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A novel approach for examining downstream thermal responses of streams to contemporary forestry

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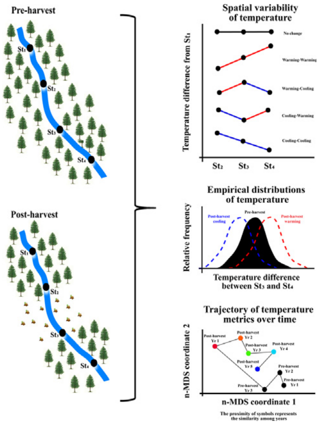
HIGHLIGHTS

- Warmer downstream habitats after timber harvest affect cold-water biota.
- Multifaceted metrics allow for evaluation of long-term responses from multiple sites.
- Greatest thermal effects occur up to the second year post-harvest.
- Effects converge towards pre-harvest conditions by the fifth year post-harvest.
- Metrics are transferable to examine downstream effects of other disturbances.

GRAPHICAL ABSTRACT



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ABSTRACT

Temperature is a fundamental driver of aquatic environments. Changes in thermal regimes due to timber harvest may be detrimental for cold-water instream biota. Although it is understood that stream temperature may increase immediately below timber harvest operations, the understanding of how thermal responses propagate downstream is less clear. Here, we examine the effects of timber harvest on stream temperature pre- (2–3 years) and post-harvest (5 years) at 16 sites (average annual streamflow rates <0.283 m^3 s^{-1}) located in the Coast Range, Oregon, USA. At each site, an array of temperature sensors were deployed on the extremes of three consecutive reaches: an upstream unharvested reference reach, a treatment reach, and a downstream unharvested reach. We used several metrics to describe and evaluate changes over time and space focusing on the responses of downstream reaches. Primarily, we evaluated the differences over time in daily maximum temperature between the two sensors located at the downstream unharvested reach. Furthermore, using a statistical ordination technique, we examined the spatial and temporal variability of an array of sensors for daily maximum temperature. Moreover, we assessed distributional shifts (statistical moments) of hourly temperature differences between the two sensors at the downstream unharvested reach over time. Lastly, we used a combination of statistical moments and the ordination technique to provide an index that describes the behavior of site-specific thermal disturbance over time. We found that stream reaches responded differently to upstream timber harvest operations between pre and post-harvest summer seasons. In addition, we showed distinct patterns of longitudinal variability of temperature across sites and summer seasons with increases, decreases or mixed responses

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including no change downstream. Overall, the net change of daily maximum temperature at the downstream reach revealed that the highest difference occurred during the first and second year post-harvest and, in some cases, a distinctive shift in stream warming and cooling occurred between the day and the night. Observed temperature patterns in downstream reaches were most similar to the pre-harvest conditions at the fifth year post-harvest. Collectively, we offer a novel approach for assessing stream temperature regime change using multiple metrics that can improve our understanding of thermal effects downstream of timber harvest, taking in consideration idiosyncratic responses across sites and time.

1. Introduction

Temperature is a fundamental driver of aquatic environments (Magnuson et al., 1979). Physiological states, mortality, growth rates, development, and the phenology of fishes are controlled by thermal regimes of streams (Fry, 1947; Brett, 1971; Beacham and Murray, 1990; McCullough et al., 2009; Crozier et al., 2011). Salmonids are cold-water species that adjust their spatial locations within streams in response to physiological constraints, at high (Ebersole et al., 2003; Breau et al., 2007) or low (Graham et al., 1996) temperature conditions. For example, when thermal maxima exceeds levels that cause stress (McCullough et al., 2009) some organisms may be able to escape to alternative refuges (Ebersole et al., 2003) although they may experience increases in competition for limited resources in those alternative habitats (May and Lee, 2004; Harvey et al., 2006). However, less-mobile organisms and others incapable of escaping to alternative habitats may be especially vulnerable to high temperature conditions. Changes to stream thermal regimes may therefore affect the distribution and survival of local salmonid populations as well as other aquatic organisms.

Elevated stream temperature conditions due to anthropogenic influences, such as forest management practices, may affect the availability of habitats usable to cold-water species (Holtby, 1988; Murphy et al., 1986; Penaluna et al., 2015). Timber harvest of riparian areas is known to affect adjacent stream temperature (see reviews by Moore et al., 2005 and Webb et al., 2008). Indeed, most of the literature has been focused on understanding stream temperature responses immediately below timber harvest units (e.g., Beschta and Taylor, 1988; Johnson and Jones, 2000; Groom et al., 2011a; Kibler et al., 2013). There has been less attention, however, related to what occurs further downstream of harvest (Moore et al., 2005). The removal of streamside vegetation typically increases daily maximum temperature immediately downstream of harvest (Beschta and Taylor, 1988; Johnson and Jones, 2000; Groom et al., 2011a; Kibler et al., 2013), but this increase may not persist downstream indefinitely (Garner et al., 2014; Davis et al., 2015). When streams pass from open areas receiving solar radiation to shaded reaches, water temperature often decrease with distance (Caldwell et al., 1991; Zwieniecki and Newton, 1999; Story et al., 2003; Rutherford et al., 2004; Cole and Newton, 2013; but see Shrimpton et al., 2000 and Garner et al., 2014). Policy makers and regulators are interested in understanding how far downstream temperature conditions change so that the extent of thermal impact is known (Terry Frueh, *Pers. Comm.*). However, there are a variety of documented responses for downstream stream temperature following an upstream temperature change. In some cases, stream temperature in reaches recovers after a couple of hundred meters downstream (Caldwell et al., 1991; Davis et al., 2015) whereas in others it takes several kilometers (Bartholow, 2000; Rutherford et al., 2004).

The majority of these studies have not considered pre-harvest conditions and, often, they are focused on few sites (e.g., paired watershed studies) that may not necessarily capture the variability of headwater streams prior to the timber harvest. In addition, both study methodologies and differences in physical processes of stream reaches play a role in generating the variety of observed responses from stream temperature conditions downstream following an upstream temperature increase. Study designs differ in the degree of control they offer. For example, Zwieniecki and Newton (1999) attribute a natural increase in maximum temperature values downstream in absence of timber harvest. Other studies that lack pre-treatment information (e.g., Caldwell et al., 1991; Story et al., 2003; Rutherford et al., 2004) assume thermal recovery as stream temperature should decrease when reaching shaded reaches downstream. Moreover, studies differ in temperature metrics offered including daily mean and/or maximum (Caldwell et al., 1991; Keith et al., 1998; Story et al., 2003; Rutherford et al., 2004), daily range (Wilkerson et al., 2006), and weekly averages of daily maxima (Zwieniecki and Newton, 1999; Wilkerson et al., 2006). Physically, the observed change in temperature between two locations in a shaded reach downstream of a warming reach can be affected by shade levels (Rutherford et al., 2004), flow volume and rate (Garner et al., 2014), groundwater inputs (Story et al., 2003), and microclimatic conditions (Benyahya et al., 2010). In addition, the main driver of daytime water temperature is the solar radiation, while at night other drivers such as long-wave radiation and convection of energy to the atmosphere are more relevant (Sinokrot and Stefan, 1993; Garner et al., 2014).

The Oregon Department of Forestry's Riparian Function and Stream Temperature (RipStream) project provides a framework to evaluate the effectiveness of forest practices rules and strategies at protecting stream thermal conditions for fish and wildlife habitat. The RipStream project examines the effects of timber harvest on stream temperature pre- and post-harvest in 33 harvested reaches (Dent et al., 2008; Groom et al., 2011a; Groom et al., 2011b) and in a subset of unharvested downstream reaches (Davis et al., 2015). Specifically, Dent et al. (2008) describe pre-harvest spatial and temporal patterns of stream temperature. Groom et al. (2011a) estimate the magnitude of temperature change in harvested reaches whereas Davis et al. (2015) provide a physical perspective of temperature change at the downstream reaches considering mean of maximum daily summer temperature. These studies, however, do not simultaneously integrate observed temperature changes over time and space.

Here, we build on the RipStream project to describe and evaluate stream temperature responses downstream of timber harvest over a variety of spatial and temporal scales. We focus on responses that may better account for changes in thermal regimes experienced by organisms, species and ecosystems; therefore, we adopt the use of a higher temporal resolution (daily and hourly) compared to moving weekly averages or other metrics used by regulatory agencies (EPA, 2003) or previous studies from the RipStream project. We hypothesized that changes in the temperature downstream of the treatment reach would be most pronounced during the first summer after timber harvest. In addition, temperature conditions downstream of the treatment reach would tend to return to the pre-harvest conditions over time. Collectively, our study is anticipated to provide novel tools that describe distinct spatiotemporal aspects of thermal regimes in streams. We predict that these proposed tools can be used to answer management questions related to downstream effects of different types of disturbances (including riparian restoration) occurring upstream over time and that these tools have the potential to be transferable to other streams elsewhere.