Project title: Effectiveness of Class II Watercourse and Lake Protection Zone (WLPZ) Forest Practice Rules (FPRs) and Aquatic Habitat Conservation Plan (AHCP) Riparian Prescriptions at Maintaining or Restoring Canopy Closure, Stream Water Temperature, Primary Productivity, and Terrestrial Habitat

PIs: Kevin Bladon, Catalina Segura, Matt House, Drew Coe

Collaborators: Oregon State University, Green Diamond Resource Company, CAL FIRE, California Department of Fish and Wildlife

Critical Question Themes and Rules or Regulations being Tested: Theme 1: WLPZ Riparian Function

Objectives and scope:

The broad objectives of the proposed research were to address critical questions associated with the high priority thematic area (EMC Strategic Plan Theme 1-WLPZ Riparian Function (Effectiveness Monitoring Committee, 2018) related to watercourse and lake protection zones (WLPZ) of Class II-L watercourses in the Coast District (See 14 CCR § 916.9 [936.9,956.9] (c) (4)). With our project, we were able to address the following questions:

a) How do the current FPRs and GDRCs AHCP Class II riparian requirements influence important controls on streamflow and water quality? Factors influencing the streamflow and water quality response that we were able to address, included catchment area harvested, riparian canopy closure, solar radiation, and near-stream air temperature during the summer low flow period.

b) What is the relative importance of the different drivers (objective a) in influencing the variability in streamflow, stream temperature dynamics (e.g., maximum, minimum, diurnal variations), nutrients, and primary productivity during summer low flow across different Class II WLPZ prescriptions?

c) Are the different Class II WLPZ prescriptions effective at mitigating undesirable changes in stream thermal conditions, as well as nutrients and primary productivity following forest harvesting activities across a range of scenarios?

Study Description

We conducted our study in 18 catchments in Northern California (Figure 1b). We selected headwater catchments that were tributaries to the lower Klamath River (i.e., Tarup, Ah Pah, McGarvey, and West Fork Tectah, East Fork Tectah; Figure 1c-1f). Catchments were located on private timber land owned by Green Diamond Resource Company (GRDC). All streams were step pool systems with a few small cascades and abundant large wood. While the streams were considered perennial, dry weather between 2019 and 2022 led to some stream sections going dry during the summer (June–August; streams 4, 11, 13, 15, and 18).

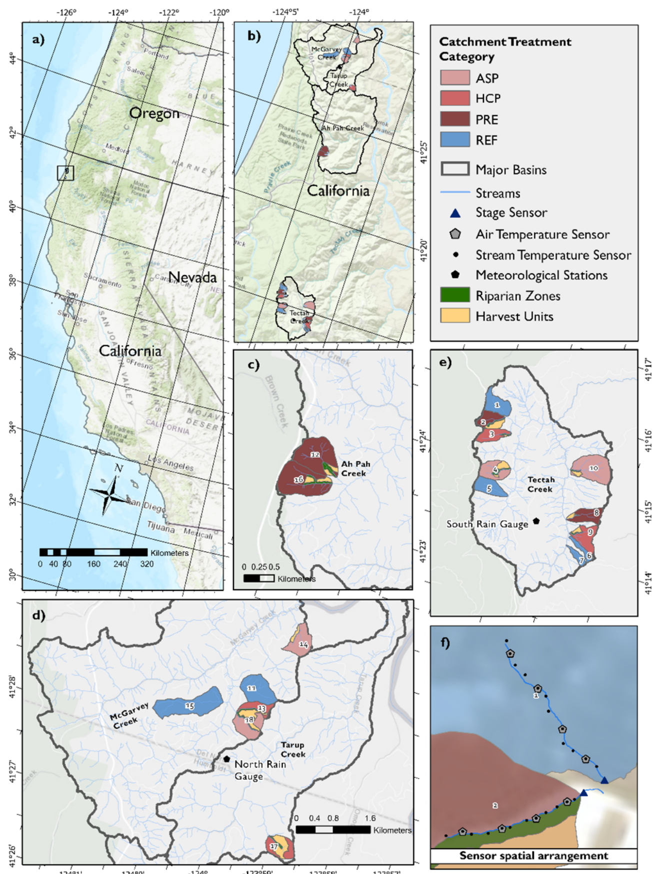

Figure 1. Maps of (a) the location of the study sites in California and (b) the spatial relation of all study catchments. Additional maps of site identification, harvest units, and riparian buffer prescriptions (reference (REF), Anadromous Salmonid Protection Rules (ASP), GDRC Habitat Conservation Plan (HCP), and before ASP regulations (PRE)) for (c) Ah Pah Creek, (d) McGarvey and Tarup Creeks, and (e) Tectah Creek. (f) Map providing an example from two sites (sites 1 and 2) illustrating the spatial arrangement of air and stream sensors along the stream channel.

The catchments ranged in area from 10 to 66 hectares and were located between 200 to 695 m in mean elevation (Table 1). Catchments varied in average aspect with east, southeast, southwest, and south directions. Average catchment slope varied between 31 and 60 %, with the steepest catchments located in McGarvey Creek sub-region. The climate in the study region is characterized as temperate and maritime with a distinct wet-dry seasonality with considerable influence from coastal fog. Summers are warm and dry, and winters are mild and wet, with average annual air temperatures of approximately 12 °C. The majority of precipitation occurs as rainfall between October and May. The average annual rainfall is 2,800 mm in Tectah Creek, 1,830 mm in Ah Pah Creek, 1,980 mm in Tarup, and 1,870 mm in McGarvey Creek according to data from PRISM (1991–2020 normals). The overall regional average for this same period was ~2,110 mm of precipitation annually (PRISM Climate Group, 2014). Accordingly, the annual peak streamflow typically occurs during mid-winter (~December to January) and the annual low flows occur during late summer (~August to September).

Table 1. Site information, including riparian buffer prescription (REF: Reference; ASP: Anadromous Salmonid Protection Coastal Anadromy Zone Class II-L; HCP: GDRC Habitat Conservation Plan; PRE: pre-ASP), catchment area, area harvested, total riparian area, and catchment topographic characteristics.

Catchment Number	Watershed	Riparian Buffer Prescription	Catchment Area (ha)	Catchment Harvested Area (ha)	Riparian Area (ha)	Mean Elevation (m)	Mean Slope (%)	Basin Aspect	Average Space betwwen T_s sensors (m)	Pre-Harvest End
1	WF Tectah	REF	32.8	-	-	541	48.1	SE	34	-
2	WF Tectah	PRE	28.5	7.7	2.0	534	47.0	SE	28	2020-11-01
3	WF Tectah	HCP	25.2	0.6	1.1	539	46.4	SE	34	2020-09-14
4	WF Tectah	ASP	37.5	7.1	3.2	539	43.0	SE	30	2020-09-14
5	WF Tectah	REF	30.6	-	-	559	34.4	E	28	-
6	EF Tectah	REF	11.0	-	-	678	32.9	SW	23	-
7	EF Tectah	REF	10.4	-	-	695	34.5	SW	13	-
8	EF Tectah	PRE	30.8	2.4	0.3	647	31.3	SW	32	2020-07-20
9	EF Tectah	HCP	33.5	2.8	1.1	678	33.6	SW	21	2020-05-31
10	EF Tectah	ASP	66.2	2.8	0.9	591	37.1	SW	28	2020-09-26
11	McGarvey	REF	39.8	-	-	209	58.7	S	26	-
12	Ah Pah	PRE	39.0	2.1	2.1	415	50.9	SE	14	2020-03-08
13	McGarvey	HCP	18.8	3.9	2.0	218	47.5	SW	24	2020-10-05
14	McGarvey	ASP	29.1	2.5	-	210	57.1	S	13	2020-08-06
15	McGarvey	REF	61.0	-	-	200	51.2	SE	26	-
16	Ah Pah	PRE	41.9	3.1	2.3	428	43.8	SE	24	2020-03-08
17	Tarup	HCP	28.0	11.9	1.8	316	59.4	S	23	2020-01-02
18	McGarvey	ASP	33.3	6.4	2.9	205	47.7	S	23	2020-10-05

The primary vegetation cover consisted of 30–60-year-old second-growth Douglas-fir (*Pseudotsuga menziesii*) and coast redwood (*Sequoia sempervirens*). Lower densities of western red cedar (*Thuja plicata*) and western hemlock (*Tsuga heterophylla*) were also present. Other commonly identified tree species in the riparian areas were red alder (*Alnus rubra*) and tanoak (*Notholithocarpus densiflorus*). Soils were typically well-drained gravelly clay loams of the Coppercreek and Sasquatch series, with depths ranging from 70 to 100 cm. The uppermost soil layers were composed of well drained organic detritus, and field observation showed that soil clay content increased with soil depth. The lithology of the study area consists of marine-derived sedimentary and metasedimentary rock of the Franciscan Complex.

Our study focused on 18 headwater catchments in Northern California, with 12 harvested catchments and six unharvested reference catchments (Table 2). The 12 harvested catchments included four replicates in each of three riparian buffer prescriptions. Potential study catchments were preliminary selected in the office using spatial data for Class II-L streams that had similar stand ages, watershed areas, stream lengths, slopes, and aspects. We then field verified all sites to ensure they met the Class II-L definition and had similar characteristics to enable comparisons. At that time the Class II-L criteria was based on channel width and drainage area. The treatments applied to the final selected streams were randomly assigned based on 4 grouped blocks to create replicates of each of the potential riparian prescriptions. The riparian buffer prescriptions included: (a) Anadromous Salmonid Protection (ASP) Coastal Anadromy Zone Class II-L prescription with a 30 foot unharvested core zone, and 70 foot outer zone where 80 % overstory canopy cover remained and 20 % of the riparian area was harvested; (b) GDRC Habitat Conservation Plan (HCP) prescription with a 30 foot inner zone where 85 % overstory canopy cover remained and a 70 foot outer zone where 70 % overstory canopy cover remained; and (c) an alternative prescription resembling the period before ASP implementation or the pre-ASP (PRE) with a 100 foot riparian zone where 50 % overstory canopy cover remained and 50 % of the riparian area was harvested (Figure 2). The percent clear-cut of the 12 harvested catchments ranged between 2% and 43% with cut-blocks and riparian prescriptions only occurring on one side of the stream.

Table 2. Core zone and inner zone width requirements for WLPZ associated with Class II-S and Class II-L streams within and outside of the coastal anadromy zone (CAL FIRE, 2017).

Water Class	**Class II-S (feet)**				**Class II-L (feet)**			
Geographic location	**Watersheds in the coastal anadromy zone**		**Watersheds outside the coastal anadromy zone**		**Watersheds in the coastal anadromy zone**		**Watersheds outside the coastal anadromy zone**	
Slope class	Core Zone (feet)	Inner Zone (feet)	Core Zone (feet)	Inner Zone (feet)	Core Zone (feet)	Inner Zone (feet)	Core Zone (feet)	Inner Zone (feet)
≤30%	15	35	10	40	30	70	20	80
30-50%	15	60	10	65	30	70	20	80
>50%	15	85	10	90	30	70	20	80

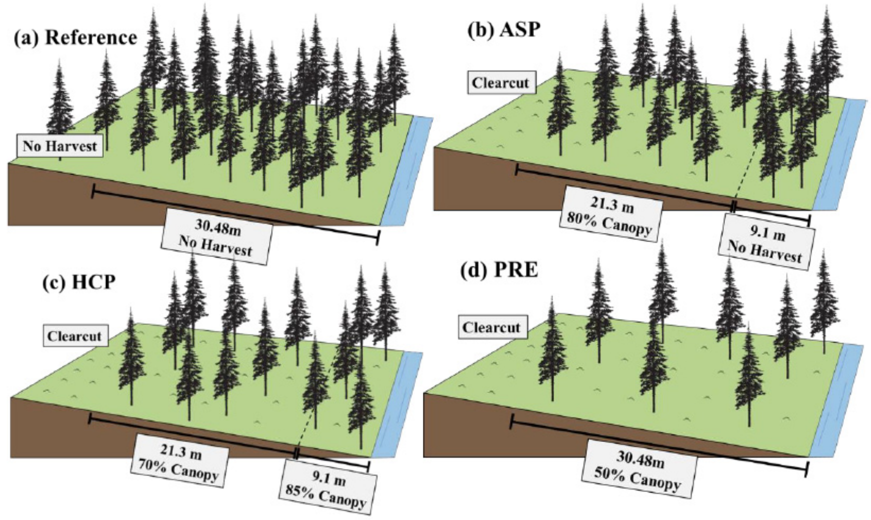

Figure 2. The unharvested, reference condition and three riparian buffer prescriptions in our study, including the (a) reference (REF) catchments, (b) current California Anadromous Salmonid Protection (ASP) riparian prescription, (c) modified ASP or approved habitat conservation plan (HCP) riparian prescription, and (d) pre-2009 riparian prescription (PRE). The percent canopy indicated below each prescription is the target percent of canopy cover retained in the riparian area.

Data collection

We quantified streamflow in each catchment throughout the summer months from 2020–2023 by recording continuous (every 15 minutes) measurements of stream stage at the outlet of each catchment with pressure transducers (Solinst Levelogger Edge Model 3001, accuracy ± 0.05 %) installed inside stilling wells. All measurements were compensated for barometric pressure (Solinst Barologger Edge model 3001, accuracy ± 0.05 kPa). We quantified instantaneous discharge using salt dilution gauging with a slug injection, which was then used to develop rating curves for each catchment.

We established two meteorological stations (Onset HOBO U30 NRC) during summer 2019. The stations were centrally located in each of the two study sub-regions, within ~3 km of all study streams. Over the period of study, the meteorological station provided data on precipitation (tipping bucket S-RGB-M002, 0.2 mm resolution, ± 1 % accuracy), barometric pressure (S-BPB-CM50, ± 3.0 mbar accuracy), relative humidity (S-THB-M008, ± 0.2 °C accuracy), net radiation (solar pyranometer S-LIB-M003, ± 10 W m-2 accuracy), and wind speed (S-WSB-M003, ± 1.1 m s^{-1} accuracy).

To quantify the change in vegetation cover after the timber harvest, we sampled six fixed-area circular mensuration plots in each of our study catchments. We spaced the mensuration plots evenly along the length of the riparian buffer, with a spacing of ~58–105 m apart, depending on the length of reach. We collected riparian vegetation data in the summer months during both the pre- and post-harvest periods. Each plot center was located ~10 m upslope from the edge of the stream, attempting to capture both the core and outer sections of the riparian buffers. Within each plot we quantified stand density (trees per unit area), basal area (based on tree diameter at breast height; m^2 ha^{-1}), and canopy closure.

To quantify the effect of forest harvesting with different riparian buffer prescriptions on seasonal stream temperature, we installed 12 thermistors (Onset HOBO Tidbit, Bourne, MA; accuracy +/- 0.21 °C) longitudinally along each study stream (i.e., 12 thermistors/stream × 18 catchments = 216 total sensors). Sensors were spaced approximately every 25 meters along the thalweg of each study stream and were enclosed in white PVC tubing with drilled holes to enable a constant flow of freshwater over the sensor and to minimize direct solar radiation. We also installed four evenly spaced air temperature sensors along each stream reach approximately 1 m above the stream (i.e., 4 air temperature sensors/stream × 18 catchments = 52 total sensors). Data were collected at a 15-minute resolution during both the pre-harvest and post-harvest periods at all sites.

We collected stream water samples (100 ml) each summer month at the downstream end (outlet) of each watershed throughout the study. Samples were kept in a cooler for transport to the laboratory for analysis. At the end of each day of sample collection, we filtered the water samples through Whatman GF/F 0.7 µm filters and then froze the samples until they could be processed for nutrients. Samples were analyzed for nitrate-nitrite (NO_3^- + NO_2^-) and orthophosphate (PO_4^{3-}) at OSU Cooperative Chemical Analytical Laboratory using a Lachat QuikChem 8500 Series Flow Injection Analysis System (Lachat Instruments, Milwaukee, WI, USA) using the EPA 353.2. cadmium reduction method for NO_3^- + NO_2^- and EPA 365.1. Ascorbic acid method for PO_4^{3-}.

We measured chlorophyll *a* as a proxy for primary productivity once per month throughout each summer of the study. We used the bbe Moldaenke BenthoTorch (bbe Moldaenke GmbH, Schwentinental, Germany) in-situ fluorometer, which measures concentrations of Chlorophyll-*a* on submerged substrates. Readings were taken every 0.5 m from the outlet of the watershed upstream to the 50-meter mark, leading to a total of 100 readings per watershed per month. To ensure readings were as accurate as possible, rock surfaces which were out of direct sunlight and had a larger surface area than the cross-sectional area of the BenthoTorch were chosen.

Key Results

- During the study period, sites received ~16–30 % less average annual precipitation relative to the long-term average (2,110 mm) for the region. Precipitation inputs varied annually and by season during the study, with the first post-harvest year being slightly wetter (WY 2021 annual precipitation: 1,765 mm) than both the pre-harvest period (WY 2020: 1,485 mm) and the second post-harvest year (WY 2022: 1,505 mm) (Figure 3).

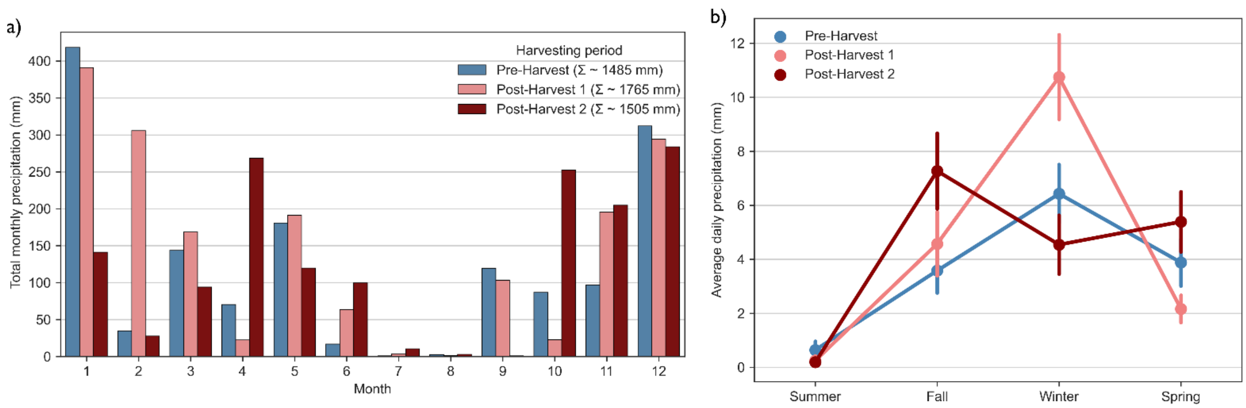

Figure 3. (a) Total monthly precipitation (mm) during each of the three time periods in our study (pre-harvest, first post-harvest year, second post-harvest year) with the total annual precipitation indicated in the legend labels and (b) average daily precipitation and standard error during each of the seasons and each of the three main study periods.

- Riparian stand characteristics
  - The median **basal area** in the riparian areas during the **pre-harvest period** was 2.8 m^2 ha^{-1} (mean ± SD: 2.9 ± 1.8 m^2 ha^{-1}) in the REF sites, 2.4 m^2 ha^{-1} (2.5 ± 1.3 m^2 ha^{-1}) in the ASP sites, 2.9 m^2 ha^{-1} (2.7 ± 1.3 m^2 ha^{-1}) in the HCP sites, and 3.6 m^2 ha^{-1} (3.2 ± 1.2 m^2 ha^{-1}) in the PRE sites (Figure 4).
  - We only found evidence for a change in **basal area** during the **post-harvest period** in the PRE sites where the median basal area was reduced to 1.8 m^2 ha^{-1}. There was no evidence for a change in basal area between the pre-harvest and post-harvest periods in any of the other site types.

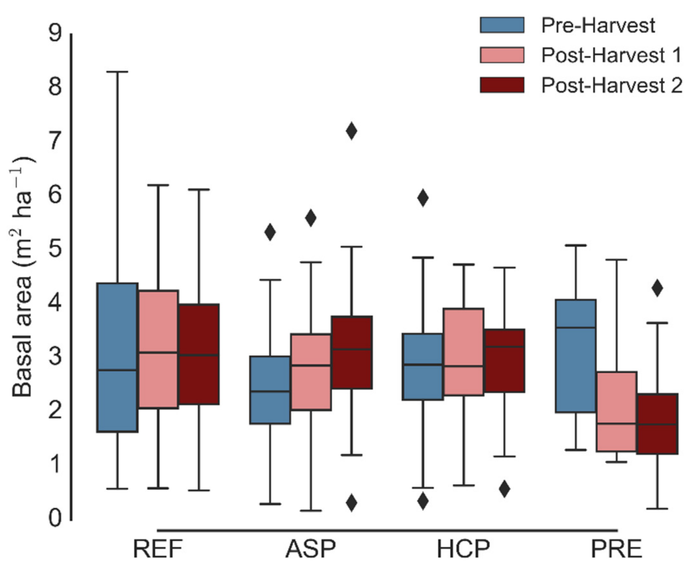

Figure 4. Box plots of basal area ($m^2\ ha^{-1}$) within each of the riparian buffer types during the pre-harvest period and the first and second year after harvesting. Site types: reference (REF), Anadromous Salmonid Protection (ASP) prescription, GDRC Habitat Conservation Prescription (HCP), and the pre-ASP prescription (PRE).

- The mean **effective shade** in the riparian areas during the **pre-harvest period** was 97.5 ± 2.9 % in the REF sites, 96.3 ± 3.1 % in the ASP sites, 95.5 ± 5.2 % in the HCP sites, and 94.0 ± 6.3 in the PRE sites (Figure 5).
- The mean **effective shade** decreased in the **post-harvest** period only in the PRE sites where there was 17.3% less effective shade relative to the ASP sites and 16.2% less effective shade compared to the HCP sites, and 17.5% less effective shade compared to the REF sites. There was no evidence for a change in effective shade in any of the other site types.

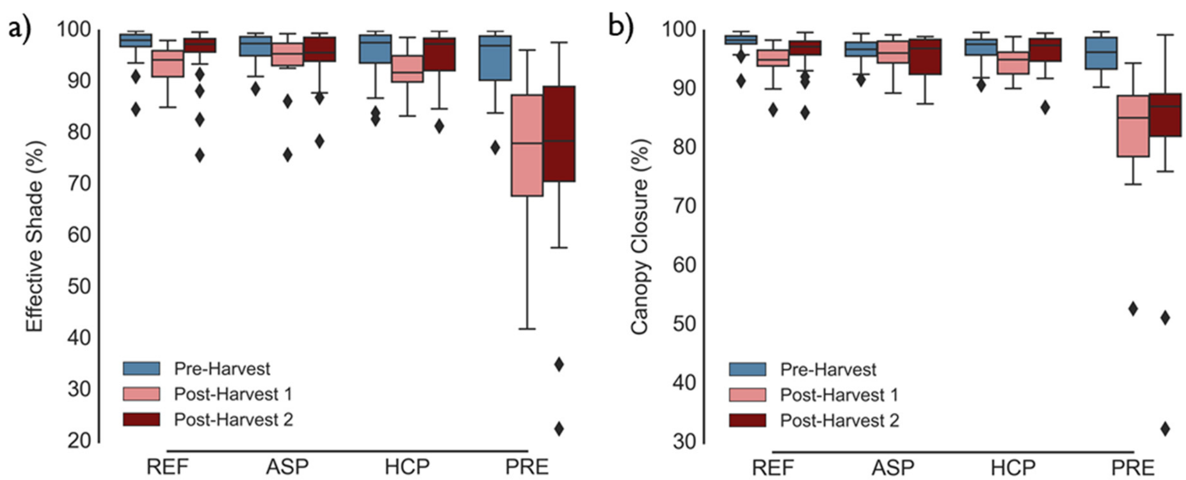

Figure 5. Box plots of (a) effective shade and (b) canopy closure for each of the site types and study time periods. Site types: unharvested reference (REF), Anadromous Salmonid Protection (ASP) prescription, GDRC Habitat Conservation Prescription (HCP), and the pre-ASP prescription (PRE).

- Interestingly, we observed strong differences in stream **nitrate (NO_3^-)** concentrations between two sub-regions, with NO_3^- concentrations approximately 10-fold greater in McGarvey (sites 11–18, Table 1), than West Fork Tectah (sites 1–10, Table 1) (Figure 6).
- There was no evidence for changes in NO_3^- or **orthophosphate (PO_4^{3-})** concentrations between the pre-harvest to the post-harvest period in any of the site types.

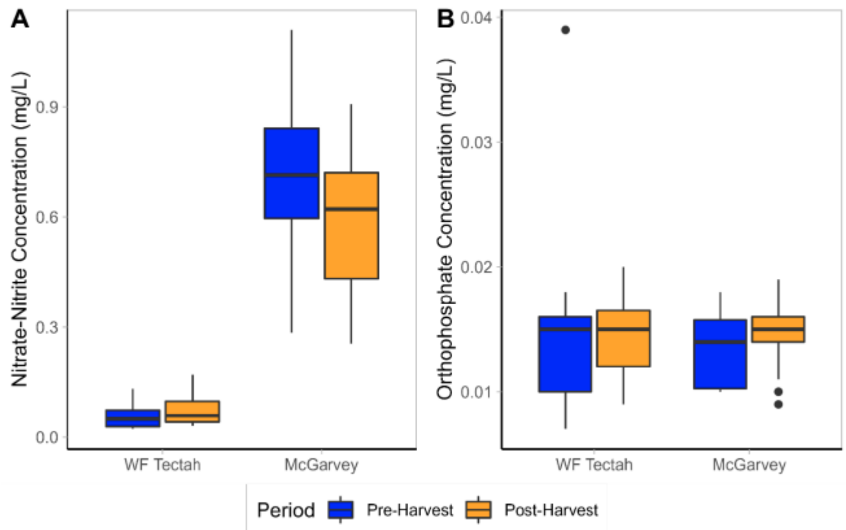

Figure 6. Boxplots pooling the (A) Nitrate-nitrite and (B) orthophosphate concentrations during the pre-harvest and post-harvest periods in WF Tectah and McGarvey.

- We observed substantial variability in **chlorophyll-*a*** across the study watersheds, with a 3-fold difference between the most productive watershed (i.e., 13-055 mean chl-*a* = 6.22 µg cm^{-2}) and the least productive watershed (i.e., 14-506 mean chl-*a* = 2.18 µg cm^{-2}) (Figure 7).
- There was no evidence of a consistent changein chlorophyll-*a* from the pre-harvest to the post-harvest periods that could be consistently related to the harvest type.

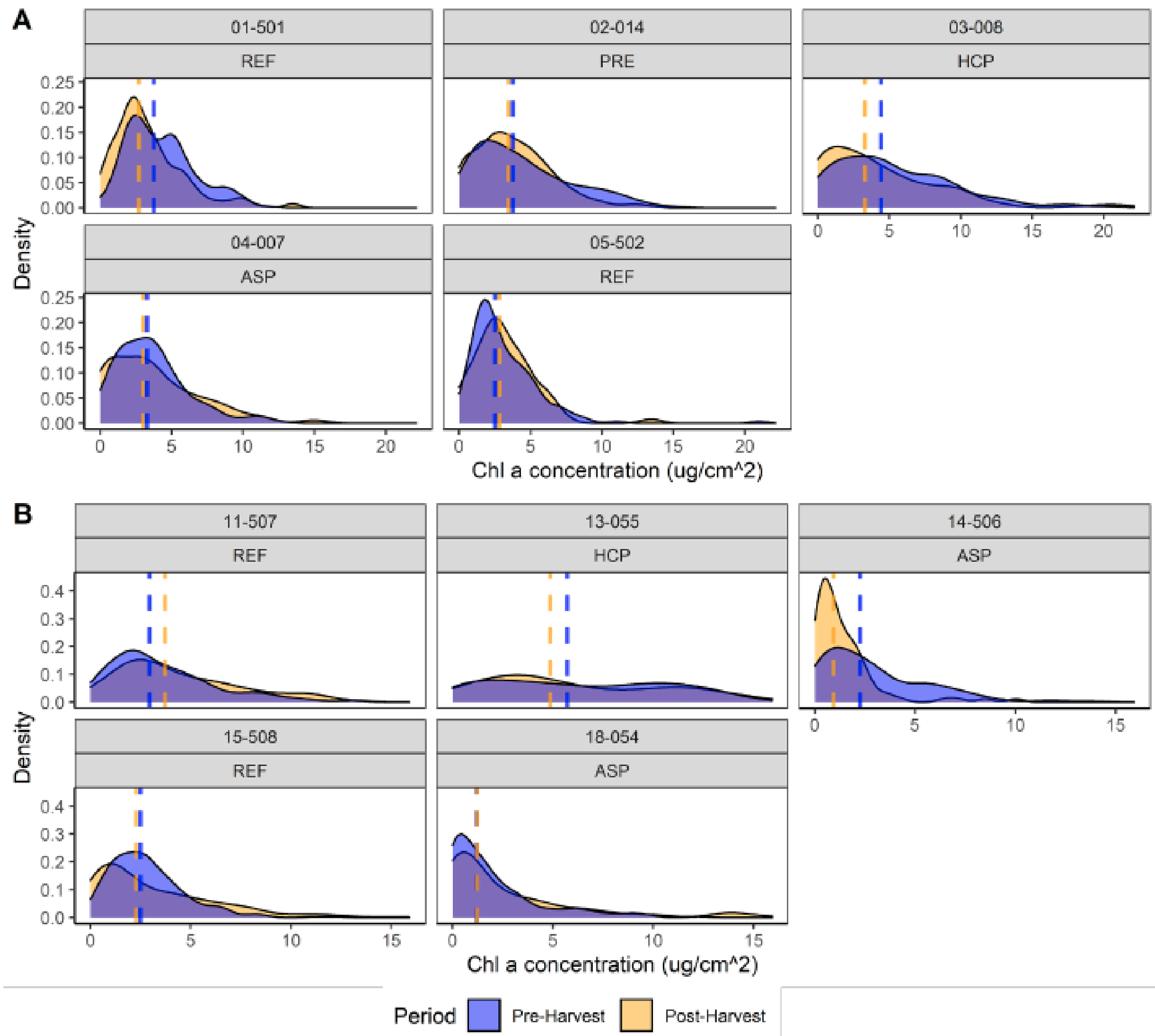

Figure 7. Probability density functions of pre-harvest and post-harvest chlorophyll-*a* concentrations for several representative watersheds of each treatment type, including watersheds in (a) WF Tectah and (b) McGarvey. The dashed lines indicate the median values for each corresponding period.

- We observed a substantial increase in **daily streamflow** during the summer low flow season in the harvested streams (Figure 8).
- The increases in streamflow appeared to be related to the proportion of catchment area harvested, <u>not</u> the riparian treatment type.
- The greatest increase in median daily streamflow occurred in the ASP stream, which had the greatest proportion of catchment harvested (25.2%). Here, we observed a 0.74 mm or 74 % increase in the first post-harvest summer and an even larger increase in streamflow in the second post-harvest summer of 1.13 mm or 113 %.

- Comparatively, the second largest increase in median daily streamflow was 0.27 mm or 54 % during the first post-harvest summer in the PRE stream, which had 19.1% of the catchment harvested. We observed a larger increase of 0.52 mm or 105 % in the second post-harvest summer.
- The smallest increase in median daily streamflow was 0.20 mm (41%) in the HCP stream during the first post-harvest summer, which had only 3% catchment area harvest. We measured a non-statistically significant increase of 0.074 mm or 12% in the second post-harvest year.

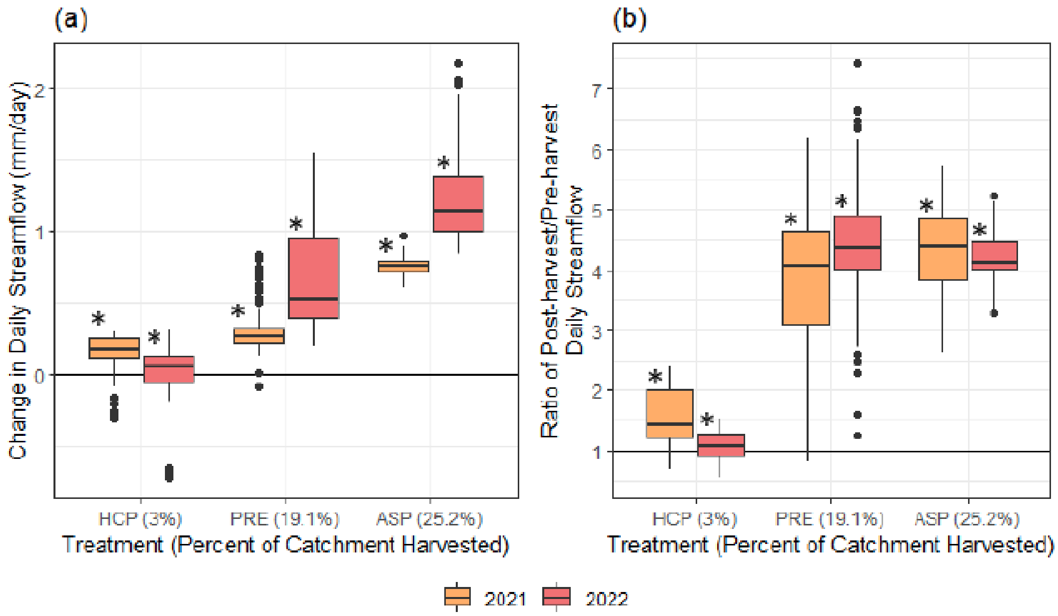

Figure 8. Boxplots of the change in daily streamflow during the post-harvest period in the harvested watersheds in WF Tectah. Changes in both years (2021 and 2022) are relative to the pre-harvest year (2020). Sites are ordered on the x-axis relative to percentage of catchment harvested.

- Results suggested that during the first year after harvesting, seasonal **stream temperature** significantly differed in the harvested sites relative to the reference sites (Figure 9).
- During the first post-harvest year, the greatest increase in the seven-day rolling maximum of stream temperature ($T_{7\text{-}day\ max}$) occurred in the HCP and PRE sites during the fall (HCP: ~0.6 °C and PRE: ~1.6 °C) and summer (HCP: 0.6 °C and PRE: 0.4 °C) seasons. The HCP sites were also slightly warmer than the ASP sites during the fall. There was no evidence for differences in $T_{7\text{-}day\ max}$ between any of the other site types during any of the other seasons.
- During the second year after harvesting, the mean seasonal stream temperature decreased compared to the first year after harvesting. The $T_{7\text{-}day\ max}$ decreased between ~0.2 °C and ~0.8 °C in the catchments that received the most intensive riparian treatment (i.e., PRE) compared to the reference sites. Additionally, there was no evidence that the seasonal stream temperatures were different in either the ASP or HCP sites compared to the reference sites.

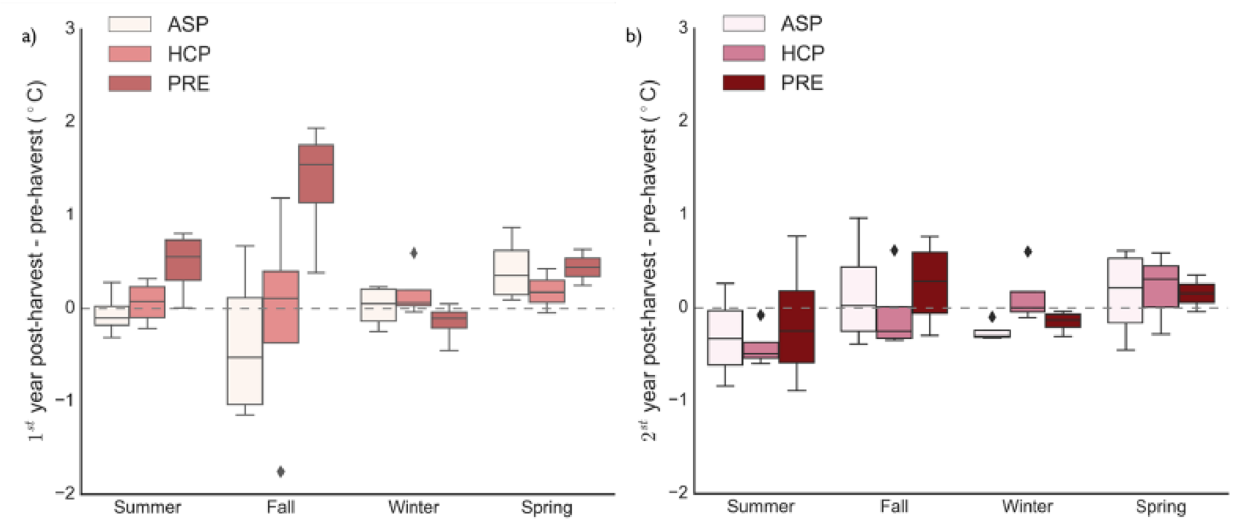

Figure 9. Box plots of (a) stream temperature ($T_{7\text{-}day\text{-}max}$) difference response weighted by the reference site $T_{7\text{-}day\text{-}max}$ response between the first year after harvesting and before harvesting, and (b) $T_{7\text{-}day\text{-}max}$ difference response between the second year after harvesting and before harvesting. Site types: unharvested reference (REF), Anadromous Salmonid Protection (ASP) prescription, GDRC Habitat Conservation Prescription (HCP), and the pre-ASP prescription (PRE).

- Deeper analysis of the stream temperature response, illustrated that the $T_{7\text{-}day\text{-}max}$ was sensitive to the changes in stream stage, precipitation, catchment elevation, and effective shade, but these factors varied with season (Figure 10).
- Importantly, there was no evidence that the harvest type was a major driver of the variability in seasonal $T_{7\text{-}day\text{-}max}$ response observed in the post-harvest period.
- Similarly, there was no evidence that stream temperature during the post-harvest period increased by more than 5 °F (2.8 °C) above the pre-harvest period stream temperature. During the Summer, the mean $T_{7\text{-}day\text{-}max}$ ranged from 13.2–13.7 °C during the pre-harvest period, 13.0–14.2 ° C during the first year after harvesting, and 12.9–13.3 °C during the second year after harvesting. We did not have stream temperature data from downstream receiving water or long-term pre-harvest data to enable us to quantify a long-term natural stream water temperature. However, our data suggest that all of the harvesting treatments met the water quality standards for temperature.
- Salmonid fish, which inhabit downstream reaches from our study sites, have several sensitive life stages and biological processes that may be impacted by elevated maximum water temperatures. There has been previous research in other regions that has illustrated the potential for changes in riparian vegetation to lead to substantial variation in stream temperature (e.g., Beschta, 1997). While we did not collect empirical data on downstream fish, there was no evidence that 7-day maximum stream temperatures exceeded temperatures that would be expected to have substantial negative impacts on smoltification, adult migration, spawning, distribution, or mortality (Richter and Komes, 2005)

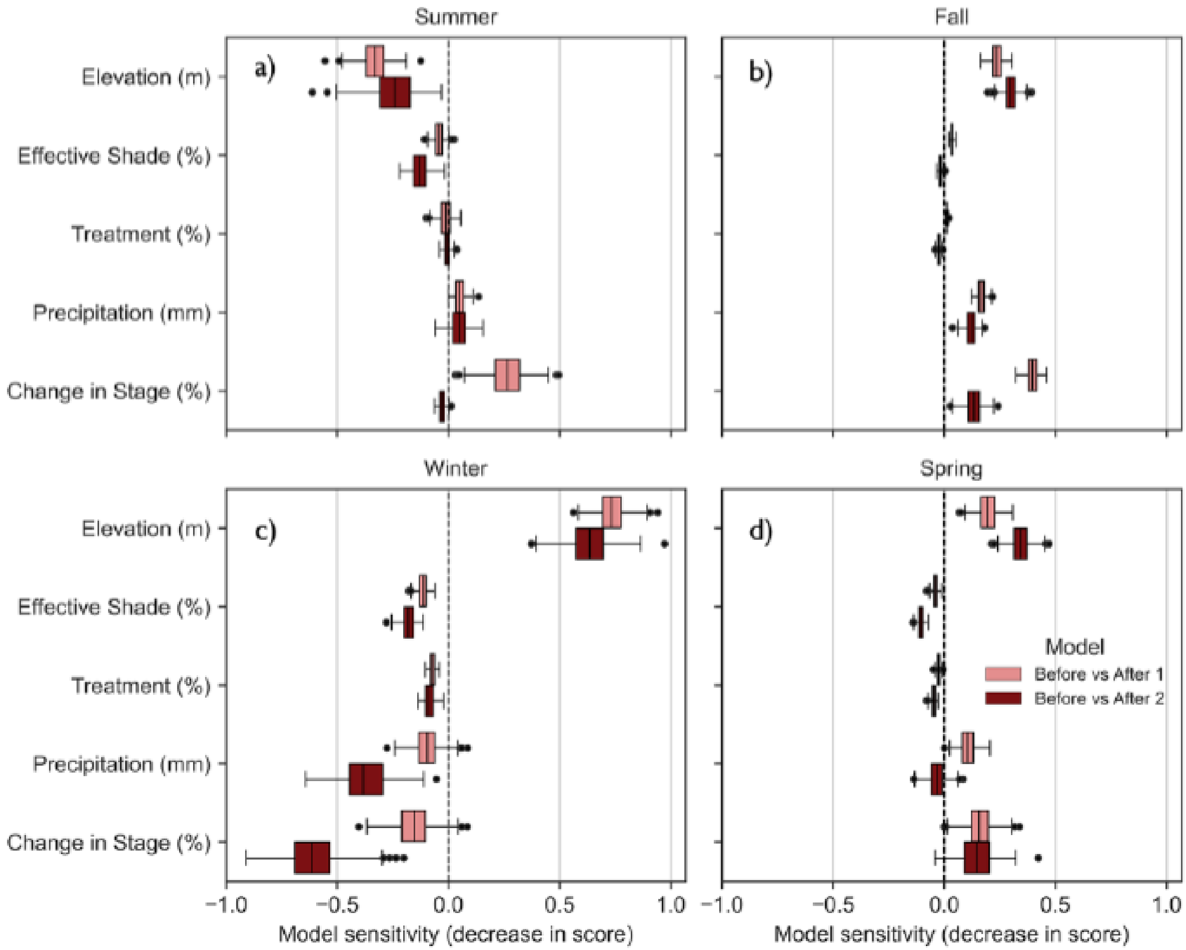

Figure 10. Permutation variable importance for (a) summer, (b) fall, (c) winter, and (d) spring $T_{7\text{-}daymax}$ random forest models per year after harvesting. Lighter boxplots indicate the models for the pre-harvest period and the first year after harvesting *(Before vs After 1*). Darker boxplots indicate the models for the pre-harvest period and the second year after harvesting (*Before vs After* 2). For illustrative purposes, we only included the variables that most influenced the model results per season in this figure.

- Interestingly, we observed consistently warmer stream temperatures in the McGarvey watersheds relative to the WF Tectah watersheds (Figure 11a) and unique stream temperature responses in the streams during storm events.
- Analysis of the stream temperature responses during storm events illustrated that stream temperature in the McGarvey streams co-varied strongly with topographic metrics (i.e., upslope accumulative area, average channel slope, topographic wetness index) (Figure 11b). Comparatively, in West Fork Tectah the variability of Ts co-varied most strongly with meteorological metrics (i.e., antecedent rainfall events, solar radiation, and air temperature). Variables such as the gradient between stream and air temperatures, slope, and wetted width were significant for both subregional hysteretic patterns.

- These results highlight the need for additional research to improve our understanding of regional differences in the controls on thermal regimes in forested headwater streams, to facilitate site-specific forest and water policy and management decisions.

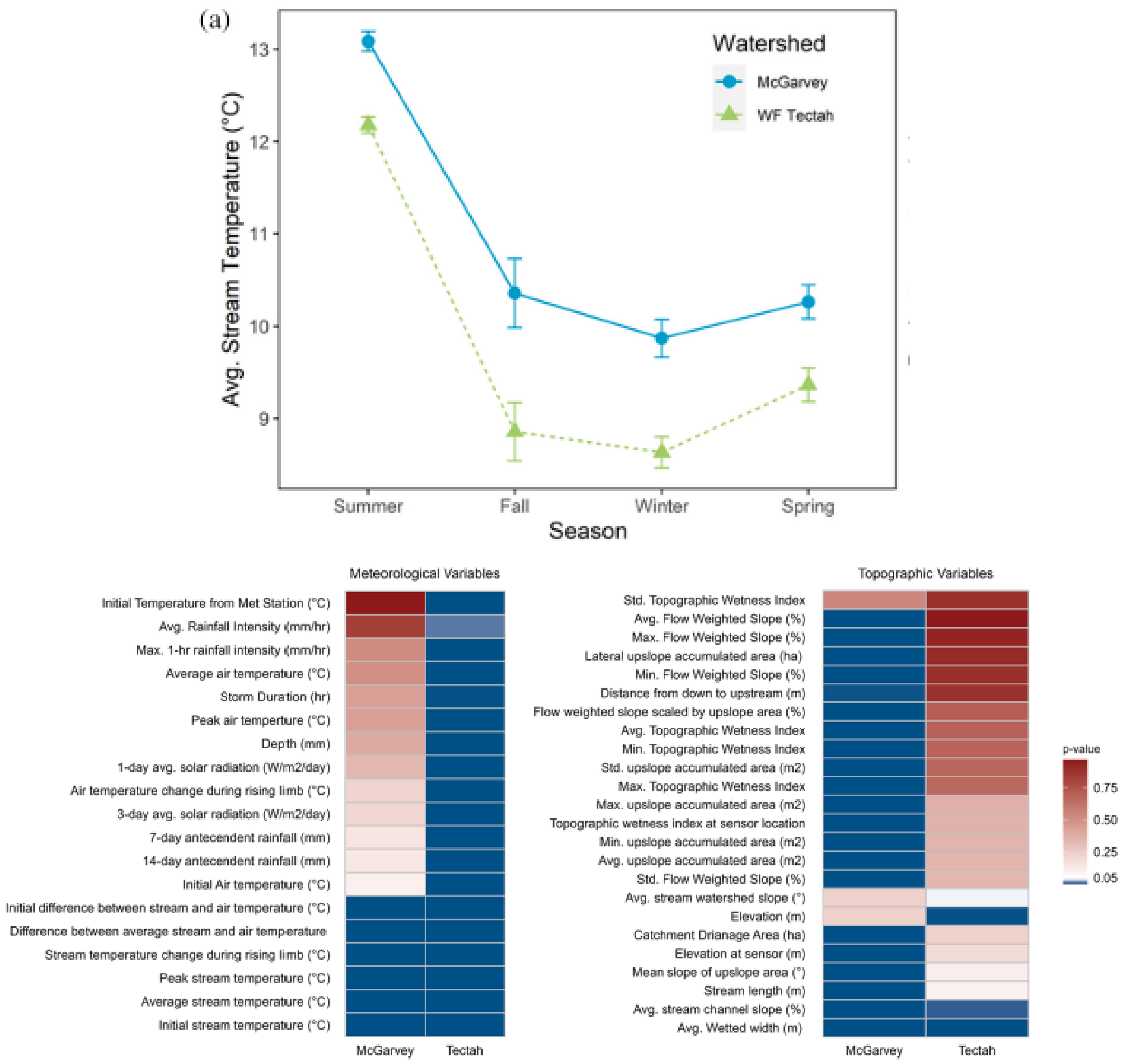

Figure 11. (a) Median average stream temperature by season in the study streams in McGarvey and WF Tectah and (b) heat maps of *p*-values for tests relating the stream temperature responses in each of the regions to meteorological variables (left) and topographic variables (right).

Summary:

- This study in 18 forested headwater catchments in Northern California provided insights into the streamflow, nutrient, primary productivity, and stream temperature responses to current harvesting practices, including smaller clearcut areas, forest harvesting on one side of the stream, and greater basal area retention in riparian areas. We were also able to compare current practices with a historical practice with only 50 % riparian canopy retention.
- Overall, our results suggested that current harvesting practices and riparian management were generally effective at limiting substantial impacts on streamflow, nutrients, primary productivity, and stream temperature. This was the case despite our post-harvest years being generally warm and dry with low streamflow, which can exacerbate stream temperature responses.
- Instead, we found that seasonal thermal regimes were strongly related to climatic variability and catchment topographic characteristics. These findings illustrate the challenges in understanding the hydrological and biophysical responses of headwater streams and their responses to forest disturbances.
- In particular, predictions of stream temperature responses to forest disturbances are complicated by the heterogeneity of the factors that influence this important physical water quality parameter. As such, there may still be observations of substantial impacts of forest harvesting on stream temperature, even with current practices, due to differences in local catchment characteristics. However, with global climate change and increasing pressures on water resources and aquatic ecosystems there remains a need for future research to provide additional insights into the relationships between forest management activities and the thermal regimes of headwater streams.
- For example, future research should (1) investigate streamflow, water quality, stream temperature, and aquatic ecosystem responses to disturbances across catchments with a diversity of forest types, geology, physiography, and forest management practices, (2) include longer pre-harvest periods to establish stronger linkages between study catchments to enable disentangling the effects of forest management from other drivers, and (3) undertake more holistic inter-disciplinary assessments that consider the effects of forest harvesting and riparian management on other important factors, such as terrestrial ecosystem health, aquatic ecosystem health, and socio-economic trade-offs to inform future forest management policy and decisions.

Problems and barriers:

- The COVID-19 pandemic created a substantial barrier to our study. The study officially began on June 1, 2019; however, on March 23, 2020 (~9 months into our study) stay-at-home orders were issued. Those restrictions remained in place until June 30, 2021, which severely limited our ability to maintain sensors, download data, and collect additional supporting data. While local employees from GDRC were able to assist with some data offloads and sensor maintenance, this was principally to enable base monitoring and limited our ability to collect key supporting data and/or adjust to field-related issues.

- Abbreviated pre-harvest calibration period: The pre-harvest data collection period generally occurred between August 2019 and December 2020, but was slightly shorter in four catchments (i.e., 9, 12, 16, 17) where it extended until January, March, and May 2020 due to the need for adjustments in the forest harvesting schedule. These different and shorter calibration periods create challenges for cross-site comparisons and for disentangling background variability from shifts in the systems related to the forest management activity. This is a normal constraint when trying to undertake research associated with an active industrial operation. However, it is important to be aware that this results in a lack of a tightly controlled study design in favor of operational reality, resulting in usual variability in the harvesting intensity in our study catchments.
- In several of the study catchments, the spatial location of the harvested area was shifted at the time of harvesting, reducing the harvest area upstream or adjacent to the installation locations of our sensors. We attempted to account for these changes in our analysis, but the catchments planned to receive the most intensive riparian harvesting treatment (i.e., PRE) were generally the catchments that had the most substantial changes in spatial location of harvesting, whereby the area harvested was downstream of our sensors in a couple of the catchments. As such, the harvesting activity wouldn't have been captured in our data. To best address these uncertainties and variability observed in this study, additional research and longer-term monitoring is needed.
- At one site (#16-552) that was designated to investigate the PRE ASP, a road crossing in the middle of the catchment was decommissioned in October 2021, creating substantial disturbance to the stream channel, nearby vegetation, and introduced sediment into the system, creating uncertainty in the data collection.
- One of our reference watersheds (#05-502) was harvested in summer 2022, approximately 9–11 months before the end of the project. As such, this limited the utility of the data from this watershed, which was key to disentangling the harvesting effects from background variability.
- While all study streams were classified as perennial and were flowing during the summer when we selected sites and installed equipment, dry weather between 2019 and 2022 led to streams 4 (ASP), 11 (REF), 13 (HCP), 15 (REF), and 18 (ASP) going dry during the summers.
- We had substantial issues with the reliability of our dissolved oxygen sensors, which were intended to provide insights into stream metabolism. At least 8 of our sensors stopped measuring data because stream sections dried up and sensors were not fully submerged under water. Moreover, much of the data has appeared to be unreliable with unstable measurements. See the attached slides in the supplemental materials, which show the raw data and some of our preliminary QA/QC and assessments of the utility of the data.
- Our original proposal had intended for a PhD student to work on this project through its entirety. Unfortunately, the PhD student that we had recruited to work on this project, chose to leave the PhD program in July 2021 for personal

reasons. As such, we had to adjust how we approached management and data collection in the project.

Graduate and/or undergraduate student engagement in project:

- Austin Wissler, MS thesis, Oregon State University
- Jonah Nicholas, MS thesis, Oregon State University
- Lorrayne Miralha, Post-doctoral scholar, Oregon State University
- This project enabled broad educational opportunities in forest mensuration, small stream hydrology, and stream ecology in the laboratory and field. Specifically, we were able to provide learning opportunities on this project to the following technicians (undergraduate students, graduate students, faculty research associates, and post-doctoral scholars): Kelly Andrus, Alessandra Bertucci, Brenna Cody, Ryan Cole, Clara Eshaghpour, Nina Ferrari, Hyunwoo Kang, Ellen Luedloff, Madelyn Maffia, Katherine McCool, Spencer McMaster, Cedric Pimont, Will Potter, Katie Wampler, Casey Warburton, Sam Zamudio

Peer reviewed manuscripts or theses (* = Student or post-doctoral scholar)

- *Miralha, L., Segura, C., and Bladon, K.D. In review. Stream temperature responses to forest harvesting with different riparian buffer prescriptions in Northern California. Forest Ecology and Management.
- *Miralha, L., *Wissler, A.D., Bladon, K.D., and Segura, C. 2023. Characterizing stream temperature hysteresis in forested headwater streams. Hydrological Processes. 37: e14795. https://doi.org/10.1002/hyp.14795.
- *Nicholas, J.N. 2022. Summer low flow response to timber harvest and riparian treatments in forested headwater streams of Coastal Northern California. Master of Science Thesis in Sustainable Forest Management. College of Forestry, Oregon State University.
- *Pimont, C. 2023. Effects of contemporary forest practices on stream nutrients, temperature, and periphyton in small headwater streams. Undergraduate Honors Thesis. Honors College, Oregon State University.
- *Wissler, A.D. 2021. Assessing the thermal sensitivity and stormflow response of headwater stream temperatures: A seasonal and event-scale exploration in Northern California, USA. Master of Science Thesis in Water Resources Engineering. Water Resources Graduate Program, Oregon State University.
- *Wissler, A.D., Segura, C., and Bladon, K.D. 2022. Comparing headwater stream thermal sensitivity across two distinct regions in Northern California. Hydrological Processes, 36(3), 17: e14517. https://doi.org/10.1002/hyp.14517.

Conference or workshop presentations (* = Student or post-doctoral scholar; underline = presenter)

- *Miralha, L., Bladon, K.D., Segura, C., *Wissler, A., and *Pimont, C. 2022. Stream temperature and biogeochemical responses to disturbance in forested headwater streams in California: The role of catchment physiography. American Geophysical Union Fall Meeting. Dec. 12–16, 2022, Chicago, IL.

- *Nicholas, J., Bladon, K.B, and Segura, C. 2022. Effects of forest harvesting and different riparian buffer treatments on summer low flows in headwater streams of Coastal Northern California. American Geophysical Union Fall Meeting. Chicago. Il. December 12–16, 2022.
- *Nicholas, J., Bladon, K.D., and Segura, C. 2022. Summer low flow and diel response to riparian canopy cover removal in forested headwater streams of Coastal Northern California. 12th Annual Pacific Northwest Water Research Symposium. April 13–14, 2022
- *Nicholas, J., Bladon, K.D., and Segura, C. 2022. Low flow response to riparian buffer treatments in Coastal Northern California. Western Forestry Graduate Research Symposium. Apr. 15, 2022
- *Nicholas, J, Bladon, K.D., and Segura, C. 2021. Summer low flow response to different riparian treatments in forested headwater streams of Coastal Northern California. Western Forestry Graduate Research Symposium. Apr. 16, 2021
- *Wissler, A., Bladon, K.D., and Segura, C. 2021. Assessing the thermal sensitivity and storm responsiveness of headwater stream temperatures: A seasonal and event scale exploration. 11th Annual Pacific Northwest Water Research Symposium. April 12–13, 2021.
- *Wissler, A, Bladon, K.D., and Segura, C. 2020. Comparing headwater stream thermal sensitivity across two contrasting lithologies in Northern California, USA. Western Forestry Graduate Research Symposium, Apr. 30–May 6, 2020. Virtual.
- Bladon, K.D., Segura, C., House, M., and Coe, D. 2019. Effectiveness of Class II riparian prescriptions: Project update. EMC Committee. Aug. 29, 2019. Virtual.