Effects of Contemporary Forest Practices on Stream Nutrients, Temperature, and Periphyton in Small Headwater Streams

by
Cedric Pimont

A THESIS

submitted to

Oregon State University

Honors College

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the requirements for the
degree of

Honors Baccalaureate of Science in Bioresource Research
(Honors Scholar)

Presented August 26, 2022
Commencement June 2023

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Cedric Pimont for the degree of Honors Baccalaureate of Science in Bioresource Research presented on August 26, 2022. Title: Effects of Contemporary Forest Practices on Stream Nutrients, Temperature, and Periphyton in Small Headwater Streams.

Abstract approved:____

Kevin Bladon

Forest harvest practices can impact nutrient concentrations and stream temperatures, altering aquatic ecosystems. To better inform future sustainable forest resource management practices, quantifying the impact of current practices on water quality, particularly in headwater streams is important. In this study, I quantified monthly nitrate-nitrite (N) and orthophosphate (P) concentrations, 7-day maximum temperatures (7DMMT), and chlorophyll-*a* prior to harvest (2020) and post-harvest (2021) in 10 non-fish bearing watersheds in 2 sub-basins, McGarvey and West Fork Tectah in coastal northern California. Three watersheds were harvested in each sub-basin, with the rest remaining as references. N concentrations varied significantly between sub-basins, with an average of 0.066 mg/L in WF Tectah compared to 0.607 mg/L in McGarvey. P concentrations averaged 0.014 and 0.014 mg/L for WF Tectah and McGarvey respectively. N concentrations increased by an average of 0.055 mg/L in harvested watersheds compared to references (p = 0.697). P concentrations increased by an average of 0.002 mg/L (p = 0.105 - 0.088). Analysis of covariance showed 7DMMT significantly increased in harvested watersheds compared to reference watersheds. Modeling results suggested a negative relationship between 7DMMT and chlorophyll-*a*, likely due to grazer-periphyton interactions. Current harvest practices have minimal impacts on water quality, but more research is needed.

Keywords: Forestry, Water Quality, Aquatic Ecology, Riparian buffers, Periphyton, Disturbance Hydrology

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Cedric Pimont, Author

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Introduction

Historical forest management practices have had substantial impacts on streamflow[1–3], water quality[3,4] and subsequently, aquatic ecology[5]. This makes forest management practices for headwater streams, which can make up 70-80% of the greater watershed area[6], especially important. In the past, harvest practices had larger clear cuts without riparian buffers[7]. Lack of a buffer in coastal forests of the Pacific Northwest (northwestern USA and southwestern Canada, PNW) has often resulted in average daily maximum stream temperature increases between 1 °C[9] all the way up to nearly 8 °C[8] . Although the specific policy requirements of buffer width and harvesting within the buffer zone vary by region and watershed type, the observed increases in temperature led to the widespread implementation of riparian buffer strips[7]. Particularly, riparian buffers have been shown to decrease summer stream temperature maximums when compared to unbuffered streams, nearly achieving similar temperatures to reference streams in the Oregon Coast range[10,11] and coastal British Columbia[9]. Current understanding of the effectiveness of buffers is largely determined by width. 30 m wide buffers have been found to increase temperatures half as much compared to 10 m buffers[5]. The density of riparian stands can also be important. Thinning of around 20% canopy cover loss along fish-bearing streams can increase maximum temperatures between 1-3 °C in coastal northern California[12], but more research is needed to understand how this would affect smaller headwater streams.

Despite the implementation of riparian buffers, forest harvesting can still have an impact on streams, principally its biogeochemical cycle. Harvested watersheds in the PNW are likely to have greater concentrations of Nitrogen (N) and Phosphorus (P) compared to old-growth forests, with concentrations of ammonia-N being twice as high and phosphate-P being 30% higher on average[13]. However, it is unclear if these patterns are attributed to differences in underlying watershed characteristics or actual effects of harvest. Across many other environments, nitrate-N concentrations can remain elevated for 3 to 5 years post-harvest in both conifer and deciduous forests, although mixed forests seem to offer some protection[14]. Increases in stream N can be explained by reduced plant uptake, as well as increased rates of N-mineralization and nitrification due to higher soil temperature and moisture[15]. However, some research has shown no significant increases in nutrients post-harvest in headwater streams in PNW forests[5] when approximately 20% or less of the watershed area is harvested. The effects of these smaller harvest units, common in modern forest practices, warrants further investigation.

Water quality plays an important role in driving the health of aquatic ecosystems. For example, temperature has been found to drive the life cycle and the survival of various aquatic insect species, influencing overall assemblage structure in montane California streams[16]. Cooler aquatic habitats are generally preferred by salmonid fishes in the PNW[17–19]. Aquatic amphibians in this region, such as *Rhyacotriton variegatus* can have much lower survival if stream temperatures exceed their critical thermal maxima[20]. As climate change increases air temperatures, protection of stream temperatures via shading through better forest management practices will become even more important for the survival of salmonids and other cold-water adapted organisms.

Periphyton abundance can be altered with changes in light availability, temperature, and limiting nutrients such as N and P. Higher levels of N and P have been associated with higher levels of primary productivity[21], and increases in nutrient concentrations through planned nutrient additions have been shown to increase periphyton concentrations in the same streams[22,23]. Temperature also plays a synergistic role along with nutrients to increase periphyton growth, which was demonstrated with geothermally-heated streams[23]. However, certain taxa of diatoms, which often dominate headwater stream ecosystems[24,25], can respond negatively to higher temperatures and nutrient concentrations[26]. Some stream environments are N-limited, while others can be P-limited[27], due to varying varying ratios of N:P that is available. These relationships exemplify the bottom-up effect of water quality on the aquatic ecosystem.

Although there are many studies quantifying the individual effects of forest management practices on water quality, few studies have put these concepts together. Specifically, studies have yet to investigate these concepts in the coastal region of northern California since the implementation of the new Watercourse and Lake Protection Zone (WLPZ) guidelines. Past research in this region has found increased nutrients and primary productivity in timber-harvested watersheds when compared to old-growth forest watersheds[13]. Summer maximum water temperatures have also increased as a result of thinning in the area[12]. However, it is not known how the current WLPZ guidelines affect stream temperature and nutrient concentrations in this region, and whether this will result in changes in in-stream primary productivity in small, non-fish bearing watersheds. In this study, my objectives were to investigate the effects of current forest practices on water quality, specifically if N and P concentrations, daily maximum temperatures, increased post-harvesting and if these changes are proportional to the percent of the harvested area; and the resultant impacts of changes in water quality on primary productivity. To achieve my objectives, I attempted to answer the following research questions:

1) Do current forest harvesting practices affect nutrient concentrations (N, P) during summer low-flow periods in small non-fish bearing headwater streams in northern California?

2) Do current forest harvesting practices affect summer 7-day maximum stream temperature in small non-fish bearing headwater streams in northern California?

3) Are the changes observed in 1) and 2) proportional to changes in primary productivity during summer low-flow periods in small non-fish bearing headwater streams in northern California?

Methods

Study sites

This study was conducted in 2 different sub-basins: West Fork Tectah (WF Tectah) and McGarvey, in northwestern Humboldt County, California (Fig. 1). This land is privately owned by the Green Diamond Resource Company (GDRC) and is part of the greater Klamath watershed. Study sites included10 watersheds which meet California's Watercourse and Lake Protection Zone Class II-L criteria for headwater streams were selected, with 5 in each sub-basin. Watersheds ranged from 18.9 to 63.8 hectares. The climate is characterized by mild, wet winters and warm, dry summers, with fog supplying most of the moisture in the summer[28]. During the period of June – August, precipitation totals approximately 25 mm on average and daily air temperature maximums typically reach 17 °C[29]. Riparian vegetation is second-growth, with the canopy largely made up of coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), red alder (*Alnus rubra*), and tanoak (*Notholithocarpus densiflorus*). These watersheds do not bear fish, but are important habitat for a variety of other aquatic animals, hence their Class-II status. Aquatic animals include the southern torrent salamander (*Rhyacotriton variegatus*), and aquatic invertebrates *Ephemeroptera*, *Plecoptera*, and *Trichoptera*, which are sensitive to habitat disturbance[20,30], as well as water striders (*Gerridae*).

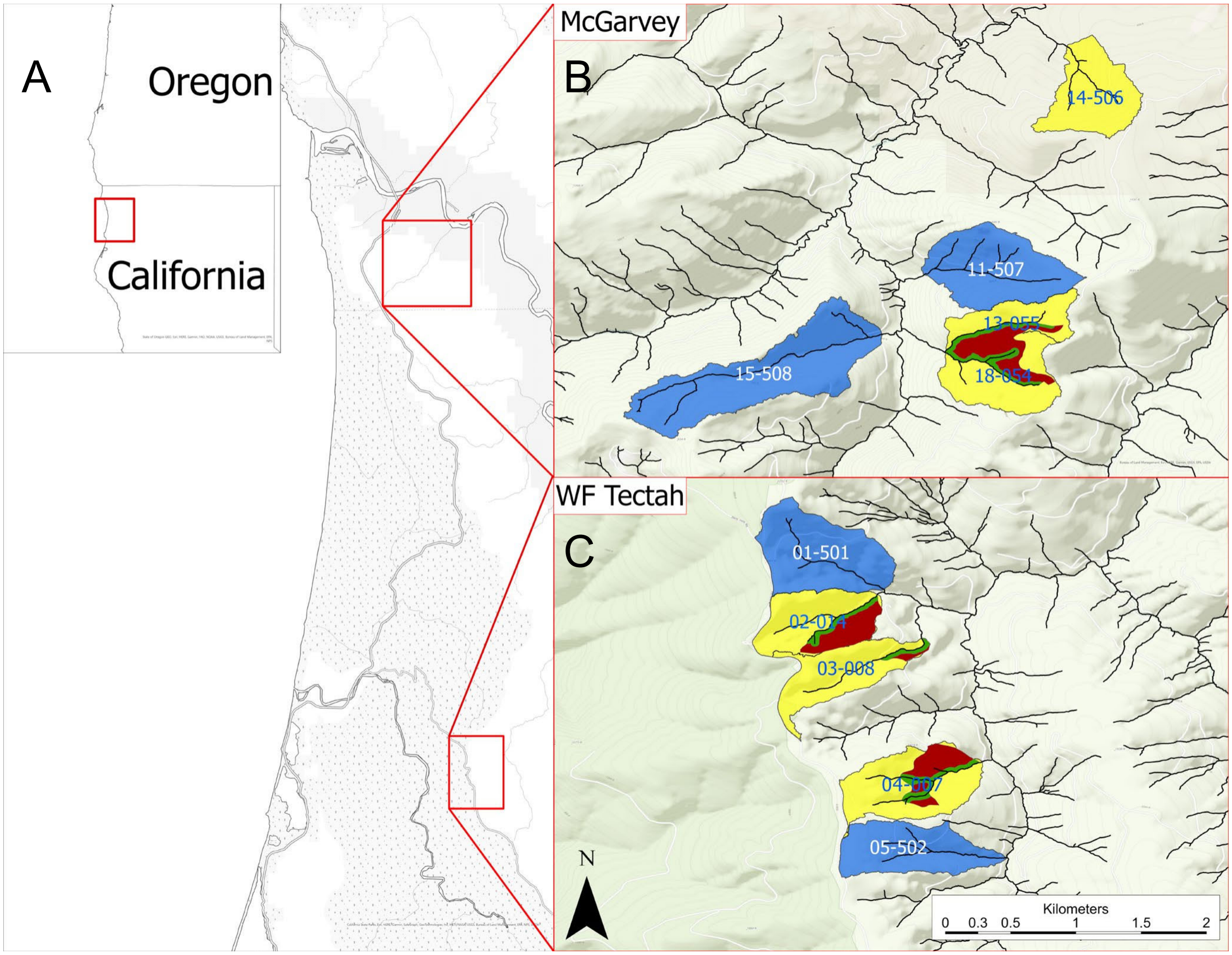


Figure 1. Map of studied watersheds. (A) shows an inset of the study location on the northern California coast. (B) and (C) show more detailed maps of the McGarvey and WF Tectah sub-basins, respectively. Yellow watersheds were harvested, with red representing the harvest unit. Blue watersheds are unharvested references. Created in ArcGIS Pro using shapefiles, digital elevation models (DEM) provided by GDRC and a publicly available base map.

Experimental design

This experiment followed the replicated Before-After-Control-Impact (BACI) approach. 6 watersheds were selected as treatments with varying amounts of the watershed area harvested and varying buffer prescriptions (see below for details on prescriptions). 4 watersheds (01-501, 05-502, 11-507, and 15-508) were left as unharvested as references throughout the study period. Pre-harvest data began in June 2020 and ended later in 2020 (date dependent on watershed, see Table 1). Post-harvest data collection began in 2021 after the harvest had been completed (see Table 1 for watershed ID/treatment). The buffer prescriptions were as follows:

A. Anadromous Salmonid Protection (ASP) Coastal Anadromy Zone Class II-L Prescription – 100-foot total with a 30-foot core zone; 70-foot inner zone with 80 percent overstory canopy cover

B. GDRC Habitat Conservation Plan (HCP) – 100-foot total with a 30-foot inner zone with 85 percent overstory canopy; 70-foot outer zone with 70 percent overstory canopy cover

C. alternative prescription resembling pre-ASP (PRE)

prescription – 100-foot zone with 50 percent overstory canopy.

The prescribed clear cut outside of the buffer zone was on one side of the stream and varied in aspect by watershed. The size of the clear cut proportional to the watershed also varied, ranging from 2.5 to 27%.

Table 1. Watershed Characteristics. Physical characteristics and assigned treatment for all watersheds (n = 10). Stream length indicates the length of each study area. Pre-harvest start designates the beginning of pre-harvest data collection, and post-harvest start indicates the beginning of the post-harvest data collection period.

Sub-basin	*Watershed ID*	*Treatment*	*Stream length (m)*	*Drainage area (ha)*	*Elevation (m)*	*Pre-Harvest Start/End (YYYY-MM-DD)*	*Post-Harvest Start (YYYY-MM-DD)*	*Watershed Area Harvested (%)*
WF Tectah	01-501	REF	304.9	39.7	432			0
	02-014	PRE	304.7	30.6	428	2020-06-01 / 2020-11-01	2020-12-16	27.0
	03-008	HCP	304.7	33.4	429	2020-06-01 / 2020-09-14	2020-11-07	2.5
	04-007	ASP	304.9	37.8	425	2020-06-01 / 2020-09-14	2020-11-07	18.8
	05-502	REF	304.5	30.5	435			0
McGarvey	11-507	REF	304.8	40.5	81			0
	13-055	HCP	304.8	18.9	108	2020-06-01 / 2020-10-05	2020-10-07	20.8
	14-506	ASP	202	32.8	69	2020-06-01 / 2020-08-06	2020-08-26	8.7
	15-508	REF	304.8	63.8	84			0
	18-054	ASP	304.8	32.3	110	2020-06-01 / 2020-10-05	2020-10-07	19.3

Stream Chemistry

A 100 mL water sample was collected once per month from the downstream end of each watershed during the summer (June, July, August). They were filtered via Whatman® GF/F .7 µm filters and then frozen on the day of collection. They were analyzed for nitrate-nitrite ($NO_3^- + NO_2^-$) and orthophosphate (PO_4^{3-}) at OSU/USGS

Institute for Water and Watersheds 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-}.

Temperature

To collect temperature data, 12 Onset HOBO® TidbiT® v2 temperature data loggers (Onset Computer Corporation, Bourne, MA, USA) were deployed in-stream along each watershed. They were held in place by metal rebar and housed in small Polyvinyl Chloride solar shields. The loggers were set to record temperature continually every 15 minutes and were offloaded once every 3 months. The data collected was used to construct a 7-day rolling average of daily maximum temperatures (7DMMT) during the summer low-flow period. Stage was monitored using a pressure transducer (Levelogger Edge, Model 3001, Solinst Canada Ltd., Georgetown, ON, Canada) housed in a PVC stilling well at the outlet point of each watershed. Temperature data was excluded when stage was less than or equal to zero, where it was assumed there was no flow and measured temperatures were reflective of air temperatures.

Topographic Variables

To account for variability between headwater catchments, I calculated topographic variables in ArcGIS Pro ver. 2.9[31] (Esri, Redlands, CA, USA) using a 0.25 m resolution digital elevation model (DEM) provided by GDRC and Spatial Analyst Tools in the toolbox. Selected parameters were percent north (a function of average slope aspect), drainage area, average slope, aspect, topographic wetness index (TWI), watershed-wide stream slope, and average active channel width. TWI was calculated using the formula $TWI = ln(a/tan(b))$, where a is the upslope contributing area and b is the local slope. It is a unitless parameter which explains ground and surface water patterns[32]. For the purposes of linear modelling, slope aspect was converted from a degree value (0-360) to percent north using the equation $\frac{|180-aspect|}{180}$.

Table 2. Topographic characteristics for each watershed. Percent north is derived from average watershed aspect, *n* = 5 for WF Tectah and *n* = 5 for McGarvey.

Sub-basin	*Watershed ID*	*Percent north*	*Mean 100 ft buffer TWI*	*Drainage area (ha)*	*Average active width (m)*	*Elevation (m)*	*Average watershed slope*	*Watershed-wide stream slope*
WF Tectah	01-501	16.92	2.02	39.70	1.70	432	25.40	0.20
	02-014	13.64	1.95	30.60	1.90	428	24.70	0.14
	03-008	7.38	1.97	33.40	2.00	429	23.70	0.15
	04-007	21.90	1.87	37.80	1.80	425	23.70	0.18
	05-502	34.76	1.90	30.50	1.40	435	19.02	0.18
McGarvey	11-507	22.30	1.86	40.50	1.80	81	30.50	0.21
	13-055	22.27	1.83	18.90	1.70	108	25.20	0.26
	14-506	23.41	1.68	32.80	1.60	69	29.70	0.19
	15-508	5.12	1.83	63.80	2.10	84	27.00	0.20
	18-054	14.44	1.76	32.30	1.80	110	25.60	0.16

Primary Productivity

Primary productivity was measured once per month in the summer using 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 up until the 50-meter mark, leading to a total of 100 readings per watershed per month. Due to obstructions such as log jams and low flows, it was not always possible to reach 100 readings. The readings were then averaged to one measurement for each 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. Measurements in direct sunlight tend to be underestimated by the BenthoTorch[33].

Statistical Methods & Model Selection

To test for the effects of harvest on nutrient concentrations, the treatments were pooled together and the post-harvest values were adjusted for changes in the reference, which was assumed to be the baseline change caused by inter-annual variability. The non-parametric bootstrapped Kolmogorov-Smirnov (K-S) test with α=.1 from the *Matching* package[34] in Rstudio[35] (Rstudio, Boston, MA, USA) was then used to determine the significance of the effect of harvest.

For quantifying stream temperature changes, reference temperature along with harvest period was used to predict treatment stream temperature with the linear model $Ts_{Trt} = Ts_{Ref} + Harvest + (Ts_{Ref} * Harvest)$. Ts_{Trt} is the 7DMMT in the treatment watershed, Ts_{Ref} is the 7DMMT in the reference watershed, and $Harvest$ is the harvest period pre- or post-harvest). The interaction term $Ts_{Ref} * Harvest$ was tested for significance to determine effect of harvest using analysis of covariance (ANCOVA) in the base version of R.

To select the best model for predicting chlorophyll-*a* concentrations, the *leaps* package[36] in RStudio was used to determine the best combination of parameters for each given number of predicters. Variables included were all of the topographic metrics in addition to 7DMMT and nutrient concentrations at the date of measurement. Out of these, the model with the lowest Bayesian Information Criterion (BIC) score was selected. Variance Influence Factor (VIF) was then used to test for multicollinearity and parameters with a score above 5 were substituted post-hoc for another using a correlation matrix for reference.

Results

Stream Chemistry

Average N concentrations were significantly different (Welch's t-test, $p<0.001$) between the WF Tectah and McGarvey watersheds (0.066 and 0.607 mg/L respectively). Average P concentrations were much lower than N concentrations and did not differ significantly between the two areas (0.015 and 0.014 mg/L respectively, $p=0.317$) (Fig. 2). Watershed 03-008 (WF Tectah, HCP) had the lowest mean N concentration at 0.033 mg/L, while watershed 11-507 (McGarvey, REF) had the highest mean N concentration at 0.812 mg/L. Watersheds 05-502 (WF Tectah, REF) and 11-507 had the lowest and highest P concentrations at 0.009 mg/L and 0.016 mg/L respectively.

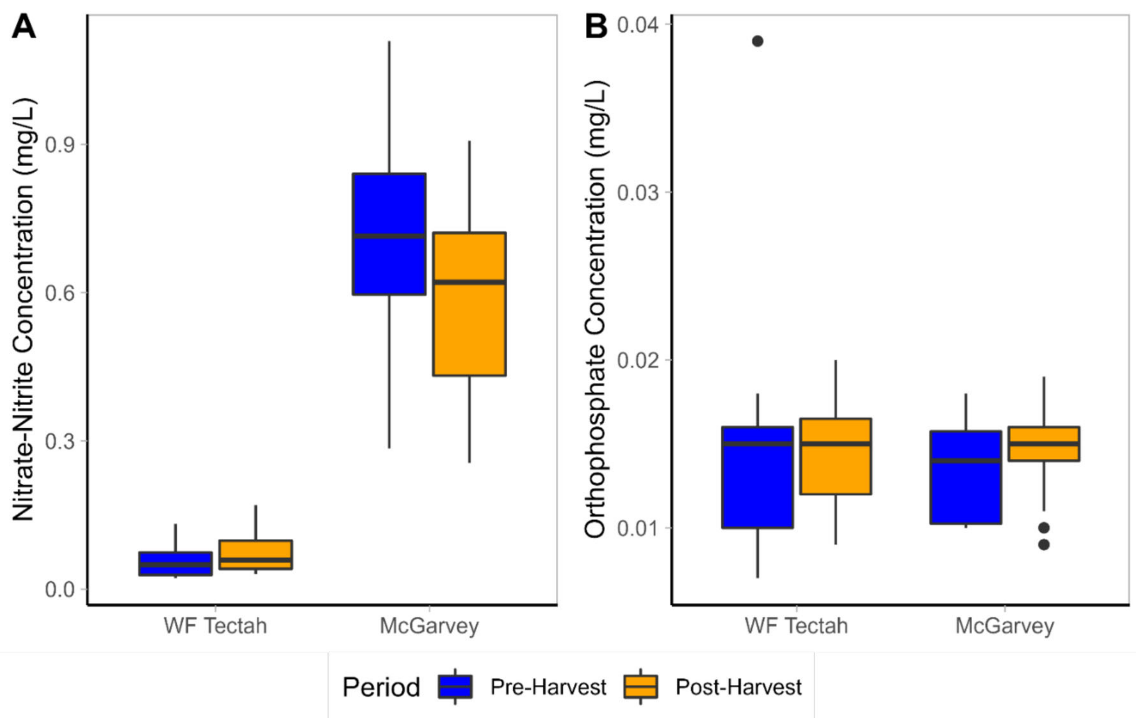


Figure 2. Nutrient differences between watersheds. Boxplots showing A) Nitrate-nitrite and B) orthophosphate concentration medians and quartiles by watershed group.

In WF Tectah, N concentrations increased as summer progressed in all watersheds and periods. N concentrations increased post-harvest, including in the REF watershed (01-501, Fig. 3A). The WF Tectah PRE watershed (02-014, Fig. 3A) saw the largest increase in N (34.8%), compared to only respective increases of 27.15% and 34.8% in the reference watersheds (01-501 & 05-502). The HCP watershed (03-008, Fig 3A) increased by 20.4% while the ASP treatment (04-007, Fig 3A) increased the least by 12.1%. At the McGarvey watersheds, N had the trend of decreasing as the summer progressed, as well as a consistent decrease in the post-harvest period to varying degrees. Reference watershed 11-507 (Fig. 3A) had the biggest decrease in N in McGarvey during this period at 24.4%. P did not follow a clear trend across the season or time period in either group (Fig. 3B), but levels were generally slightly higher in the post-harvest period.

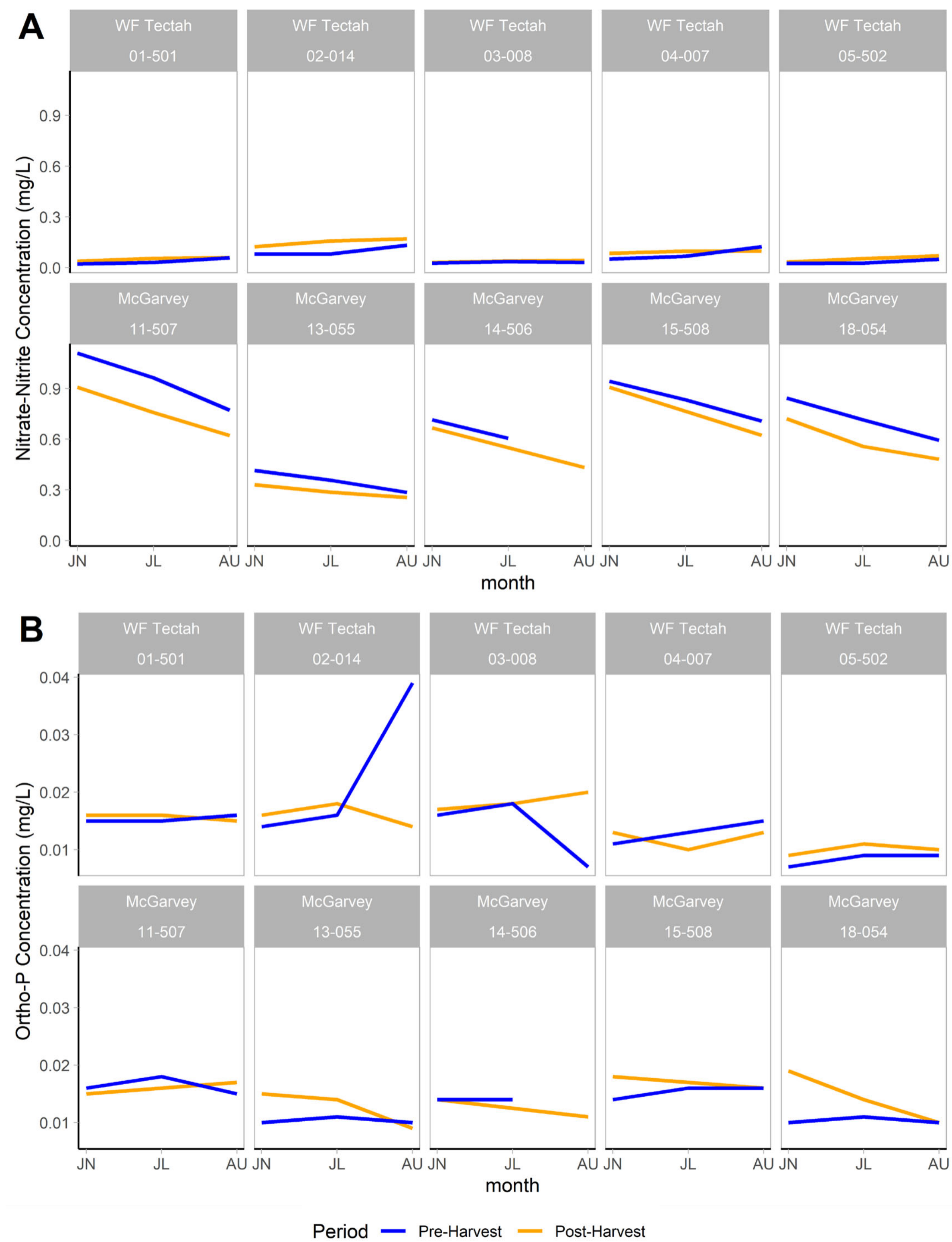


Figure 3. Nutrient changes over time. Concentrations of A) nitrate-nitrite and B) orthophosphate for each watershed over the summer comparing pre- vs post-harvest. 01-501, 5-502, 11-507, and 15-508 are reference watersheds. 14-506 (ASP treatment) was harvested in August 2020, hence the shorter pre-harvest period.

For the purpose of analyzing the effects of harvest on nutrient concentrations, I pooled all treatments together and subtracted the time-period and watershed-specific reference value. Mean N increase post-harvest using this method was 0.055 mg/L, while for P the increase was 0.002 mg/L. The cumulative density function for N and P (Fig. 4A & 4B) show a slight shift in concentration favoring the treatment. When the two-sided, bootstrapped Kolmogorov-Smirnov (K-S) test was performed, the difference for N was not significant (p = 0.697). For P, there was some evidence to suggest there was a significant difference (p = 0.105 - 0.088).

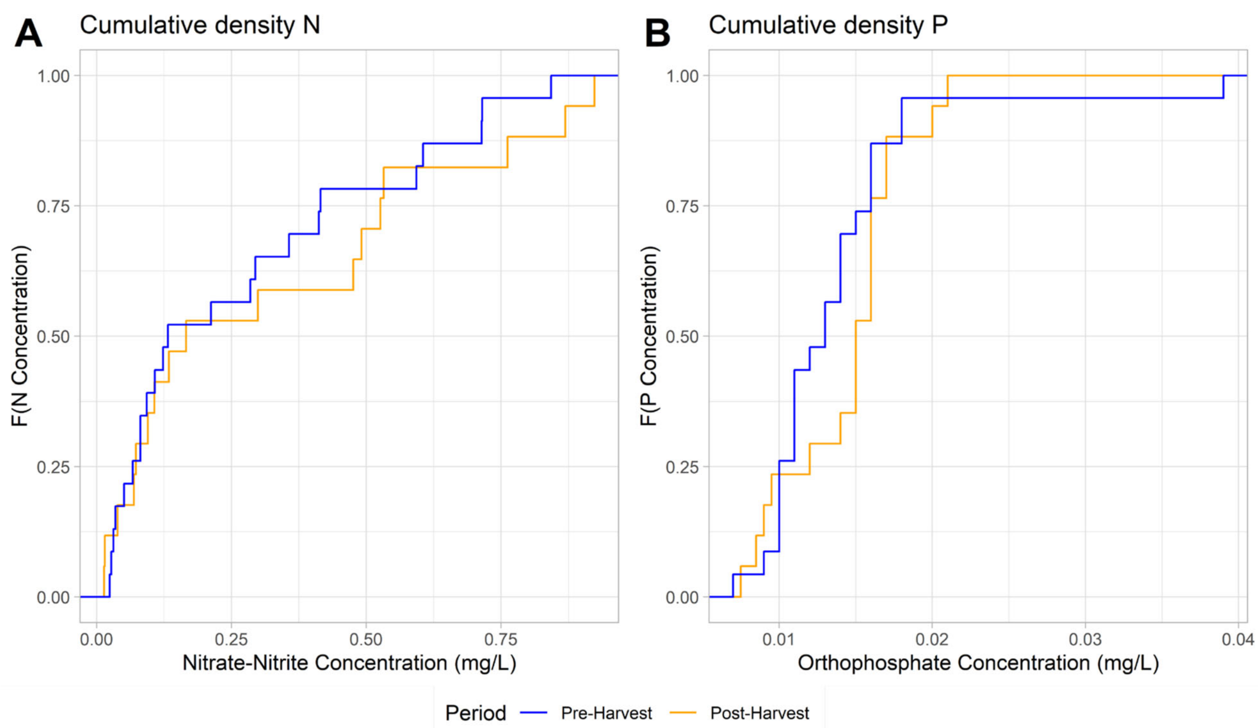


Figure 4. Pooled nutrient concentration responses to harvest. Cumulative density function of a) nitrate-nitrite and b) orthophosphate for the pre- and post-harvest periods. The post-harvest curve was adjusted for changes in references between the two periods.

Stream Temperature

Mean 7-day moving maximum temperatures (7DMMT) were significantly different between WF Tectah and McGarvey (Welch's t-test, p<0.001). McGarvey mean temperatures were 13.03 °C, around 0.18 °C higher than the mean of 12.85 °C in WF Tectah watersheds. The post-harvest period also had a marginally higher mean 7DMMT (12.89 vs. 12.99 °C, p=0.017) than the pre-harvest period independent of harvest effects, but this difference was smaller than the difference between McGarvey and WF Tectah. The median 7DMMT was slightly higher in McGarvey compared to WF Tectah during the pre-harvest period, but was slightly lower during the post-harvest period (Fig. 5).

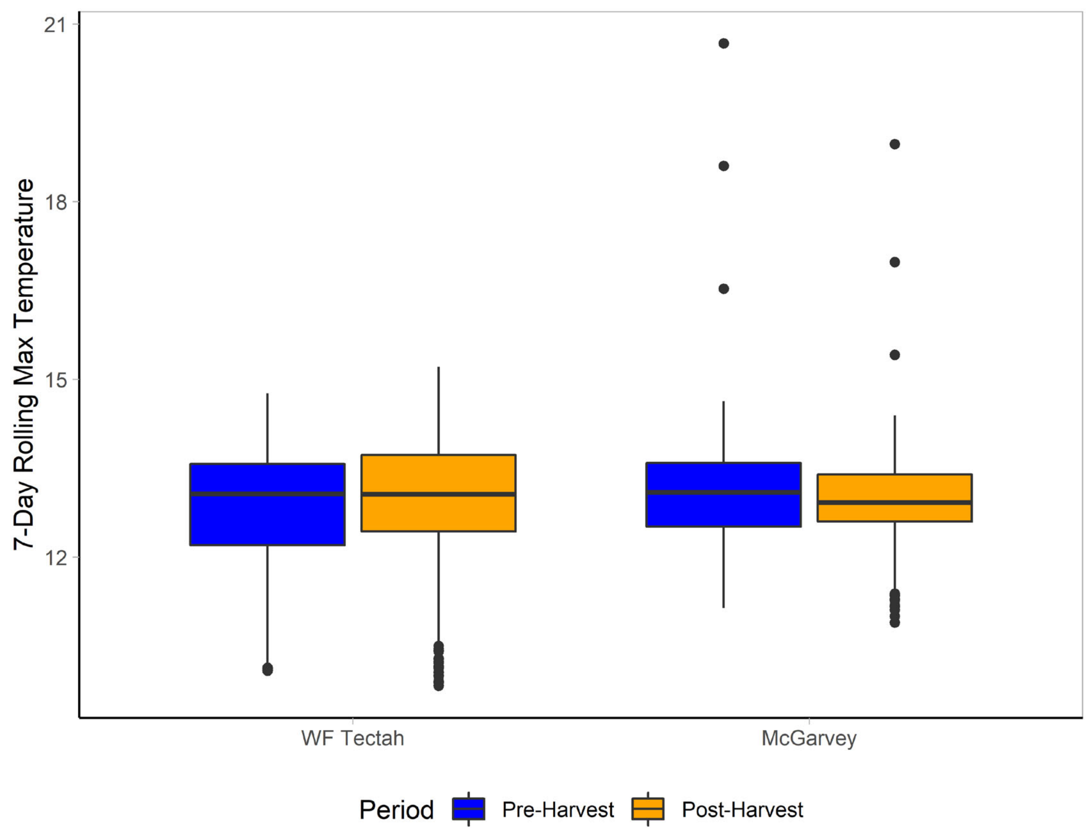


Figure 5. Differences in temperature between watershed groups. Boxplot of 7DMMT showing the medians and distribution of temperature ranges of each sub-basin between harvest periods.

Changes in 7DMMT relative to reference varied by treatment watershed and were small overall. The ANCOVA test on the interaction between harvest period and reference temperature found a small but statistically significant increase in stream temperature for watershed 2 (WF Tectah PRE, p=0.015) (Table 3 & Fig. 6) and 4 (WF Tectah ASP, p<0.001). However, no significant changes were observed in watershed 3 (HCP, p=0.678). In the McGarvey watersheds, only watershed 18 saw a significant change in temperature (McGarvey ASP, p=0.014).

Table 3. Slope difference estimate of post vs. pre-harvest and *p*-value for each harvested watershed. Bolded *p*-values indicate significance at α=0.05.

Sub-basin/Watershed	*Treatment*	*Estimate*	*p-value*
WF Tectah			
02-014	PRE	0.029	**0.015**
03-008	HCP	0.011	0.678
04-007	ASP	0.093	**<.001**
McGarvey			
13-055	HCP	-0.175	0.111
14-506	ASP	-0.122	0.444
18-054	ASP	-0.122	**0.014**

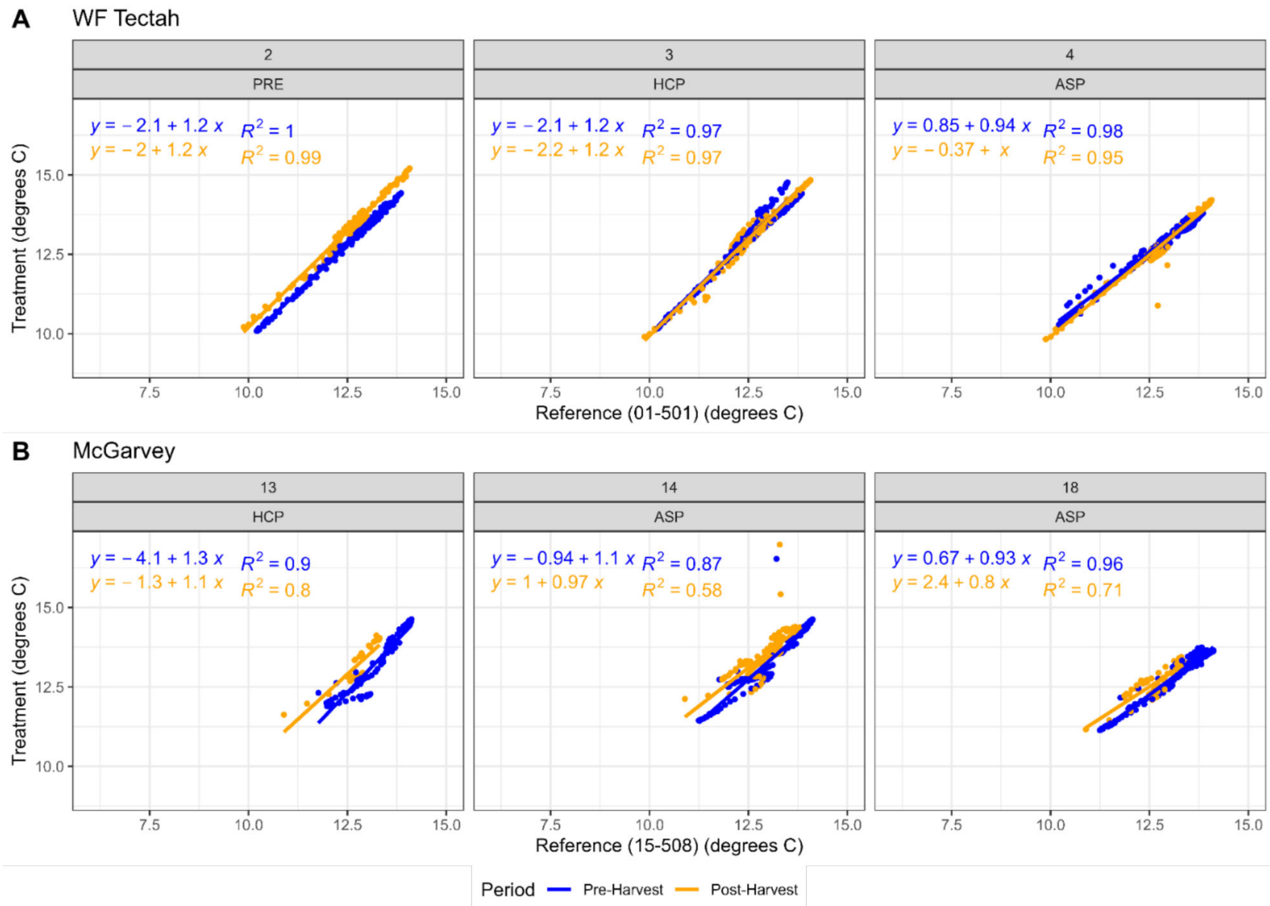


Figure 6. **Stream temperature responses to harvest.** Relationship between reference temperature and treatment watershed pre- and post-harvest for **A**) WF Tectah and **B**) McGarvey. R^2 value indicates how well the reference predicted the treatment temperature. The R^2 almost always decreased in the post-harvest period.

Physical Environmental Factors

Several topographic variables were significantly correlated with each other when combining all 10 watersheds from both groups (Figure 7). Mean watershed aspect was negatively correlated with watershed aspect and positively correlated with average slope. Elevation was positively correlated with 100 ft buffer TWI and negatively correlated with mean N, mean 7DMMT, and average watershed slope. Increasing degree of northerliness was highly negatively correlated with active width, and moderately negatively correlated with P. Increased stream slope was moderately positively correlated with mean 7DMMT.

Figure 7. Pearson Correlation coefficients for topographic factors for WF Tectah (top) and McGarvey (bottom). * indicates significance level $\alpha = 0.05$, ** indicates significance level of $\alpha = 0.01$, and *** indicates significance level of $\alpha = 0.001$.

Primary Productivity

Chlorophyll-*a* concentrations were significantly different between watersheds (Mann-Whitney U test, W = 1683125, $p<0.001$), with WF Tectah having higher median values (Fig. 8). Mean concentration was 3.49 μg/cm^2 (std. deviation = 1.95) for WF Tectah and 3.09 μg/cm^2 (std. deviation = 1.24) for McGarvey. Mean concentrations decreased significantly post-harvest in WF Tectah from 4.25 μg/cm^2 to 3.80 μg/cm^2 (Figure 9, Welch's t-test, p=.001), but did not change significantly in McGarvey (Figure 9, p=0.812).

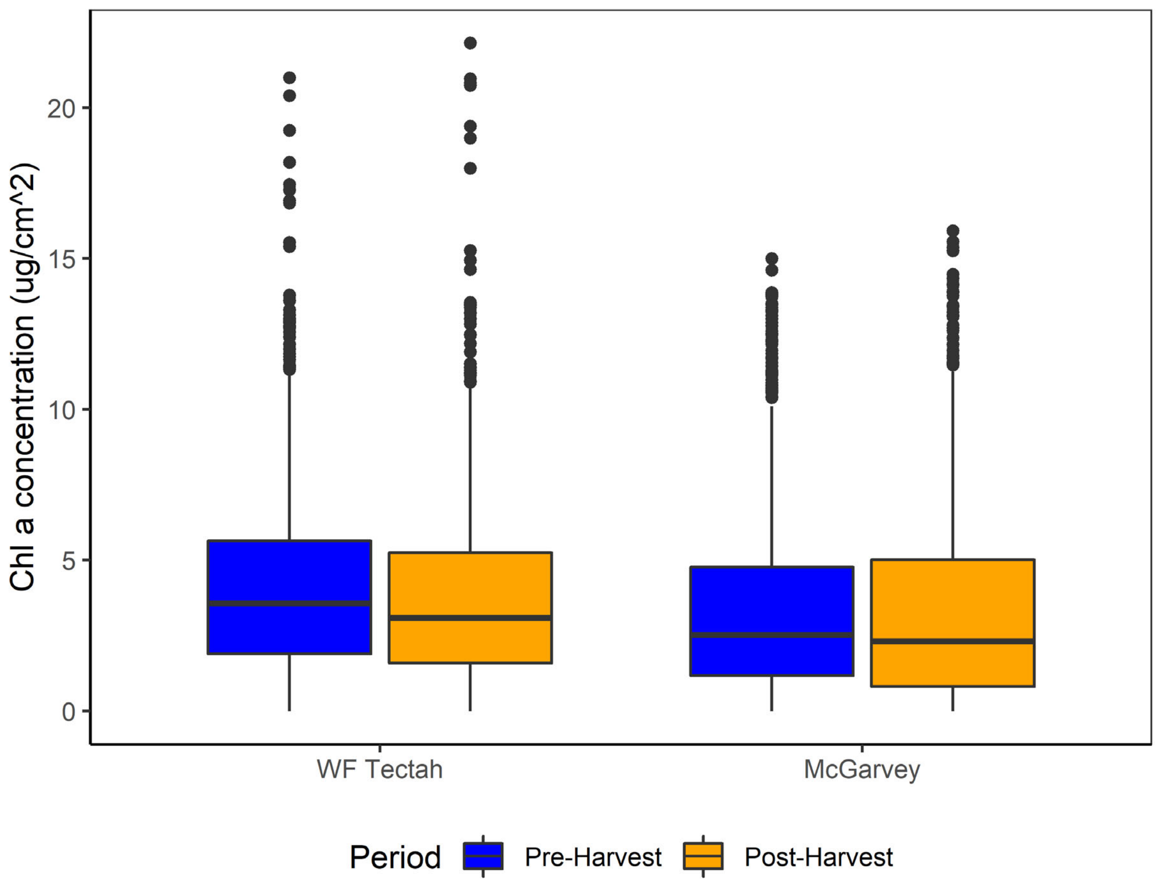


Figure 8. Primary Productivity. Boxplots of Chlorophyll-*a* concentration medians and quartiles by sub-basin and harvest period.

The most productive watershed on average was 13-055 (mean chlorophyll-*a* concentration = 6.22 μg/cm^2), while the least productive watershed was 14-506 with a mean concentration of 2.18 μg/cm^2. Changes in chlorophyll-*a* varied by watershed during the pre- and post-harvest periods and were not consistent by treatment. In WF Tectah, 01-501 (REF) the concentration median decreased by 1.06 μg/cm^2 while watershed 05-502 REF increased by .29 μg/cm^2 from the pre- to post-harvest period (Fig. 9A). McGarvey reference watersheds 11-507 increased by 0.79 and 15-508 decreased by 0.23 μg/cm^2. The one Pre-ASP watershed, 02-014, decreased less than the adjacent reference from a similar starting point (3.75 μg/cm^2) to 3.45. The HCP watersheds in both sub-basins, 03-008 and 13-055, had medians that decrease by 1.13 and 0.85 μg/cm^2 respectively. 14-506 had the largest change in median concentrations across all watersheds, decreasing by 1.32 μg/cm^2.

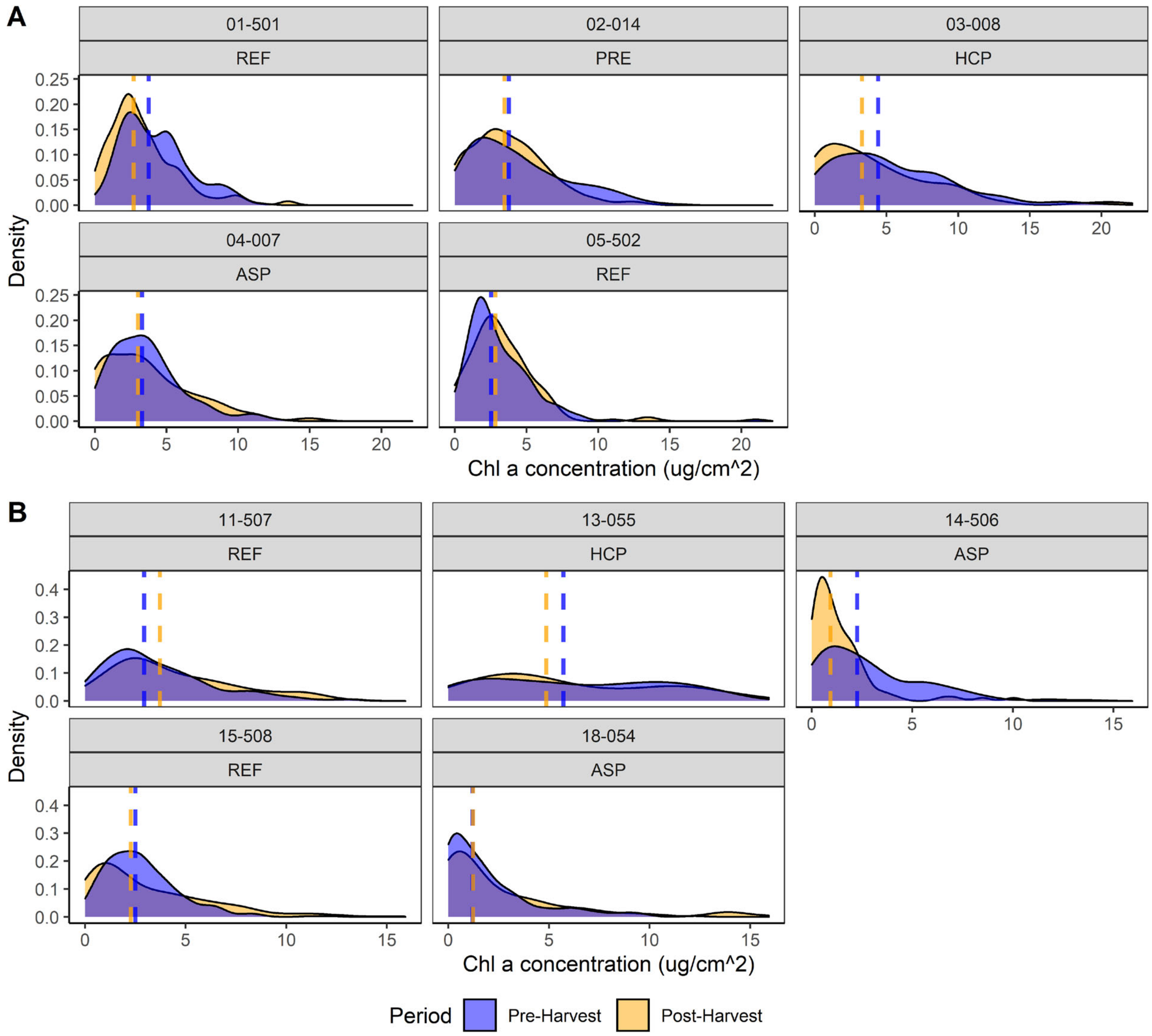


Figure 9. Pre and Post-harvest Chlorophyll-*a* concentration probability density functions for each watershed. A) is WF Tectah and B) is McGarvey. Dashed lines indicate median values for each corresponding period.

Using a forward selection process for multiple linear regression models and then ranking them by Bayesian Information Criterion (BIC) score indicated that 7DMMT and percent north of the watershed aspect were the best predicters for chlorophyll-*a* for WF Tectah, with 35% of the variability predicted. Both parameters had negative coefficients. In McGarvey, Buffer TWI, N, and 7DMMT were the most important parameters for predicting chlorophyll-*a* concentrations while avoiding multicollinearity, explaining 57%

of the variability. 7DMMT and N were negatively associated while average buffer topographic wetness index was positively associated (Table 4).

Table 4. Multiple linear regression forwards selection results. Lowest BIC model is displayed with temperature and nutrient model for comparison underneath for each watershed group**.** (+) and (-) indicate whether parameter coefficient is positive or negative. *n* = 34 for McGarvey and *n* = 38 for WF Tectah.

Sub-basin		*Parameter*	*Parameter p-value*	*BIC*	*Adj.* R^2	*F-statistic*	*Model p-value*
WF Tectah	Best Model	7DMMT (-)	**<0.001**	119.259	0.3505	10.98, 2 & 35 DF	**<0.001**
		Percent North (-)	**0.006**				
	Temp + Nutrient Model	N (-)	0.44	129.638	0.202	5.899, 3 & 34 DF	**0.014**
		P (+)	0.316				
		7DMMT (-)	**0.005**				
McGarvey	Best Model	Mean Buffer TWI (+)	**<0.001**	127.020	0.566	15.35, 3 & 30 DF	**<0.001**
		7DMMT (-)	**<0.001**				
		N (-)	**0.002**				
	Temp + Nutrient Model	N (-)	0.066	143.955	0.286	5.405, 3 & 30	**0.004**
		P (+)	0.695				
		7DMMT (-)	**<0.001**				

Testing for the impact of harvest for the purposes of a BACI analysis using the term $trt * year$ suggested it had no significant, independent effect (*p* = 0.45 – 0.65).

Discussion

I hypothesized that the post-harvest period would have modestly higher N and P concentrations in the harvested watersheds relative to the reference watersheds during the summer low-flow period. Both N and P saw slight increases in concentration post-harvest, but neither of these changes were considered significant. These results correspond with nutrient responses found in similarly-sized watersheds with similarly-sized buffers in southern British Columbia[5]. This could be because of the low percentage of watershed area harvested, although this percentage still varied greatly (Table 1). Other studies showing an increase in nutrients also had much higher harvested area percentages, ranging from 36% reported in some Oregon Cascades watersheds[37] to 100%[1,38] in other locations.

Additionally, since the measurements were taken during summer, there was no recording of nutrient concentration responses to storm events. These responses can vary between harvested and unharvested watersheds[37] and illuminate nuances that are otherwise too difficult to capture. The large differences in N concentration between WF Tectah and McGarvey may be driven by differences in slope, as steeper slopes have been found to correlate with higher stream N levels[39,40]. The steepest watershed (11-507) had the highest nitrate-nitrite concentration while the shallowest watershed (05-502) had the lowest N concentration, but this did not explain the entirety of the variation (R^2 = 0.57, Supp. Fig. 1). Conversely, there was a weak negative correlation between Topographic Wetness Index and average N concentrations found in this study (Fig. 7). This is hypothesized to be because of higher hydrologic residence times[41] which increases N uptake and denitrification processes[42]. Elevation could also play a role in the percent area of a watershed covered by broadleaved trees, which has been shown to increase N-concentrations in streams[41,43]. This difference is largely attributed riparian N_2-fixation, primarily by Alder species such as *Alnus rubra*, as greater watershed coverage of alder has been shown to increase stream N concentrations[44]. An additional explanation could be differences in nitrogen deposition driven by topography, but this would need to be explored further.

I initially hypothesized that temperature would increase slightly in the harvested watersheds during this time period compared to the references. This was observed in all of the watersheds that had above 10% of the area harvested. Differences between watersheds can also be explained by other factors that influence shading of the stream channel, mainly: channel aspect. All watersheds in the study had channel aspects that were either west, east, or slightly north from west. Additional important factors not taken into account that may be influencing differences in temperature between watersheds are phreatic aquifer interactions[45], and geomorphologic factors such as active channel width, riffle width, and mean pool depth[16]. Overall, stream temperatures were higher in the post-harvest period regardless of treatment, which demonstrates the need to consider inter-annual variation when accounting for disturbance effects. However, part of this variation can be explained by a lack of June data of the post-harvest period in McGarvey.

I expected temperature and nutrients would play an important role in predicting chlorophyll-*a* concentrations. The average concentration I measured was 3.293 $\mu g/cm^2$, which is in the 2-4 $\mu g/cm^2$ range where the BenthoTorch was found to be most accurate by Kaylor et al. The values that I measured were 10 to 20 times greater than concentrations reported in headwaters in Kings River Experimental Watershed in the California Sierra Nevada mountains during late summer/early fall[46], but were similar to values measured summer in non-headwaters with the BenthoTorch in the Upper Grand Ronde river basin[33].

WF Tectah achieved similar levels of chlorophyll-*a* concentrations compared to McGarvey despite much lower N concentrations. Additionally, there was no significant relationship between N and chlorophyll-*a*. This indicates that there could be higher levels of in-stream N fixation, which has been shown in other areas to be able to meet or even exceed inorganic N uptake levels[47], but is impaired by higher levels of in-stream inorganic N[44,47]. This, along with the negative effect of N concentrations on periphyton in McGarvey, indicate that N is not a limiting factor in these ecosystems and is more likely limited by light availability[22,48], although this was not quantified in this study. Light has been shown to be the most important control on chlorophyll-*a* in other forested Pacific Northwest headwaters[49]. The two least productive watersheds, 14-506 and 18-054, both had fallen logs which directly shaded large sections of the sampling portion of the watershed.

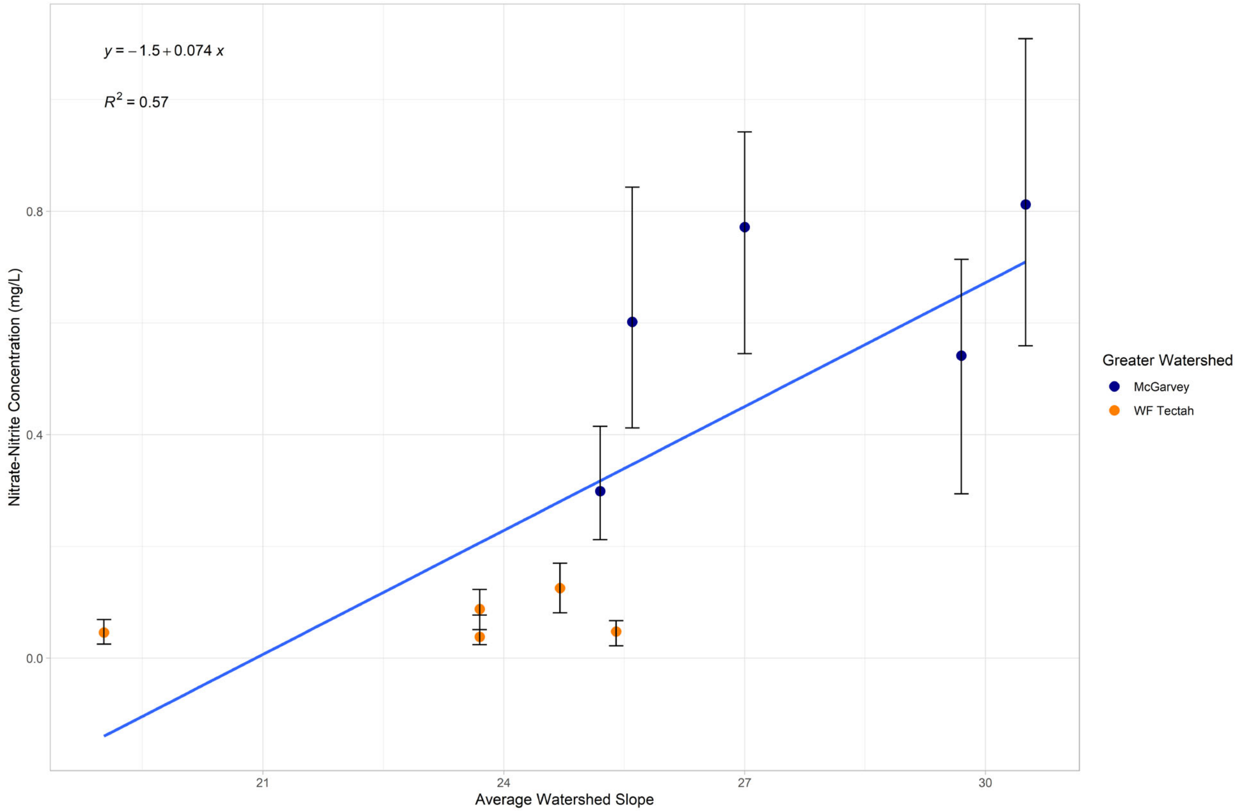
Temperature was a key predictor in both. The negative correlation between temperature and chlorophyll-*a* is likely due to dominance of diatoms in these watersheds, as autochthonous primary productivity in headwater systems with cooler temperatures, oligotrophic nutrient levels, and lower light levels tends to largely be controlled by diatoms[24,25]. Alternatively, this relationship could be indicative of the top-down effect of grazing macroinvertebrates. Temperature increases have been shown to change periphyton-grazer dynamics, causing periphyton biomass to peak at the beginning of summer in shallow lake environments[50]. This is likely especially the case for the streams used in this study, as the study occurred during drought years and the absence of insectivorous fish would not provide alleviations to grazing pressures.

Important metrics I did not measure that future research in this area should focus on with respect to primary productivity are light, which is important for overall in-stream primary productivity[22,48], and dissolved silica, a diatom and cyanobacterial growth driver in other environments such as intertidal sediments[51] and subtropical rivers[52]. Very little, if any, research has focused on the role of dissolved silica in headwater periphyton communities and how this relationship is affected by harvest. I was limited by the number of watersheds I had (n = 10) and by time (1 summer pre-harvest, 1 post-harvest) in addition to low sampling frequency for nutrients and primary productivity.

Conclusion

In my study, I found that current forest harvest practices (large riparian buffers >30 m, small clear cuts <30% of drainage area) have no significant impact overall on nitrate-nitrite and phosphate concentrations during summer months. The effects were mixed on stream temperature, and even those significantly impacted increased no more than 0.25 °C. Furthermore, harvest did not appear to significantly impact in-stream chlorophyll-*a* concentrations, which were largely driven by topographic characteristics and temperature. Water quality during high flow and runoff periods was not considered in this study, but could be an important period to focus on in future research. All together, these results will aid in the overall evaluation of current forestry practices, particularly in the state of California.

Appendix



Supp. Fig. 1. Scatterplot of average watershed slope vs. N concentrations. Points represent watershed means and bars represent minimum and maximum values.

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