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EVALUATING LINKS BETWEEN FOREST HARVEST AND STREAM TEMPERATURE THRESHOLD EXCEEDANCES: THE VALUE OF SPATIAL AND TEMPORAL DATA[1]

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ABSTRACT: We present the results of a replicated before-after-control-impact study on 33 streams to test the effectiveness of riparian rules for private and State forests at meeting temperature criteria in streams in western Oregon. Many states have established regulatory temperature thresholds, referred to as numeric criteria, to protect cold-water fishes such as salmon and trout. We examined across-year and within-year patterns of exceedance at control and treatment stream temperature probes. Determining whether an exceedance at the downstream end of a harvest was unambiguously related to harvest proved surprisingly difficult. The likelihood of a site exceeding its numeric criterion appeared related, in part, to the site's preharvest temperature range. Four control reaches as well as three preharvest treatment reaches exceeded their numeric criteria, necessitating additional analysis to evaluate timber harvest impacts. Nine percent of sites (3 of 33) both exceeded their numeric criteria and exhibited a potential harvest effect (16.7% of private sites [3 of 18], 0% of State sites [0 of 15]). After harvest, exceedances were typically observed in only the first of the two post-harvest years. These findings highlight the importance of including temporal and spatial controls in temperature assessments of numeric criteria when the assessment's purpose is to determine whether exceedances are related to human activities.

(KEY TERMS: monitoring; environmental regulations; nonpoint source pollution; temperature; best management practices; forest harvest.)

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INTRODUCTION

Water temperature is a crucial habitat characteristic for fish (Lantz, 1971), affecting their growth (Beckman *et al.*, 1998), immune system functions (Alcorn *et al.*, 2002), and the timing of life-history traits (Brannon *et al.*, 2004; Richter and Kolmes, 2005). Where streams contain cold-water fishes such as salmon, steelhead, and trout, contemporary forest management practices are regularly evaluated with the intention of minimizing increases of stream temperature and protecting beneficial uses while maintaining a viable forest products industry.

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Past research in Oregon demonstrated that forest harvest practices in the 1960s dramatically increased stream temperatures (Brown, 1969; Brown and Krygier, 1970; Johnson and Jones, 2000). Riparian studies across North America, from Maine (Wilkerson *et al.*, 2006) and Georgia (Hewlett and Fortson, 1982) to British Columbia (Moore *et al.*, 2005b), also demonstrated similar increases in temperature with forest harvest, particularly (but not always) where minimal or no streamside buffers were retained. Oregon, like other states, enacted timber harvest regulations to maintain stream shade following timber harvest to mitigate stream temperature increases, and the rules have continued to evolve over time to incorporate emerging information. Early rules (ODF, 1975) had broad guidance to meet riparian management goals, including shade targets (*i.e.*, maintain 75% of original shade). Current riparian protection rules for State and private forest in Oregon (ODF, 2014) are more prescriptive and are intended to meet additional objectives, such as large wood recruitment. These vary across ownerships by stream size, presence of fish, and other beneficial use designations (ODF, 2014).

Background of Stream Temperature Criteria and Their Assessment

Timber harvest effects on stream water quality parameters, including temperature, are regulated by both federal and state agencies. The United States' Clean Water Act requires that states adopt water quality standards designed to maintain the chemical, physical, and biological integrity of the nation's waters (*U.S. Water Pollution Control Act Amendments of 1972*, Sections 101(a) and 303(c)). As the administrator of the Clean Water Act, the U.S. Environmental Protection Agency (USEPA) is charged with providing guidance to states to develop compliant water quality regulations (Section 304(a)(7)). USEPA's guidance for the Pacific Northwest (EPA Region 10) includes recommendations that states incorporate numeric criteria, or temperature thresholds, to protect cold-water salmonid life stages (USEPA, 2003). The states within the Northwest region (Oregon, Washington, Alaska, and Idaho) and those in other regions use research to inform numeric criteria thresholds for cold-water species.

In Oregon, the Oregon Department of Environmental Quality (ODEQ) established several stream temperature thresholds, referred to as the Biologically Based Numeric Criteria (numeric criteria; OAR 340-041-0028 (4)(b) and (c); ODEQ, 2004). The numeric criteria include a 16°C criterion for summer maximum temperatures for salmon and anadromous trout [*Oncorhynchus* spp.] core cold-water habitat and an 18°C criterion for sites that are used for rearing and migration by salmon and trout. Stream classifications are based upon fish distributions (ODFW, 2002), fish uses and habitats, and upon provision of cold water for downstream habitats. The temperature metric used to determine compliance is the 7 day moving average of daily maximum temperatures (7DAYMAX). The USEPA recommends this metric because it is not overly influenced by the measurements of a single day and can be used to protect against acute effects such as migration blockage conditions (USEPA, 2001). Oregon has an additional metric, the Protecting Cold Water (PCW) criterion, that prohibits degradation (warming) of existing cold waters and anthropogenic increases in 7DAYMAX stream temperatures of more than 0.3°C (ODEQ, 2004).

Assessments of numeric criteria are conducted in one of two ways and trigger different follow-up activities. The first type of assessment is a programmatic evaluation, where the impact of a single land-use activity like forestry is assessed across multiple sites to determine the efficacy of an established suite of best management practices (BMPs) or other regulatory programs for meeting legal or policy requirements. Programmatic evaluations can use an experimental design, incorporating site selection parameters and spatial and/or temporal controls. Findings from a programmatic evaluation may be used as evidence for the efficacy of current land-use BMPs or may trigger a process to reevaluate and potentially change them. The second method by which numeric criteria may be evaluated, *i.e.*, an "impairment assessment," is an official action under the Clean Water Act, and is generally more observational, involving monitoring within a stream, reach, or watershed of concern. Numeric criteria exceedances identified during an impairment assessment trigger a water quality impairment listing (*i.e.,* 303(d) listing) followed by an assessment of conditions (*e.g.*, modeling) to identify causes of and remedies for the exceedance through a water quality restoration plan (*i.e.*, Total Maximum Daily Load, 33 U.S. Code § 1313(d); ODEQ, 2008). Impairment assessments are not based on site-specific historical temperature data or reference (control) conditions and are triggered solely by numeric criteria exceedance in Oregon.

In many situations, land-use activities are considered compliant if they follow preidentified processes. All non-federal Oregon timber harvest operations are considered compliant with state water quality standards for enforcement purposes if harvest operations conform to the Oregon Forest Practices Act (FPA) (ODEQ, 2004). In turn, the Oregon Department of Forestry must periodically conduct studies to evaluate or verify that FPA rules are resulting in harvested sites meeting state water quality standards (ODF, 2014). Oregon Department of Forestry (ODF) initiated their Riparian Function and Stream Temperature (RipStream) study in 2002 as a programmatic evaluation of the efficacy of riparian rules and strategies at meeting water quality standards and achieving desired future riparian stand conditions on small- and medium-sized fish-bearing streams on State and private forests.

Objectives of This Study

Here, we measure the effectiveness of the current FPA rules (ODF, 2014) and the ODF State Forest Northwest Forest Management Plan (FMP, which includes riparian protections in addition to those required by the FPA; ODF, 2001) at maintaining stream temperatures below the numeric criteria following forest management. The study was designed as a programmatic evaluation with multiple years of pre- and post-harvest measurements on small and medium fish-bearing streams in the Oregon Coast Range.

We structured our analysis to achieve three goals: (1) examine numeric criteria exceedance patterns across control and treatment reaches; (2) where criteria are not met, evaluate whether exceedances are related to timber harvest; and (3) evaluate the efficacy of current state and private forest management programs and BMPs at meeting the numeric criteria for stream temperature. We intend for this analysis to serve as an example for other regions with similar water quality guidelines or regulations.

METHODS

Study Sites and Background Information

For this portion of the RipStream study, we examined stream temperature numeric criteria at 33 forested streams in the northern and central regions of Oregon's Coast Range (Figure 1). The streams were typically first- to third-order (1:24,000 scale), with 15 streams on Oregon Department of Forestry's State Forests (State forest sites) and 18 streams on privately owned timberland (private forest sites). Every stream site was divided into an upstream control and a downstream treatment reach (Figure 1 in Groom *et al.*, 2011b). The control reach remained unharvested over the course of the study. Here, we evaluate stream temperatures collected during two summers preharvest and two summers post-harvest.

Harvest treatments outside the riparian buffer were either clear-cut or partial-cut (thinned), with private forest sites predominantly harvested on both sides of a stream while State forest sites were harvested primarily on one side (Table 1). On non-federal forestland with fish-bearing streams, the FPA requires riparian management areas 15 and 21 m wide on designated small and medium fish-bearing streams, respectively. Contingent on the amount of conifer basal area available, landowners may conduct harvest within the riparian management area so long as they leave 3.7 m^2 (small stream) or 11.1 m^2 (medium stream) of conifer basal area per 305 m of stream length per side. No harvest may happen within 6 m of the stream. On State forests, the FPA applies along with the additional riparian retention measures of the FMP (ODF, 2001). The FMP prescribes three management zones for small and medium streams, measured as distance from the stream's bankfull width edge: an 8 m no-harvest zone adjacent to the stream, a middle zone from 8 to 30 m that is only entered to advance the stand toward a mature forest condition, and an outer zone, from 30 to 51 m in which harvest intensity depends on riparian stand characteristics (ODF, 2001). At RipStream sites, mean buffer widths for State and private sites ranged from 25 to 61 m and 19 to 41 m, respectively (Groom *et al.*, 2011a).

Water temperature data were collected pre- and post-harvest and in treatment and upstream control reaches to enable the separation of treatment effects from site and year effects. Optic Stowaway Temp and HOBO Water Temp Pro (Onset Computer Corporation, Bourne, Massachusetts) temperature data loggers (probes) were deployed each summer, from July 1 to September 15, at three stations at each site (Dent *et al.*, 2008; Figure 1 in Groom *et al.*, 2011b). Probes were placed in shaded locations where streamflow was relatively constant, with expected reliable summer depth and a well-mixed water column. Probe accuracy was verified pre- and post-deployment against National Institute for Standards and Technology-calibrated digital thermometers (Oregon Watershed Enhancement Board, 1999). The upstream control reach was bracketed by two temperature probes, with the Station 1 probe (St. 1) above the control reach and the St. 2 probe at the upstream harvest boundary, 137-345 m downstream from St. 1. The treatment reach was bracketed upstream by the St. 2 probe and at the downstream edge of the harvest unit by the St. 3 probe, 272-1,768 m downstream of St. 2.

Dent *et al.* (2008) described the study area and study design and summarized preharvest (2002-2005) site conditions. Riparian forests were harvest- or fire-regenerated and between 50 and 70 years old (Dent *et al.*, 2008). Conifer basal area (primarily Douglas-

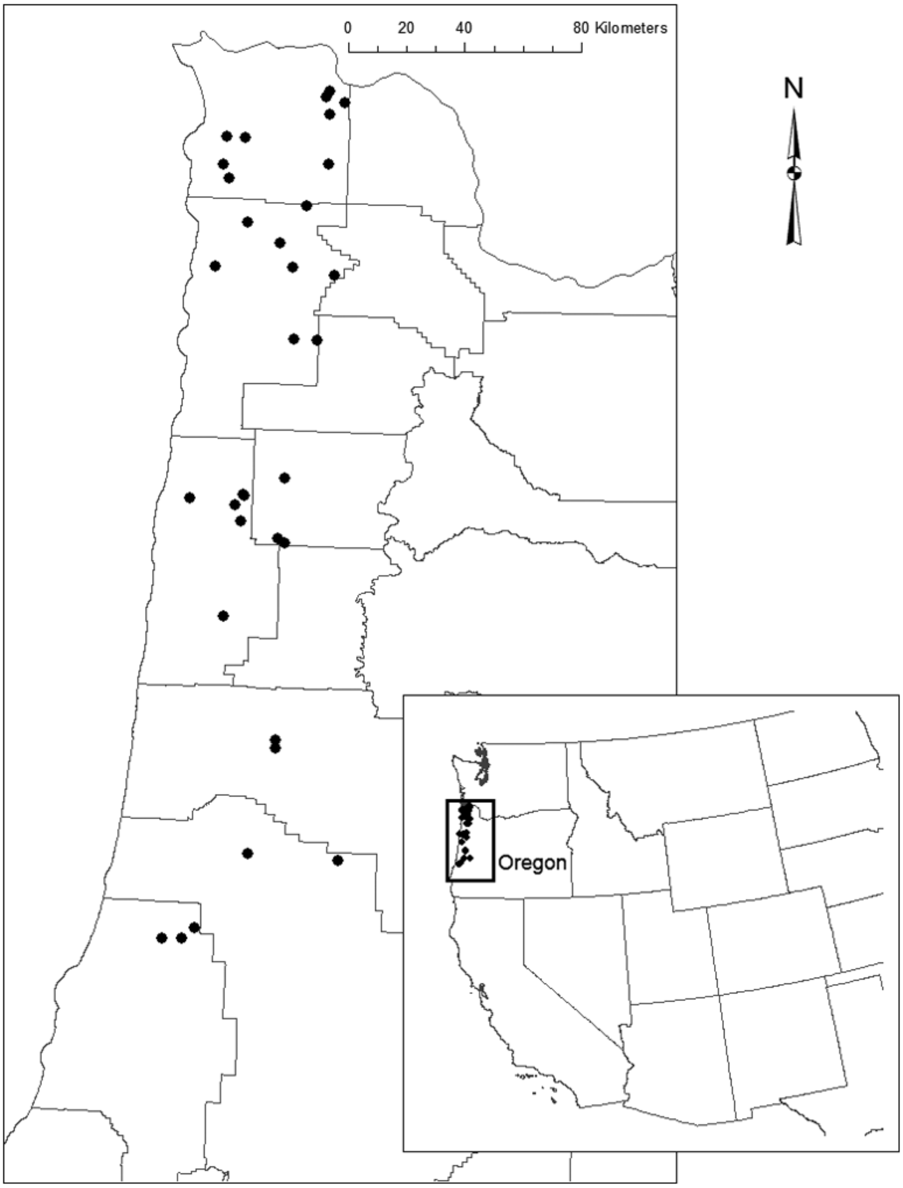

FIGURE 1. Map Study Site Locations. Locations are indicated relative to county boundaries (main map) and state boundaries (inset).

fir, *Pseudotsuga menzeisii*) increased with distance from the stream, with hardwoods (*e.g.*, *Alnus rubra*) generally more common closer to the streams. Streams were generally confined and well-shaded (preharvest mean effective shade for all reaches = ~ 86%, SD ~ 7%, $n = 36$), with fines and gravel mainly comprising the substrate. Mean channel gradient in treatment reaches was 6.5% (SD = 4.2%), and wetted width averaged 2.1 m (SD = 0.8 m). Discharge data were unavailable for individual sites, and most sites lacked air temperature measurements. Site selection criteria for these small (mean annual streamflow <57 L/s) and medium streams (57-283 L/s) (ODF, 2014) required that they were not influenced by recent beaver activity or recent debris flow impacts.

Three post-harvest analyses addressing other criteria and responses have been published to date. Groom *et al.* (2011b) performed a programmatic evaluation of site stream temperatures relative to the Protecting Cold Water criterion and found that harvest on privately owned forests increased the frequency of criterion exceedances, while harvest on State-owned forests did not. Groom *et al.* (2011a) evaluated site characteristics associated with observed temperatures before and after harvest, and estimated the magnitude of stream temperature change related to harvest after controlling for site

TABLE 1. Study Site Riparian Harvest Treatment and Numeric Criteria Information.

		Harvest Type		Sides Harvested		Numeric Criteria	
Ownership	Sites	Clear-cut	Partial-cut	One	Two	16°C	18°C
State forests	15	8	7	13	2	6	9
Private	18	18	0	4	14	10	8
Total	33	26	7	17	16	16	17

features. On privately owned sites, maximum stream temperatures increased on average 0.7°C (range = −0.9 to 2.5°C). Post-harvest stream shade was an important variable for a statistical model of stream temperature increases; shade levels were positively related to the remaining riparian stand basal area and, more weakly, inversely related to tree height. Davis *et al.* (2016) developed a mechanistic model predicting changes in stream temperature downstream of harvest and predicted that 50% (range = 82% to < 1%) of the temperature increase would persist downstream after streams flowed through 300 m of unharvested riparian forest.

Analysis

For this study, we calculated 7DAYMAX values using hourly stream temperature data from all pre-harvest and the first two post-harvest years to evaluate the maximum responses of stream temperatures following treatment (Quinn and Wright-Stow, 2008). We then examined 7DAYMAX water temperatures at St. 1 through St. 3 to identify reaches that exceeded their numeric threshold (16 or 18°C) on at least one 7-day period in each year. We labeled 7DAYMAX data points that exceeded the numeric criteria and coincided with dates of extreme air temperature or low flows (see below) to determine whether their removal would affect results. We also examined 7DAYMAX temperature exceedances between treatment and control stations and between pre- and post-harvest conditions to contextualize numeric criteria exceedance patterns and identify potential harvest signals.

In our initial analysis, we found that not all numeric criteria exceedances coincided with timber harvest (see Results), necessitating a statistical approach for addressing the second and third goals of this study. We developed a statistical test of all sites that exceeded numeric criteria at St. 3 for one or more years post-harvest. For these sites, we examined paired 7DAYMAX St. 2 and 3 temperatures, and considered a statistically significant change in the relationship between the two temperatures, coinciding with timber harvest, to indicate that timber harvest was responsible for the observed increase. These findings are subject to a degree of error; insufficient statistical power, due to limited data, may result in false-negative findings if harvest-related warming occurred but tests were not significant. Conversely, we may falsely attribute warming to harvest if the warming spuriously coincides with timber harvest (*i.e.*, the relationship between St. 2 and 3 changes during the first year post-harvest due to other causes). The approach's strength is that for an individual site it incorporates both control and treatment (St. 2 and 3) data over all years used in the study. We modeled these sites' St. 3 temperatures with a Generalized Least Squares (GLS) regression with the following three linear models:

$$St_3 \sim \beta_0 + \beta_1 St_2 + \beta_2 I + \beta_3 St_2 I + \varepsilon_t \quad (1)$$

$$St_3 \sim \beta_0 + \beta_1 St_2 + \beta_2 I + \beta_3 St_2 I + \beta_4 day + \beta_5 day I + \varepsilon_t \quad (2)$$

$$St_3 \sim \beta_0 + \beta_1 St_2 + \beta_2 I + \beta_3 St_2 I + \beta_4 day + \beta_5 day I + \beta_6 day^2 + \beta_7 day^2 I + \varepsilon_t \quad (3)$$

In Equations (1-3) St. 3 (St_3) 7DAYMAX values are expressed as a function of St. 2's 7DAYMAX temperature (St_2) plus an indicator variable signifying whether data were collected from a preharvest ($I = 0$) year or a post-harvest ($I = 1$) year and an interaction term for the two variables. The term *day* refers to the (centered) Julian date corresponding to the mid-point date of the 7DAYMAX temperatures. We included *day* and day^2 to allow the temperature relationship between the St. 2 and St. 3 probes to change over the course of the season in a linear or quadratic fashion (*i.e.*, avoid forcing a static relationship between the stations when streamflow or other features may seasonally change). The Julian date and St. 2 temperature values were centered for the analyses. As in Groom *et al.* (2011b), we interpret a significant *p*-value for *I* indicates that for average values of St. 2 (and *day* and day^2 if in the model) the temperatures differ between pre- and post-harvest at St. 3 by the value of β_2. We interpreted such a finding, at $\alpha = 0.05$, as indicative of a possible harvest signal.

We modeled the error term ε_t for all models as a first-order autoregressive term and two moving-average parameters to account for the non-independent nature of the 7DAYMAX temperatures

$$\varepsilon_t = \phi_1\varepsilon_{t-1} + \theta_1 a_{t-1} + \theta_2 a_{t-2} + a_t \quad (4)$$

where ϕ_1 is a first-order autoregressive parameter at time $\varepsilon_{t\text{-}1}$ and θ_1 and θ_2 are the moving-average parameters at lags t-1 and t-2, respectively. Term a_t is the homoscedastic (white) noise term centered at 0 and is assumed independent and identically distributed at times t, t-1, and t-2 (Pinheiro and Bates, 2000).

We examined model Akaike information criterion (AIC) values, q-q normal plots, and residual plots to find a model that adequately fit the data. We also graphically evaluated the sufficiency of the error term structure at minimizing autocorrelation. This analysis is similar to the one presented in Groom *et al.* (2011b), but differs in that it examines a mean response of temperatures across all years considered at a site instead of determining if individual data points from the second of two years fell outside of specified intervals.

Special exemptions to the ODEQ numeric criteria occur when air temperatures are extremely high (air temperature exclusion [ATE]) or when streamflows are low (Low Flow Conditions [ODEQ, 2004]). High temperatures are determined by examining at least 10 years of continuous air temperature data and finding if, on the dates when exceedances were observed, the daily maximum air temperatures for the day(s) in question were above the 90th percentile of annual maximum of the 7-day average of maximum daily air temperatures (ODEQ, 2004). We used air temperatures from Remote Weather Stations (RAWS) geographically closest to our study sites for which we could obtain 10+ years of continuous data, including our study period as an index of extremely warm days in this region. The maximum distance between any one of the ten local RAWS used and a site was 49.1 km (median = 17.7 km). We calculated the warmest 7DAYMAX air temperature for each year of the previous 10-15 years (depending on availability) of daily air temperature data and used a log gamma distribution to calculate 90th percentiles of the maximum annual 7DAYMAX. We compared untransformed daily temperatures against the ATE distribution's 90th percentile. We recorded the dates for which maximum air temperatures exceeded the 90th percentile and discounted water temperature exceedances detected at nearby study sites whose 7DAYMAX values were centered on those dates.

Oregon water quality rules also allow the exemption of 7DAYMAX temperatures from numeric criteria evaluation when streamflows fall below the 7Q10 Low-Flow Conditions for that water body (ODEQ, 2004). The term 7Q10 is defined as the lowest 7-day average flow that occurs (on average) once every 10 years (Water Quality Standards Regulation, Proposed Rule, 63 Fed. Reg. 36764 [7 July 1998]). We calculated low-flow conditions according to the documentation provided by the USEPA program DFLOW (version 3.1, http://water.epa.gov/scitech/datait/models/dflow/index.cfm, referenced by ODEQ [2008]) to calculate the 90th percentile and to identify Low-Flow Conditions. Only two gages, USGS gage 14303200 (Tucca Creek near Blaine, Oregon) and 14306340 (East Fork of Lobster Creek near Alsea, Oregon) were available that (1) provided 10 or more years of data, (2) were active during our study, (3) were not impounded upstream, and (4) gaged watersheds whose drainage area was within an order of magnitude of our watersheds' areas. The greatest geographical distance from the nearest gage to a site was 90 km. We removed 7DAYMAX dates from the analysis that coincided with Low-Flow Conditions. We recognize that stream gages and weather stations at distance from sites may not accurately represent site-specific conditions but we use them as representative of regional weather patterns that determine the magnitude and duration of the warmest summer air temperatures and lowest flows.

RESULTS

Numeric criteria exceedances were not always associated with harvest. Of the 33 sites, ten (30%) exceeded their numeric criteria at least at one station, and seven (21%) exceeded their numeric criteria at St. 3 post-harvest (Figure 2). Three of these seven sites also had exceedances of 7DAYMAX stream temperatures during their preharvest years and four sites were below the threshold preharvest. Two of the seven sites (5,205, 7,854) with only post-harvest exceedances at St. 3 did not have exceedances at St. 1 or St. 2. The other five sites showed a mix of exceedances preharvest or at their control stations. Three of the five exceeded their numeric criterion at St. 3 both before and after harvest (5,355, 7,353, and 7,801), while two others did not exceed St. 3 preharvest but did exhibit exceedances at the control probes (5,201, 5,556).

Air temperatures exceeding the 90% ATE criterion resulted in the removal of two site-level exceedances (Figure 2): St. 1 for site 5,202 (post-2) and St. 1 for site 5,355 (post-1). These removals did not affect the interpretation of any St. 3 exceedances. July and August air temperatures for post-harvest years (for 32 out of 33 sites, 2004 onward) appeared similar to or lower than preharvest years (2002-2005, with two sites having preharvest status in 2006; Figure 3). The Low-Flow Conditions rule did not trigger removals as only one date at one gage (14303200 on 6

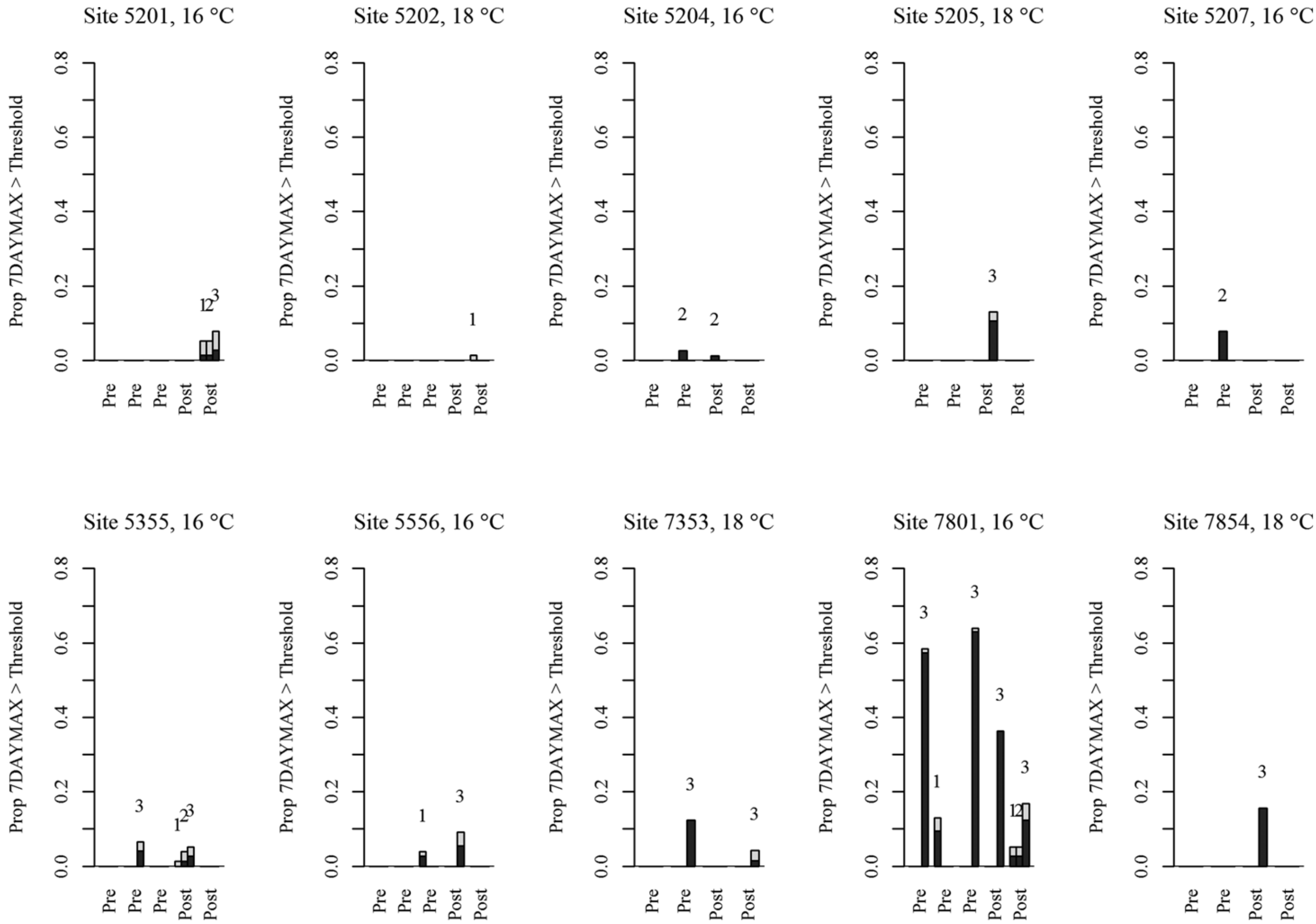

FIGURE 2. The Proportion of Time that Mean of 7 Daily Maximum (7DAYMAX) Temperatures Exceeded Numeric Criteria at Sites That Had Exceedances during the Study Period. Years are indicated as pre (harvest) or post (harvest). The number above each bar identifies the station (St. 1, 2, or 3) at which the exceedances took place. Light gray section of bars represents 7DAYMAX values not considered exceedances according to the Air Temperature Exclusion.

September 2003) qualified for exemption. No recorded temperatures at nearby sites exceeded 16 or 18°C on that date.

We examined the distributions of St. 3 temperatures relative to harvest by plotting 7DAYMAX temperature values pre- and post-harvest at St. 3 (Figure 4). Seven sites exceeded their numeric criteria at St. 3 though other sites did appear to exhibit possible harvest-related temperature increases, with the range of 7DAYMAX values extending to higher temperatures post-harvest. The frequency of site exceedance of numeric criteria appears to be related to the background temperature regime of individual streams; streams that approached or exceeded the numeric criteria preharvest appeared more likely to exceed the numeric criteria than colder sites. For instance, site 5,204 seems to have experienced a temperature increase post-harvest, but it would require approximately a 2°C increase in the highest preharvest values to broach its 16° numeric criteria limit. Considering all sites and preharvest years together, the median value of summer maximum 7DAYMAX values at St. 3 would require an increase of 2.5°C for 16°C numeric criterion sites to register an exceedance, while the median value for 18°C sites would need an increase of 3.6°C. The coolest summer maximum 7DAYMAX values were 11.6 and 11.38°C for 16 and 18°C numeric criteria sites, respectively.

We examined the frequencies of numeric criteria exceedance patterns by determining the proportion of a station's summer 7DAYMAX measurements above the numeric criteria (Figure 2). For those sites that exceeded their numeric criterion at least once, the proportions of summer measurements greater than numeric criteria ranged from 1.3 to 64% across all St. 1, 2, and 3 probes (with ATE days removed). Generally, if a station's 7DAYMAX temperatures exceeded

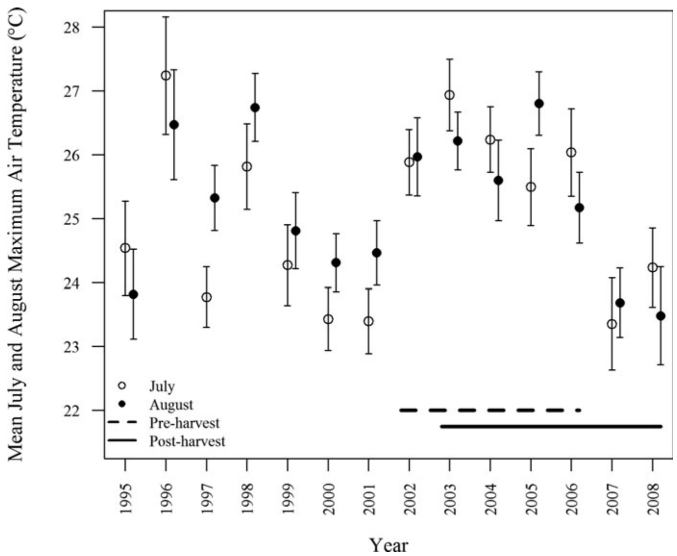

FIGURE 3. For Calculation of Air Temperature Exclusion Periods, Which Are Used as an Indicator of an Especially Warm Period, Means and Standard Errors (SE) of Maximum Air Temperatures from Coastal Remote Area Weather Stations (RAWS) Are Shown. Means of July and August daily maximum air temperatures (± 2 SE) are shown from the ten sites closest to our study streams. Five RAWS stations were operational in 1995 and 1996, eight in 1997, and all ten for remaining years. Horizontal lines indicate years in which one or more sites were either in preharvest (dashed) or post-harvest (solid) conditions.

their numeric criteria in a season, they did so on fewer than 20% of the days. Of the 22 station-years that exceeded their numeric criteria, seven station-years (32%) exceeded it for more than 10% of the days during a single summer, four of which (18%) were site 7,801's St. 3 (Figure 2). During those years, 7,801's St. 3 exceeded the numeric criteria for 60% of preharvest 7DAYMAX values and for approximately 40 and 20% of 7DAYMAX values in post-harvest years 1 and 2, respectively, indicating that the stream was not meeting its numeric criteria irrespective of timber harvesting effects.

Of the seven sites that exceeded their numeric criteria at St. 3 post-harvest (Figures 2 and 4), three appear to have done so as a consequence of harvest. The GLS analysis found that sites 5,205, 5,556, and 7,854 had statistically significant pre- to post-harvest increases in stream temperatures between St. 2 and St. 3 (control and treatment stations, Table 2). These three sites, which exhibited statistically significant p-values for I, the harvest indicator variable, each had smaller p-values than corresponding false discovery rate corrections ($\alpha = 0.05$) or a Bonferroni correction factor of $\alpha/7 = 0.0071$. Two out of the three sites, 5,205 and 7,854, had their only exceedances at St. 3 during the post-harvest period. Site 5,556 exceeded St. 1 during one preharvest year. The numeric criteria exceedances at the remaining four sites (12%) did not appear to correspond with harvest as their changes in slope intercept were not statistically significant and generally negative (three out of four sites). Site 7,854 (one year of post-harvest data) exhibited a 2.16°C across-season post-harvest increase, site 5,205 a 2.06°C increase, and site 5,556 a 1.04°C increase. The GLS models predicted that these three streams would have remained below their numeric criteria in the absence of harvest, assuming that the relationship between St. 2 and St. 3 remained constant between preharvest and post-harvest years. All three of these sites were on private forestland.

DISCUSSION

In this study of current riparian management practices during forest harvest in the Oregon Coast Range, temperatures in small and medium streams were generally below their numeric criteria before and after timber harvest. This analysis, using temperature data collected pretreatment and at upstream control sites, allowed us to begin to disentangle the forest harvest effect from other drivers of stream temperature exceedances of numeric criteria. Three sites had exceedances that appeared to be related to timber harvest, while other sites appeared to exceed their numeric criteria for other reasons. Although some sites exhibited treatment reach temperatures that exceeded their numeric criteria post-harvest, a portion of these sites also exceeded their criteria during the preharvest period. Sites additionally exceeded their numeric criteria upstream of harvest. These findings highlight the importance of including temporal and spatial controls in programmatic assessments of best management practice effectiveness relative to numeric temperature criteria.

Absolute thresholds for numeric criteria can serve multiple functions but also have limitations. Assessing a stream's compliance with a numeric criterion is relatively straightforward for managers and landowners. Thresholds provide a simple screening metric for potentially limiting conditions, designed to alert us to stream conditions warm enough to impair aspects of fish biology and physiology (*e.g.*, growth, survival, movement, disease resistance, spawning success; see references in USEPA, 2001).

One challenge with using thresholds for numeric criteria is that exceedances of the thresholds do not incorporate causes, severity, or duration of high stream temperatures. Thresholds can be exceeded in undisturbed streams or during pretreatment periods. In this study, some sites were frequently above their

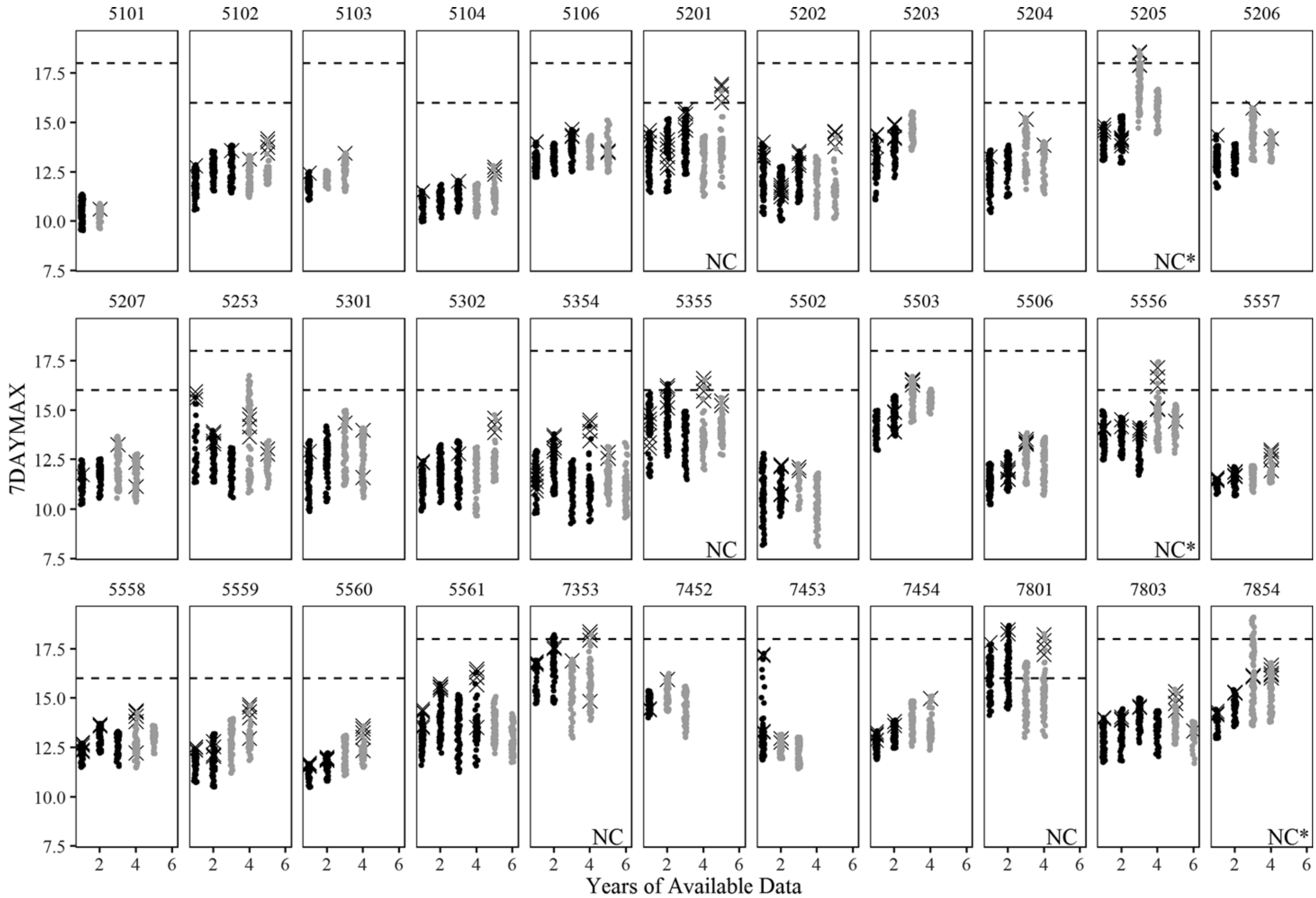

FIGURE 4. 7DAYMAX Temperatures at St. 3 for the Period July 1-September 15 for All Years Included in the Analysis. Site identification numbers appear above each site's data. Black dots are preharvest years, gray dots are post-harvest. X's are temperatures that would not have been considered exceedances because of high summer air temperatures during that period (ATE). The dashed lines show the numeric criteria threshold for each site. Sites that exceeded their numeric criteria at St. 3 are identified with an "NC", and those that additionally exhibited a potential harvest signal have an asterisk ("NC*").

numeric criteria prior to harvest, and therefore are less likely to exceed their numeric criteria as a consequence of recent timber harvest. Ice *et al.* (2004) noted examples of "least impaired" streams that exceeded their numeric criteria even in wilderness areas in the Northwest U.S.

Absolute thresholds also allow differential warming due to land management activities. Some of our streams could have exhibited temperature increases of up to 6.0°C and would still be below their numeric criteria, while an already warm stream could cross the threshold with little increase. For more than half the years in the study, increases of more than 2.5°C could have occurred at the treatment reaches without causing numeric criteria exceedances. Similarly, Bladon *et al.* (2016) showed significant increases in summer stream temperature after harvest, yet they observed no exceedances of the relevant numeric criterion. A different Oregon water quality criterion, the PCW, prevents the warming of waters cooler than the numeric criteria in order to preserve the diversity of stream temperatures across stream networks. It does not allow anthropogenic increases of more than 0.3°C, and is more labor- and data-intensive to measure than simple absolute thresholds (see Groom *et al.*, 2011b).

An examination of exceedance frequency and spatial distribution within and among years (Figure 2) provided information on numeric criteria exceedance occurrence and duration patterns that was of value in assessing harvest impacts on stream temperatures as well as the severity of impairment. Without preharvest and control data, we could have falsely interpreted some sites' exceedances as responses to current timber harvest. For these streams, exceedances could have been in response to sources and flow paths of stream water, upstream disturbances, or the legacy effects of prior disturbance or management practices

TABLE 2. Model Selection and Parameter Estimation for Detecting Possible Timber Harvest Effect for Sites with Post-Harvest St. 3 7DAY-MAX Exceedances.

	Sites						
	5,201	**5,205**	**5,355**	**5,556**	**7,353**	**7,801**	**7,854**
Threshold	16°C	18°C	16°C	16°C	18°C	16°C	18°C
Model selected†	1	1	2	1	3	2	1
Parameters							
Intercept	13.566***	14.113***	14.047***	13.472***	15.049***	16.180***	14.053***
St_2	0.903***	0.923***	1.050***	0.923***	0.815***	1.239***	0.500***
I	−0.044	2.063***	−0.077	1.040***	1.174	−0.720	2.158**
St_2I	0.082***	0.237*	−0.084***	0.282***	−0.004	−0.140*	0.665***
Day	-	-	−0.003	-	−0.021*	−0.010	-
$dayI$	-	-	−0.002	-	0.001	−0.002	-
day^2	-	-	-	-	0.000	-	-
day^2I	-	-	-	-	−0.001	-	-
ΔAIC Model 1	0.00	1.34	7.63	0.00	7.50	2.75	0.00
ΔAIC Model 2	3.42	0.00	0.00	2.79	0.36	0.00	3.79
ΔAIC Model 3	6.48	1.77	3.22	0.74	0.00	3.14	4.51
Pre-post change‡	No	Yes	No	Yes	No	No	Yes

Notes: AIC, Akaike information criterion.
†Refers to formulation of linear models (Equations [1], [2], or [3]).
‡Term for I significant and positive, indicating possible timber harvest effect.
Parameter $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

on flows, substrates, stream structure, or riparian vegetation (Poole and Berman, 2001; Johnson, 2004; Hester *et al.*, 2009).

Identifying sites that have high potential to exceed temperature thresholds following harvest may help refine management practices and standardize outcomes. For example, sites frequently near or above thresholds prior to harvest could be targeted for harvest plan modifications or additional riparian protections during and after harvest. Comprehensive site assessments and customized management strategies could be a viable approach for avoiding warming with harvest at these more sensitive locations so long as stream temperatures preharvest are known. Site assessments could discover legacy conditions in need of remediation, such as simplified bedrock channels, streams widened by sedimentation, or disturbances upstream, for example. Alternatively, strategies to generally preserve existing stream shade or increase riparian vegetation retention could serve the same function.

Current forest harvest practices on State and private forests in western Oregon have resulted in smaller increases of temperature than occurred with historical forest practices (Levno and Rothacher, 1967; Brown and Krygier, 1970; Hewlett and Fortson, 1982). Groom *et al.* (2011a) found small average increases in maximum daily temperatures (mean increase for State sites = 0.0°C, private sites = 0.7°C). The magnitude of temperature exceedances was much smaller than following previous forest harvest activities, demonstrating a substantial improvement in protection of water quality during forest management.

Our observed differences between State and private sites may have been due to differences in harvest intensity and/or riparian management. State forest sites experienced less loss of shade (Figure 4, Groom *et al.*, 2011a), likely due to greater riparian retention, thinning rather than clearcutting, and a greater prevalence of one-sided harvests (Table 1). We cannot disentangle the individual effects of these three differences in management approaches with this dataset and suggest that all three are worthy of further consideration, although effects of riparian shade on temperature have been much studied (Johnson, 2004; Moore *et al.*, 2005a; Groom *et al.*, 2011a).

The PCW criterion analysis (Groom *et al.*, 2011b) and this analysis of the Biologically Based Numeric Criteria call attention to different aspects of the thermal regime of streams. The PCW analysis found that 7DAYMAX temperatures were more likely to warm by more than 0.3°C between pre- and post-harvest periods at private sites compared to control reaches or other time periods. State forest sites were not more likely to warm after harvest. The numeric criteria analysis showed potentially harvest-related increases at three private forest sites, indicating that current forestry activity generally met criteria conditions. These different metrics and approaches (a temperature change analysis *vs*. a temperature threshold analysis) are targeting two complimentary aspects of stream temperatures. The PCW highlights anthropogenic degradation of existing cold water, whatever the stream temperature might be, and the other highlight those increases that exceed a biologically based absolute threshold.

Although the ATE and 7Q10 were expected to identify and exclude exceptional conditions from the numeric criteria evaluation, their consideration did not alter our overall results. The number of 7DAYMAX temperatures examined was reduced, but because of the timing of warmer than normal air temperatures and low flows relative to harvest responses, few stations that exceeded numeric criteria were excluded from the analysis. The post-harvest years, including 2007 and 2008, did not exhibit exceptionally warm weather (Figure 3), nor did they correspond to exceptional low-flow events. In a warm and dry year, we might expect more sites, both with and without harvest-related temperature increases, to exceed their numeric criteria. Additional field work and model simulations could examine site-specific ATE and 7Q10 periods under a broader range of climatic conditions, as well as investigate the synchrony of regional RAWS stations and regional stream gages with local microclimatic and hydrologic conditions at streams across the Coast Range. These results indicate that during this study's time frame, exceptional flow and air temperature (*i.e.*, climatic) conditions were less important in driving numeric criteria compliance than site-specific conditions and management actions.

Conceptually, there are some analytical similarities between the GLS analyses and an impairment assessment. An exceedance of numeric criteria detected as part of an impairment assessment triggers a federal water quality listing that then requires further evaluation to determine whether the exceedances were due to anthropogenic factors and/or whether the stream temperature at that site is likely to be below the criterion under "natural" conditions. The evaluation involves analysis of human and natural heat sources and loads and the development of a plan to attain the temperature water quality standard if necessary (*e.g.*, development of a Total Maximum Daily Load; TMDL). Had the sites in our study been evaluated as part of a routine impairment assessment, seven sites with harvest-reach exceedances would have been listed, evaluated further, and required development of a TMDL or other plan. A simple examination of numeric criteria exceedance patterns and frequencies was not informative regarding whether or not exceedances were likely due to harvest. The GLS test was necessary to simultaneously incorporate preharvest and upstream control data, and the statistical power of the GLS analyses benefitted from the study's multiple pre- and post-harvest years of data collection per site. Although the RipStream study took longer to execute than a standard impairment assessment, the resulting data enabled an empirical test of anthropogenic effects (harvest) on stream temperature that is not possible with an impairment assessment.

This study examines the immediate and local effects of forest harvest on stream temperatures. It does not address effects of multiple harvests, in space or time, on compliance with numeric criteria thresholds. Because of the rapid rate of riparian vegetation reestablishment in western Oregon, we do not anticipate that harvest-related exceedances of numeric criteria from individual harvests will extend beyond 5-10 years, especially because the reductions in shade measured in the RipStream study were small (on average, 7% reduction in shade on private forests, 1% on State sites; Groom *et al.*, 2011a). Other studies of stream temperature responses to forest harvest had complete or nearly complete removal of shade (Harris, 1977; Andrus and Froehlich, 1991; Johnson and Jones, 2000), and showed return to preharvest conditions and temperatures in 10-15 years.

CONCLUSION

Forest harvest activities conducted according to the Oregon Forest Practices Act rules and the State Forest Northwest Oregon Forest Management Plan met ODEQ biologically based numeric criteria at 26 of the 33 treatment sites. Streams that were already warm appeared most likely to exceed the numeric criteria. Three of the seven treatment sites that exceeded numeric criteria did so in a manner that was consistent with a timber harvest signal; at only one of these three sites were exceedances measured both years post-harvest. All sites that showed exceedances were harvested according to FPA rules for private forest land. Sites on State forest land harvested according to the FMP rules did not show exceedances. These results contrast with analysis results for another temperature criterion, Protecting Cold Water (Groom *et al.*, 2011b), where these private sites exhibited a greater probability of increasing more than 0.3°C following harvest than preharvest years or control reaches. Overall, forest harvest conducted according to current FPA rules has some potential to result in exceedances of absolute stream temperature thresholds, especially if the streams are near their numeric criteria thresholds already.

Although regulatory thresholds have strengths and weaknesses, benefits of the numeric criteria's framework include its simplicity in application and its relevance for cold-water salmonids. It is a functional means of screening or identifying locations of water quality problems, but does not by itself convey information on causes. Exemptions intended to excuse exceedances of numeric criteria during periods of exceptionally warm air temperatures or low streamflows did not generally change findings at our sites. We found pre- and post-treatment stream temperature data at upstream control sites and at the downstream harvested (treatment) sites necessary for interpreting and disentangling the response of stream temperature to forest harvest from observations of spatial and temporal variability in stream temperature, and we recommend similar monitoring approaches for studies of land management program compliance with water quality regulations.

DATA AVAILABILITY

Data are available from the Oregon Department of Forestry's Private Forests Division (http://www.oregon.gov/ODF/Working/Pages/default.aspx).

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