each species (Huff et al. 2005), they did not exceed the critical thermal maxima for any species (de Vlaming and Bury 1970, Bury 2008, McCullough et al. 2009).

Thermal heterogeneity influences a wide range of species behavior including their distribution, habitat use, growth and development, and movement patterns (Torgersen et al. 1999, Ebersole et al. 2003, Armstrong et al. 2013). In contrast to previous studies documenting the importance of thermal heterogeneity as cold-water refuges in otherwise warm-water systems (Torgersen et al. 1999, Ebsersole et al. 2003, Brewitt et al. 2017, Fullerton et al. 2018, Wang et al. 2020), the increases in thermal heterogeneity that we observed added warm-water patches to otherwise cool-water systems. However, it is challenging to predict the effects of this heterogeneity on thermally sensitive ectotherms in these watersheds. First, the extent of thermal fluctuations in space and time varies seasonally. While warm patches may be problematic during summer months when temperature increases exceed the thermal tolerance of the cold-water-adapted species, these temperature changes may not cause stress during cooler seasons and instead may actually increase growth rates (Benjamin et al. 2020). Second, the species that occupy these watersheds are highly mobile organisms and have the capacity to avoid warm patches if there is sufficient longitudinal connectivity (Schlosser 1995). In addition, thermal stratification observed in low-flow pools may provide finer-scale thermal refuges in thinned and downstream reaches (Schlosser 1991, Nielson et al. 1994). Third, the ecological effects of warming temperatures on ectothermic animals depend on the availability of sufficient prey resources to support increases in metabolism (Schlosser 1991, Hughes and Grand 2000, Armstrong et al. 2013). The collective influences of these factors could be addressed by modeling frameworks that integrate these local and landscape influences on multiple responses (e.g., Railsback et al. 2009, Penaluna et al. 2015).

Management implications

Riparian forests play an important role in regulating stream temperatures (Moore et al. 2005). Thus, it is important to evaluate the potential for cumulative watershed effects when considering changes in riparian forest conditions (Reid 1998, Erdozain et al. 2021). This is especially relevant for resource managers considering thinning and other restoration strategies (e.g., gaps, variable retention buffers) for second-growth riparian forests recovering from previous harvest. In our watershed experiment, we gained valuable insights from a riverscape approach that have direct application to the management of cumulative watershed effects. These considerations include the intensity, scale, spatial proximity, and ecological context of the riparian management actions.

First, downstream effects depended on sufficient local increases in solar radiation and reductions in shade to cause a thermal response. Downstream effects were most pronounced in the Tectah watersheds, which experienced more intensive thinning treatments (20–30% loss in shade) compared to the Lost Man watershed ($\sim$4% loss in shade). These results support the hypothesis that thinning less intensively can ameliorate thermal loading of streams—similar to the findings of sufficiently wide riparian buffer widths (Anderson et al. 2007, Groom et al. 2011). As a result, one way to minimize the potential for downstream effects is to thin less intensively. Second, fine-scale Lagrangian profiles indicated that temperatures continued to increase as water traveled through the thinned reaches, peaking at the downstream end of the reach. This suggests that limiting the spatial exposure to the stream channel by reducing the extent of treatments (treating shorter reaches of stream) may be an effective strategy to minimize local and downstream temperature changes. For example, recent studies have shown smaller temperature responses with small-scale riparian gaps <30 m in length (Coats and Jackson 2020, Swartz et al. 2020). Third, we observed the emergence of distinct waveforms depending on the spatial proximity of thinning treatments. Cumulative effects only occurred when thinning treatments were spaced close together (<400 m apart). Thus, spacing treatments farther apart (>1000 m) could minimize the chances of cumulative effects (Reid 1998). Fourth, fine-scale longitudinal profiles indicated that downstream effects were associated with finer-scale habitat features such as low-flow pools formed by old-growth redwood logs that reduced downstream propagation of temperature increases. As a result, geomorphic and hydrologic conditions inherent in the system may influence responses that contribute to the context dependency observed among studies. Consideration of such conditions (e.g., underlying lithology, geomorphology, hydrology, watershed attributes, reach-scale attributes, and climate) provide ecological context to better understand responses to change (Moore et al. 2005, Burnett et al. 2007, Leach et al. 2017, Bladon et al. 2018, Coats and Jackson 2020).

Conclusions

We believe our approach of pairing complementary analyses of spatial and temporal patterns of heterogeneity in a stream network with an interpretive framework is an effective means of bridging the gap between research and management as originally envisioned by the concept of riverscapes (Fausch et al. 2002). Overall, the results of this study point to the value of framing management questions so that the unique insights revealed by a riverscape approach are immediately apparent. Furthermore, this approach can reveal emergent patterns that are not easily envisioned within the confines of applied frameworks, which may be based on simplified representations of reality due to practical constraints (Poole et al. 2004). It may not be realistic to expect any generalized set of management objectives or criteria to address every conceivable scenario posed by the complex interplay of patterns and processes in riverscapes. Therefore, explicitly pairing these perspectives is an effective means of overcoming the inherent limitations of each. We propose that the approach developed here can be adapted more broadly to inform decisions regarding human influences on riverscapes at multiple scales.

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Data Availability

Data are available from the Open Science Framework: https://doi.org/10.17605/OSF.IO/XFSZN

Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3775/full